Neurophysiology of Mindfulness Meditation: A Narrative Review Based on Buddhist Perspective

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ABSTRACT

Meditation, an inward journey to explore profound levels of consciousness rooted in Buddhism, has significant physical and psychological benefits, including enhanced well-being, improved concentration, emotional stability, and positive cognitive shifts. This narrative review consolidates past two decades of research on the neurophysiological effects of Buddhist mindfulness meditation based on neuroimaging findings, and aims to examine the Buddhist view of mindfulness meditation in relation to the structural and functional changes in the brain areas in health and diseases. Meditation practices, such as Vipassana in Buddhism, emphasize mindfulness and non-judgmental awareness of oneself and surrounding. Neuroimaging studies have revealed its significant impact on brain regions including structural changes involving anterior cingulate cortex (ACC), temporal lobe, insula, hippocampus, amygdala, thalamus and other areas.

Four fundamental mechanisms summarize the mindfulness meditation: attention regulation, body awareness, emotion regulation, and a transformed self-perspective. The scientific explanation of effects of meditation is challenging, and we are only beginning to understand in neurophysiological terms. Previous research on mindfulness meditation has employed diverse methodological approaches, including self-reported measures, behavioral tasks and neuroimaging techniques; but there lacks a standardization, making it difficult to compare the findings. However, the cognitive processes are thought to underlie the potential benefits of mindfulness meditation in promoting mental well-being on an individual and societal level.

This review highlights the mechanisms of mindfulness meditation to improve cognitive flexibility and promote mental well-being, in relation to Buddhist philosophy, with implications for individual and societal benefits.

KEY WORDS

Buddhism, Cognition, Consciousness, Meditation, Mindfulness, Neurophysiology

INTRODUCTION

Buddhism describes meditation as the path towards inner awakening, a journey of self-discovery that leads to profound transformation of the mind and spirit. The practice of meditation to achieve inner peace and enlightenment is widespread and well known throughout the human history. Different religions have given meditation the utmost importance to achieve the ultimate truth. But it cannot be confined within the religious boundaries; rather it is a phenomenon for achieving the higher alertness and greater potentials of mind.¹ In an attempt to answer the question "why should we meditate?" the great Buddhist teacher and peace activist Thich Nhat Hanh replies, "To feel the total relaxation of mind and body, including during sleep". He argues that a complete state of tranquility is possible only during meditation.² Herbert Benson, one of the pioneers in scientific research on meditation has also described meditation as a state of total relaxation.³

The term meditation is used broadly, and includes different practices like mindfulness meditation, mantras, tratak, pranayam, Zen, transcendental meditation, kundalini yoga etc. Among these varieties, mindfulness meditation which is referred as non-judgmental living in the present moment has been widely studied in neuroscience in past few decades.⁴ The earliest evidences related to meditative culture prevalent in the world is of around 2500 to 3000 BCE in Indus valley civilization which was spread from Pakistan of present era to Ganges valley.⁵ More than 2500 years ago, Gautama the Buddha stated mindfulness meditation as the true key to the liberation. Buddhist mindfulness techniques including Anapanasati (breathing awareness) and Vipassana meditation practices has been practiced by monks around the World to achieve the highest spiritual realizations.⁶

In recent years, much emphasis has been given to yoga, meditation and related discourses. Most studies have primarily focused on the behavioral, clinical, and subjective outcomes of mindfulness meditation, such as improvements in attention, reduced anxiety and enhanced emotional regulation. However, the neurobiological basis of such effects are challenging to delineate for several reasons. First, the diverse methods and techniques within the broad category of mindfulness meditation can lead to varied neural responses. The heterogeneity in participant populations, including differences in meditation experience and baseline mental health, can introduce confounding variables. Also, the complex interplay between psychological, physiological, and environmental factors means that the specific effects of meditation cannot be easily selected among many nonspecific effects. Finally, to observe the structural and functional changes in brain, researchers utilize tools such as electroencephalography, functional magnetic resonance imaging (fMRI) and Positron Emission Tomography (PET), which have their own limitations, and are also expensive. EEG provides excellent temporal resolution but has poor spatial resolution, making it difficult to locate specific brain regions involved. MRI and functional MRI, on the other hand, offer high spatial resolution, enabling precise localization of brain activity, but they have low temporal resolution and require subjects to remain still inside a noisy and confined scanner, which may disrupt natural meditation states. PET, though valuable for measuring metabolic changes, has low temporal resolution and involves the use of radioactive tracers, making repeated studies less ideal for long-term meditation research. In spite of convincing theoretical proposals and about five decades of research reports, little has been discovered about the neurophysiological basis of meditation.⁷⁻⁹ But a combined approach of these methods allows us to build a more comprehensive understanding of how meditation shapes brain structure and function over time.

In this study, articles regarding effects of Buddhist mindfulness meditation on neurophysiology in the past two decades has been reviewed and consolidated them in line with Buddhist literature and philosophy on meditation. By synthesizing and analyzing relevant studies, we shed light on the potential mechanisms underlying the effects of mindfulness meditation on brain function and structure. The objectives of this review include examining the findings of neuroimaging and electrophysiological studies on mindfulness, investigating the structural changes in the brain associated with long-term mindfulness meditation practice, and discussing the potential implications of the neurophysiological changes observed in relation to mental health and well-being.

Mindfulness is about developing complete awareness, to what is happening in the present moment.¹⁰ The term mindfulness is the English translation of the Pali word sati which means awareness and attention.¹¹ The Sanskrit word for the same is smriti which literally means remembering. So, mindfulness is the art of remembering to live in the present moment.¹² It is also an art of being an observer of the present moment without any judgment.¹³ Jon Kabat Zin, a founding member of Cambridge Zen Center, defines mindfulness as "the awareness that emerges through paying attention on purpose, in the present moment, and non-judgmentally to the unfolding of experience moment by moment".¹⁴

Though there are widespread views on the concept of Buddhist mindfulness, there is general agreement on two integrative and complementary facets of mindfulness meditation i.e. focused attention (as Samatha, in Buddhist practice) and Vipassayana.¹⁵⁻¹⁷ In literal sense, these are not the different types of meditation; rather, these are the virtues of mind that should be cultivated. Samatha is referred to as single pointed attention practice. It includes variety technique to achieve tranquility of mind. Vipassana is insight-oriented meditation which is referred to as seeing, exploring and discerning of activities. Bhikku Sujato has explored these two facets of meditation as follows, "Broadly speaking, Samatha refers to the emotional aspects of our minds, the heart qualities such as peace, compassion, love, bliss. Vipassanā refers to the wisdom qualities such as understanding, discrimination, and discernment. Samatha soothes the emotional defilement such as greed and anger, while Vipassanā pierces the darkness of delusion with understanding".5

In the "Discourse on the Four Establishments of Mindfulness" (Satipatthana Sutta) which is considered as the most important discourse ever given by the Gautam Buddha on mental development, he describes, "we can focus on four objects for mindfulness practice: our body, our feelings, our mind, and the objects of our mind".^{5,12} During this practice, one should begin by observing closely to the nature of the body. Then the practitioner shifts the focus to their feelings like pleasure and pain. One should be persistent in their observation like a scientist who wants to understand this phenomenon. Feelings arise and fade away but one should observe it wholeheartedly in a nonjudgmental way. Then the attention should be increased on other mental phenomenon and consciousness itself and finally should try to witness diverse mental processes like imaginations, thoughts and dreams.¹

Mindfulness meditation nurtures higher awareness and clarity in life. This practice of living consciously is the

practical way to live with the fullness of one's being which opens the path of greater wisdom through a systematic process of self-observation, self-inquiry, and mindful action.¹⁴

Effects of mindfulness meditation in neuronal circuitry

The states of awareness during meditation and the underlying neurological phenomenon behind this has been researched in past few years by the scientists across the world.¹⁸⁻²² The primary goal of mindfulness meditation is to attain a state of heightened awareness. Besides, physical and psychological benefits are also achieved as byproducts of mindfulness which may include greater well-being, the ability to concentrate better, release of stress, improvement in quality of sleep, and reduction in symptoms of anxiety, depression and psychological distress.²³⁻²⁹

A number of cross-sectional as well as longitudinal studies throughout the world in recent past have proved the significant impact of mindfulness on neurophysiology.³⁰⁻³⁴ Basically, the brain areas involved are the functional areas, including the anterior cingulated cortex (ACC), orbitofrontal cortex, inferior temporal gyrus, lateral frontal region, insula, cerebellum, hippocampus, amygdala, thalamus, basal ganglia, subcortical grey and white matter and brain stem which suggest that there is widespread impact on large scale networks of brain.^{4,35}

Hölzel and colleagues have proposed a framework encompassing four interacting mechanisms that underpin the benefits of mindfulness meditation: attention regulation, body awareness, emotion regulation, and a change in perspective on the self.³⁶ They highlight the cognitive, emotional, and neurobiological processes involved in the practice. We now explore these mechanisms in relation to our current knowledge of neurophysiology.

Attention regulation

From the Buddhist era, mindfulness meditation is practiced to cultivate the virtue of attention. Several scientific researchers have consistently documented heightened attention in meditation practitioners.^{7,37-40} According to Buddhist philosophy, chronically tormented mind is the reason behind all the negative impacts on health and can also cause somatic disorders. Objective awareness allows one to interpret emerging thoughts as the spontaneous activity of mind and prevents experiencing it irrationally as fact.

Mindfulness meditation has shown improvement in such conditions as it brings positive psychological changes.^{41,42} And has clinical implications for disorders such as attention-deficit hyperactivity disorder (ADHD) and bipolar disorders.^{17,32,43}

Neuroimaging researches have established that various areas including ACC, Dorsomedial prefrontal cortex (dmPFC), and right parietal cortex are responsible for execution of attention regulation.^{44,45} Mindfulness meditation increases

activity in PFC and ACC, the constituents of default mode network (DMN).^{46,47} It modifies all three neural processes for attention as per Michael Posner's model of the attention system. The model includes the alerting system (involving the thalamus and frontal areas), the orienting system (involving the superior parietal region, temporo-parietal junction, ventrolateral PFC, and frontal eye fields), and the executive control system (involving the ACC, dorsolateral PFC and basal ganglia).47-49 ACC, known for executive attention, exhibits increased activity in meditators, although it may decrease with experience. ACC is heavily involved in attention regulation, error detection, and cognitive control. During mindfulness meditation, the ACC becomes more active when individuals notice their mind wandering and redirect their focus back to the present moment, thus helping in selective attention and reducing distraction.^{36,50} Though most of the studies have revealed fruitful outcomes of attentional regulation, few studies have frowned upon the poor methodology and hence the findings of previous studies.⁵¹

Body awareness

The sensory experience can be used as a tool to focus our mind. In the Kayagatasati Sutta, Buddha has offered several methods for being aware of the body during mindfulness practice, recognizing the interconnectedness of the mind and body.⁵² He has emphasized on focusing on breath sensations, which can serve as an anchor line to tether one to the present moment and a guide to come back when the mind wanders.^{12,14}

Scientific researchers have revealed that insula plays key role in body awareness and is involved in introspection and attention; and insular gray matter volume is proportional with accuracy of the practice.53-55 An increased awareness of the body's response to an emotional stimulus leads to greater awareness of one's own emotional life. Thus, awareness of sensation increases empathy and develop an insight to observe emotions leading to their better management. It has been proposed that awareness of sensation or emotion facilitates its acceptance, which leads to better controlled behavior in its response.⁵⁶ This has beneficial effect in management of psychological disorders related to the emotional instability.⁵⁷ Furthermore, insula and temporo-parietal junction gets activated not only in awareness of body sensations but also in social cognition and empathic responses.⁵⁸ This suggests a potential mechanism by which mindfulness may enhance empathy. Such findings align with cognitive science theories on embodied cognition, which propose that bodily experiences shape higher-order cognitive processes.

Mindfulness is found to be effective in the management of chronic pain by altering our perception to pain and increasing its tolerance. Therapies like mindfulness-based stress reduction (MBSR) are equally effective as cognitive therapy or behavioral therapy for treatment of chronic pain.^{59,60} The basal ganglia also seem to play a multifaceted role in mindfulness practice. Notably, during meditation, it inhibits irrelevant thoughts, which aligns with the aspect of 'Attention Regulation.' Simultaneously, it is also involved in maintaining a focused mental state, contributing to bodily awareness.⁶¹ As most of these studies include narrow population sample (such as western demography, persons without mental illness), studies in diverse population analyses could provide further insights into the unique benefits of mindfulness practices. Future research should also focus on refining these interventions, exploring individual differences to maximize their therapeutic potential, and investigating the precise biological mechanisms involved.

Emotion regulation

Emotional regulation is the mindful observation of emotions in regards to their origin, effect on thought process and their experience and expression.⁶² Abhidhamma, which is a collection of texts from the third division of the original Theravada scripture, provides a detailed classification of 51 different kinds of mental formations that Buddha describes. One of them is feeling (vedana), which is described by monk Tich Nhat Nahn as an experience that can be pleasant, unpleasant, or neutral, arising in response to life's conditions. He emphasizes mindful recognition of emotions – observing them without attachment or aversion – rather than impulsively reacting. By acknowledging and naming emotions, one fosters greater awareness, balance, and inner peace.¹²

While scientific evidence regarding mindfulness and affect is currently limited, studies have demonstrated an increase in positive affect and a reduction in negative affect.63 Neuroimaging studies have indicated that mindfulness meditation modifies emotional regulation through changes in different structures. Increased engagement in lateral frontal regions supports executive functions such as attention control and mental adaptability.27 Modulation of anterior and posterior cortical midline structures such as medial PFC and cingulate cortex improves selfawareness and emotional regulation.⁶⁴ Left amygdala gets downregulated during emotional processing in beginner meditators and is associated with decreased stress and heightened emotional resilience.⁶⁵ These changes have been associated with reduced symptoms of anxiety, depression and stress.

Prefrontal regions, such as the dorsolateral and ventromedial PFC are central to thought and emotion regulation which have distinct roles in relation to thought, cognition, and emotion. Nejati and colleagues have described the dIPFC is involved in the control and regulation of the valence of emotional experiences, while the vmPFC might be involved in the extinction of arousal caused by emotional stimuli.^{66,67} During the meditative state, the dIPFC initiates mind wandering while the vmPFC inhibits it. Emotion regulation by mindfulness meditation involves modification of processing in lateral frontal area,

regions involved in interoceptive attention (such as insula) and amygdala. Higher mindfulness, as per the Mindful Attention Awareness Scale is associated with increased activation of PFC areas, stronger inhibition of amygdala by the PFC and reduced amygdala activity.^{32,36}

An 8-week mindfulness-based intervention (MBI) practice has been associated with increased gray matter thickness in the hippocampus and pre frontal cortex, decreased gray matter in the amygdala, and enhanced emotion regulation, correlating with a reduced stress response.^{32,36} Although amygdala shows reduced response in meditators to painful stimuli (suggesting less subjective pain), they show activation in the ACC, thalamus, and insula-regions associated with primary pain processing.⁶⁸ This has been explained as mindful awareness increases responsivity to interoceptive signals, suggesting a better control on the affect the external events.⁵⁶ Mindfulness-mediated increased amygdalafrontoparietal network connectivity might translate as improved emotion regulation. An increased focus after MBI might be reflected in enhanced default mode network (DMN) – prefrontal cortex connectivity.⁶⁹ Studies have also found that mindfulness training is associated with the reorganization of hippocampal circuitry and enhanced connections with somatosensory cortex, contributing to extinction of fear.⁷⁰ In short, individuals who practice mindfulness meditation are not devoid of emotions; instead, they gain better control over their emotions by mobilizing valuable mental resources, ultimately mitigating the destructive consequences of emotional reactions on themselves and others.

Thus, studies have highlighted the beneficial effect of mindfulness in structural changes in brain, including improved neuronal connectivity and increased cortical thickness. However, it is not devoid of contradiction. For example, the extent to which anatomical changes in brain affect emotional regulation is not completely understood. Furthermore, the extent to which continuation and discontinuation of the practice had impact on emotional regulation is still to be explored.

Change in perspective of the self

Buddhist philosophy underscores the impermanent nature of the self, describing the self as just a creation of mind. Buddha described, we are influenced by five changing processes: the processes of the physical body, of feelings, of perceptions, of responses, and of the flow of consciousness that experiences them all. Identifying one as a static self is cause of suffering. Mindful perspective seeks to enhance cognitive flexibility and thereby increase behavioral adaptability and the ability to navigate one's current environment in a meaningful manner.⁷¹ Mindful living increases the clarity in thoughts and the awareness of mental processes.⁷² Research supports that "observing self" and "changing self-concept" through mindfulness meditation lead to stress reduction and positive selfrepresentation, higher self-esteem, and increased selfacceptance.⁷³ This practice increases the activity in brain regions associated with self-awareness, such as the insula and medial prefrontal cortex.³² Additionally, it also increases self-compassion by increasing self-kindness and reducing self-critic. Similar modern therapies like Mindfulness-Based Cognitive Therapy (MBCT) which combine the principles of mindfulness with cognitive approaches, help in maintaining a balanced self-perspective and psychological resilience, and is useful in depressive episodes.⁷⁴

DISCUSSION

In the present era, the life has become more mechanistic and materialistic. Whole humanity is busy in humdrums of external world while inner journey of knowing the self is being forgotten. The result is increasing dissatisfaction and stress in life. At the same time, this has also led humankind to become curious to find the meditative ways for inner peace and long-lasting happiness.

According to Buddhist philosophy, the root of all the sufferings of our life is our mind itself. The primary goal of Buddhist practice is to eliminate suffering by mindful and conscious living. Mindfulness practices are the effective methods that bring cognitive and emotional changes to achieve desired psychological states.¹⁰ Mindfulness involves recognizing the thoughts and emotions that are in constant flux, facilitating a gradual decentering, thereby making a person less identified with the self and helping develop adaptive coping mechanisms. This flip in the selfconcept may be argued to develop detachment with social connectedness, highlighting the complexity of mindfulness. In the long run, however, this practice reduces ego-centric processing, potentially fostering excessive detachment may pose challenges to interpersonal functioning. So, in the future studies, understanding the interplay between selfperspective and social dynamics are essential harnessing the transformative potential of mindfulness in both therapeutic and everyday context.

One of the most significant benefits of regular mindfulness practice is cognitive flexibility. This concept refers to our ability to adapt, adjust, and reorganize our thoughts, emotions, and behaviors in response to changing circumstances. From a neuroscientific perspective, cognitive flexibility can be understood as an emergent property of complex brain networks. In a mindful state, different parts of Default Mode Network become selectively active, allowing us to focus on the present moment and let go of distractions; at the same time, it helps us detect and respond to salient stimuli to stay focused on the task at hand. The state is also related to enhancement of the three neural processes of attention-alertness, orientation and execution, helping us detect and respond to salient stimuli objectively, without the emotion affecting our judgment. As we cultivate a greater sense of awareness of our body, thoughts and sensations, we train our mind to reframe the perspectives, embrace uncertainty and adapt to change. Such cognitive flexibility can help one to (a) improve decision making by considering diverse perspective and having open mind to alternatives, (b) enhanced creativity by flexibly connecting the dots, and (c) better manage stress and everyday challenges by adapting to given situation. In the context of Vipassana meditation, this increased cognitive flexibility can lead to a deeper understanding of the impermanent nature of all phenomena. As we develop greater insight into the fleeting nature of our thoughts, emotions, and physical sensations, we become better equipped to navigate life's challenges with equanimity and compassion.

Previous research on mindfulness meditation has employed diverse methodological approaches. Some studies have relied solely on self-reported measures of cognitive function and subjective experience, while others have utilized behavioral tasks to assess executive function. However, there appears to be a lack of standardization among various methods, making it challenging to compare findings across studies. Many investigations have also focused exclusively on either mindfulness meditation or cognitive flexibility, neglecting their potential interplay and their effect in neuronal circuits. Moreover, it is also unclear whether the neurophysiological changes are the outcomes of mindfulness practice, or are simply the results of the sociopsychological factors like decreased stress, improved relaxation and motivation. So, the methodology, sample size and population can be improved for identifying the actual mechanism of mindfulness on neurophysiology. In addition, a comparable control or pre-test data can improve the comparison, especially with single or double blinded trials.

CONCLUSION

In this narrative review, we have explored the interplay between mindfulness meditation, neurophysiology, and the rich tradition of Buddhist philosophy. The four intertwined mechanisms of attention regulation, body awareness, emotion regulation, and a transformed self-perspective have been scrutinized in their role in shaping the human mind. Current study findings suggest that regular mindfulness practice can lead to improved cognitive flexibility, enabling individuals to adapt more effectively to changing situations. While our understanding of the neurophysiological mechanisms is limited by current study designs and sample sizes, future research should aim to address these limitations to further elucidate the benefits of mindfulness for individual well-being and societal impact. It is evident that mindfulness meditation extends beyond religious boundaries, offering a means

to attain higher alertness and unlock the vast potential for invaluable cognitive and emotional enhancements of humankind.

As our understanding of the neurophysiological underpinnings of meditation deepens, the harmonious integration of this ancient practice into society emerges as an essential tool in the contemporary world. Mindfulness practice transcends personal well-being, extending its influence to our collective existence. Meditation like Vipassana offers the potential to unlock new dimensions of human capabilities, fostering a more harmonious and

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compassionate society, one individual at a time. As science and spirituality converge, the path to enlightenment for humanity appears brighter than ever before.

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