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Review

Meditation, Sleep, and Performance

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Abstract

Meditation describes a large variety of traditions that are extremely variable, but all include the conscious focus or awareness of attention. By maintaining their attention, meditators experience both acute and long-term changes in physiology, anatomy, and cognitive performance. The literature shows that the type of performance benefits may depend on the specific type of mental training. During meditation practice there is a documented increase in neuronal coordination and slowing of neuronal firing across many regions in the brain, a similar process to nonREM sleep physiology. Due to these commonalities, meditation may reduce the homeostatic pressures of sleep need and positively impact sleep architecture. Poor sleep and sleep loss are known to negatively affect performance, but meditation may be able to overcome these fatigue-induced detriments. Another factor that negatively affects performance is excessive stress, which is known to be impacted by meditation and sleep. The bidirectional relationship of meditation and sleep is apparent, but the mechanism is still unknown showing a need for more systematic investigations into the relationship between meditation, sleep, and improved performance. Meditation shares neurophysiological similarities with sleep, and these processes may have similar effects on improving attentional and cognitive performance. Also, limited evidence shows that performance detriments due to sleep loss may be partially overcome by meditation.

Keywords
Meditation; sleep; performance; stress; attention; cognition; physiology

1. Introduction

The conscious control of attention is the similarity of all meditation traditions, but meditation has been utilized for a variety reasons related to religion, self-actualization, stress reduction, and/or improving mental well-being. Meditation comes from a variety of cultures, with some of its earliest references in India going as far back as 3000 BCE. Since that time, almost all major religions have developed some form of meditation, showing the pervasive appeal of these practices.

Meditation research, at least in the "West", became more popular in the 1960s and 70s when researchers began looking at the physiology of yogis, and practitioners of Transcendental meditation (TM) and mindfulness meditations in more detail. Yoga is wide variety of religious and philosophical traditions that span many centuries in India, with meditative practices focusing on inner peace or enlightenment achieved in part by reducing distractions due to internal or external stimuli. TM is a type of concentrative meditation that focuses on a mantra/sound which was brought to the West in the late 1950's. Another widely studied type of meditation, mindfulness is a broad category of practices that focus on external and internal observations without passing judgement. Both mindfulness and yoga meditations were shown to induce a hypometabolic state, with practitioners having slower respiration rates, decreased galvanic skin response, and reduced heart rate [1-3]. TM and other concentrative meditations have also been shown to induce a hypometabolic state during practice, as compared to baseline conditions [4-6]. These changes have been attributed to lower sympathetic nervous system activation [7, 8] and increases parasympathetic activation [9]. These findings are not conclusive with other studies showing meditation did not change or was even shown to increase heart rate or respiration [10]. The inconsistency of these results are likely attributed to the variability in meditation practices and experimental designs.

Studies of this era showed that experienced meditators had different neurophysiology as compared to non-meditators, with early studies using electroencephalography (EEG) to investigate the neuronal dynamics during meditation. Early EEG studies show the slowing of cortical neuronal firing as a result of meditation, resulting in the increased appearance of alpha and theta rhythms when awake, although the interpretation of this cortical slowing differed between studies [2, 11-15]. Specifically, some authors mischaracterized that their EEG traces showed increases in alpha activity that were described as looking visually similar to early sleep [11, 16, 17]. When subjects were asked, or when their meditation was interrupted, the meditators reported being awake, showing that this visual similarity of the signal was misleading and misinterpreted [13]. Other EEG studies of this time specifically reported that the cortical activity was clearly distinct from sleep [18, 19].

During this time, analyses of performance changes and cognition and their relation to meditation neurophysiology were not systematically studied. Few studies included some reaction time studies, stating that TM practitioners had faster reaction times than non-meditator groups [20] and TM practice increases reaction time from baseline [21]. Beyond this, there were occasional reports of exceptional abilities in long-term meditators. Anand, Chhina, and Singh [11] reported that a subset of their yogi subjects were more resistant to pain induced by putting one's hand in cold water for 45-55 min. The pain response to temperature has been more recently studied in TM practitioners, showing that experienced meditators and also those with 5 months of practice had lessened brain activation to painful hot water [22]. Another study of the 1960s, Kasamatsu and Hirari [2], reported that some Zazen meditators in their study had increased far-sighted vision. Other mentions of performance enhancement were seen in that experienced meditators were found to be able to habituate more quickly to distracting and stressful stimuli, showing the anxiety reducing properties of meditation [11, 22-24]. Meditation practice was also shown to acutely reduce levels of anxiety [23, 25]. Although far from systematic, meditation research did have these occasional mentions of potential performance enhancement.

Meditation research has gained popularity since this time, but there is still much unknown in this field. The clinical benefits of meditation have been shown in a variety of clinical studies, to improve insomnia, ADHD, anxiety disorders, and hypertension [26-31]. There have even been claims that meditation elongates life [32]. Even though the benefits of meditation on disease states have been shown, there is still very limited data and a general lack of knowledge of the processes involved in meditation and how they interact with normal or abnormal physiology. Normal attention and cognitive performance can be impacted by sleep quality and quantity, meditation experience, and stress. This review will summarize the literature to date on how meditation's neurophysiological changes impact attentional and cognitive performance, as well how meditation and performance interact with sleep.

2. Temporal Aspects of Meditation and Performance

Broadly, meditation traditions can be split into two broad categories based on the object of focus: focused attention and open monitoring. Concentrative or focused attention (FA) meditations rely on focus on a single "object" (such as the breath, body part, a single word, or a mantra). One type of FA is transcendental meditation (TM), which specifically focuses on a mantra or sound. The other category is, in some sense, the opposite with the focus of open monitoring (OM) or mindfulness meditations not being on any single stimulus or experience, but having the intention is to not pass judgment on any stimulus or thought. More recent categorization of meditation also includes loving kindness meditation as a third distinct type of meditation [33]. Compassion or loving kindness (LK) meditations have elements of both FA and OM meditations, but with the focus on developing love and kindness toward the self and then extending to others [33]. Current research broadly considers each different type of meditation to induce specific neuro-physiological changes. These specifics of each meditation type are outside the scope of this paper and have been reviewed by others [34-36].

Regardless of the type of meditation, the changes induced by meditation can be broken into two categories based on timing. State changes are those short-term changes that take place directly during or after meditation practice. Trait changes, on the other hand, are more permanent changes that take place after extensive meditation practice and repetition of the same attentional processes. These are thoroughly reviewed by Cahn and Polich [34].

2.1 States

When considering the timing of meditation's effects, those taking place during meditation or immediately after are classified as state changes. Due to the lack of long term changes due to meditation, the neurological state changes that directly result from meditation practice can most easily be studied in novice meditators. Without this experience and long term exposure to meditation, there are no trait changes to influence the brain and performance. Most state effects of meditation are directly due to the variable neuronal activity that takes place during the session. Studies using EEG and fMRI support the notion that each type of meditation has some characteristic neuronal dynamics; while there are also some similarities, each meditation type has a different focus resulting in differential neuronal activation. This literature has been reviewed previously [34, 35, 36].

One widely reported state change indicative of meditation practice are EEG alpha (8-13 Hz) power increases and increases in alpha synchrony. This indicates the slowing and increasing coordination of cortical neurons during meditation sessions. Alpha power increase are commonly seen due to simply closing eyes in the occipital lobe [37-39], but this localization during meditation is in the frontal and parietal lobes with distinct regionalization based on meditation type [12, 35, 40-42]. The amount of coordination may rely on the amount of meditation experience with experienced meditators having higher alpha power than novices [2, 36, 43, 44]. This increase in alpha power has been associated with increased relaxation and attention that takes place during meditation [34, 45] and can even be induced from simple paced breathing [46, 47]. This increased prevalence of alpha frequency represents a slowing and coordination of neuronal firing throughout the cerebral cortex.

This slowing of neuronal firing can even extend into the theta frequency range (4-8 Hz). The physiological change commonly attributed to FA meditation is increase in EEG theta power [12, 36, 46, 48]. This neuroelectrical activity is similar to that which takes place during attention tasks [49], complex cognitive tasks [50], and during consciousness and sensory perception [51]. Also during FA meditation, there is an increase in theta synchronization between prefrontal and posterior association regions during meditation, showing the coordination of these regions [45, 52], which are associated with working memory [53, 54] and learning [55]. It is possible that this coordination of neuronal activity is improving performance after meditation due to the similar neurophysiological activity between meditation and the task being tested [34].

FA meditations have been shown to increase performance after short training. Due to FA utilizing attentional processes on a specific object of focus, attentional tasks may be more susceptible to improvements from FA than other types of meditation. Three weeks of training in FA (Dhammakaya Buddhist) meditation showed a faster reaction time [56]. This short amount of training may not be necessary for improved performance; reaction time and psychomotor vigilance have also been shown to improve after a single FA meditation session [57].

Meditation has been shown to mobilize mental resources and improve information processing. Attentional blink is a term that describes a deficit in identifying the second of two quickly presented stimuli, and meditation can lessen this via theta phase synchrony [58]. The mobilization of mental resources has been described in the literature to happen specifically after FA meditations and not after other meditation subtypes [59]. These other types of meditations have been shown to have performance benefits based on the focus being maintained during meditation. For example, OM practices are based on a broader attentional scope. Long term OM meditators have been shown to outperform FA meditators when there was an unexpected stimulus [60]. OM meditations, although they still involve conscious control of attention, have broader attention focuses than FA meditation, which could cause the ability to respond more quickly to unexpected stimuli.

Due to the specifics of each meditation, different types may be limited in their ability to improve task performance. But, meditation can benefit practitioners in other ways. Two studies utilized an 8-week Mindfulness-Based Stress Reduction course (MBSR) and showed that subjects had no differences in attention before and after their training [61, 62]. Even though attention was not affected, improvements in amounts of mindfulness and emotional well-being were reported after meditation [61].

OM may not affect attentional performance of normal, well-rested subjects, unlike FA traditions, but OM may be able to improve attention after sleep deprivation [63]. Losing sleep decreases attention and increases fatigue and sleepiness [63]. Rather than directly improving attention regulation and the associated regions in the brain, Kohler and colleagues stated that mindfulness can increase mental resource mobilization to counteract the increased sleep drive from lack of sleep [63]. OM meditations have been shown to increase occipital gamma power and decrease in delta power [64]. This bilateral, frontal decrease in delta power may reflect OM, decreasing the homeostatic pressure of sleep.

2.2 Traits

Research with long-term meditators brings into question the trait changes from their practice, and how these changes relate to task performance. One study of experienced Buddhist OM practitioners analysed their ability to supress interfering information using the Stroop task and d2-test of attention. During the Stroop task, subjects must say the color of the text rather than the word, and the d2-task that has participants cross out the letter "d" with two marks above or below it. These long-term practitioners showed that they had less Stroop interference than non-meditators, indicating better cognitive control and control of automatic responses [65]. Another study shows that this improved performance on the Stroop task demonstrates higher executive control and better emotional control in meditators of a variety of traditions [66]. Experienced meditators also performed better on the d2- test, having less errors of omission and commission, which indicate better attentional and inhibitory control, and better speed and accuracy of performance [65].

Hodgins and Adair used a large sample of meditators from different traditions [67]. When compared to non-meditators, the meditators showed less change blindness and were able to identify changes more quickly. They were also able to think more flexibly when describing an ambiguous image and were more flexibly able to redirect attention to new information. All of these data imply better visual perception and flexibility in processing visual information [67]. These performance improvements can be considered trait effects, because the subjects did not systematically meditate before testing, meaning performance enhancement is not due to the immediate effects of mediation.

But are these performance enhancements directly related to meditation experience? A study of experienced OM Zen meditators showed a correlation between amount of meditation practice and attention, mindfulness, and awareness [68]. As practitioners become more experienced and have more extreme trait changes, attentional focus and mindfulness may improve.

These improvements in performance may be due to the functional and anatomical changes associated with long-term meditation [69, 70]. One physiological trait positively correlated with meditation practice is increased EEG gamma power. Studies have found that increased EEG gamma power in the parietal-occipital area takes place in experienced meditators during meditation but also during rest [71, 72]. FA, OM, and a combined FA/OM meditations have all been shown to have higher mean gamma power both during meditation and an instructed mind-wandering task [72]. Since this happens both during meditation and persists afterward, this gamma power increase is most likely a trait change.

There have also been some reported anatomical changes due to long-term meditation practice. Expert meditators have also been found to have changes in cortical thickness in the prefrontal, frontal, and temporal cortices [73, 74]. These regions are associated with attention, interoception, and sensory processing, which implies more cognitive function in these processes [73-76]. Meditation also leads to improved coherence between cortical regions, especially in the prefrontal and frontal regions [34, 39].

The impact on drowsiness and fatigue may also be a trait of meditation. More years of daily OM meditation have been correlated with less drowsiness during a non-meditative thinking task [64]. This same study showed a correlation between number of daily meditation hours and drowsiness during meditation [64]. Meditation experience may impact how a person experiences lack of sleep and general fatigue. To understand how sleepiness and fatigue are impacted by meditation, the interactions between sleep and meditation must also be understood.

3. Meditation Experience and Sleep

Meditation and its impact on sleep was studied by Mason and colleagues [77] in TM. It was found that experienced TM meditators had greater REM density and less muscular activity during deep nREM sleep, as compared to short-training meditation controls [77]. This sample of experienced practitioners were also shown to have more stage 1 sleep, which is indicative of worse sleep. The implications of this study is that meditation can in fact impact sleep, although from this single study it was unclear if their TM meditation improved or worsened sleep.

More recent studies support this idea that experienced meditators may sleep differently than non-meditators. Total sleep time may be reduced in meditators, but this finding is based on only a few studies with small sample sizes [57, 71]. Kaul and colleagues used actigraphy and self-report to determine that their subset of concentrative meditators who meditated over 2hrs per day slept only 5.2 hours as compared to the 7.8 hours of the non-meditating controls [57]. This effect of long-term concentrative meditation on sleep amount was also reported by Ferrarelli and colleagues, with experienced Buddhist meditators sleeping an average of 6.14 hours, as compared to meditation novices which slept an average of 6.75 hours [71]. In contrast, research in mindfulness and compassion meditations indicate no differences in total sleep time between long-term meditators and non-meditator controls [65, 78-80]. It's unclear if this is due to differences in meditation practices, as there have been no systematic studies of sleep duration and meditation experience. These findings raise the question: how does meditation influence sleep? Is this a trait of meditation experience or a state effect?

3.1 How Can Meditation Impact Sleep?

To determine if sleep is different between meditators and non-meditators, investigations must be made into the processes that control sleep, either via circadian influences or homeostatic drive. Meditation may impact melatonin secretion. One study of experienced TM practitioners, showed that meditation at night can increase melatonin, as compared to a night when they did not meditate [81]. The subjects in this study meditated during an unusual time, and more research needs to be completed with meditation during times of normal practice. Another study has shown that 3 months of yoga and FA meditation training can increase the amplitude of the night-time melatonin peak [82]. It is unclear by what mechanism meditation can impact melatonin dynamics. The impact of meditation on other circadian rhythms such as body temperature and sleep timing has yet to been studied in a comprehensive manner.

It is possible that meditation interacts with sleep via homeostatic processes. The most reliable measure of sleep need is slow wave activity (SWA) during the first bout of nREM sleep. SWA during nREM sleep can be predicted almost entirely by the amount of time spent awake, and this SWA decreases rapidly during nREM sleep [83]. Limited research indicates that meditation experience may have no effect on delta power during sleep [77, 80], but no one has assessed acute effects of recent meditation on this process. If meditation works to decrease the homeostatic pressure of sleep, this may take place in faster frequencies (theta or alpha), as homeostatically controlled frequencies have been shown to extend from 0.25 to 12 Hz [83], well beyond the widely accepted delta band (0.25 to 4 Hz).

Investigations into sleep homeostasis and meditation show that long term yogic meditators have an increase in EEG lower frequency activity during nREM [80]. This study showed that the amount of increased low frequency activity depended on the amount of sleep. During the first episode of nREM sleep, meditators were found to have an increase in the EEG theta/alpha range of the prefrontal and parietal electrodes. But later in the night, during the second nREM episode and after some sleep debt has been "paid off", this increase in low frequency wave shifts more into the delta slow wave frequency [80]. The first increase in the theta/alpha range may mimic the activity seen during meditation practice. By the third episode of nREM, there was no difference in low frequency activity between meditators and non-meditators [80]. Each sleep episode pays off more sleep debt, and the effects of meditation may dissipate as there is less homeostatic pressure. These studies may be difficult to interpret, as there are likely multiple and potentially opposing forces. For example, the neuronal synchronization seen in meditation may "pay-off" a small portion of sleep debt, thus reducing subsequent EEG delta power during initial sleep periods, but meditation may also reduce stress and improve sleep quality thus leading potentially to increased EEG delta power. Whether frequencies higher than delta (theta/alpha range) are relevant to paying off sleep debt is certainly not clear. Careful studies correlating specific frequency bands over specific cortical regions during meditation and during subsequent sleep may be able to parse these different processes.

Vipassana meditators and Kriya yogis have been shown to have increased amount of REM sleep [78, 79]. This fits into the meditation- homeostasis framework, causing a lesser need for nREM sleep and allowing them to spend more time in REM sleep. These daily meditators did not have their meditation practice temporally controlled around the sleep study [78, 79], and this raises questions on whether their finding was a state or trait effect of meditation on sleep. OM meditations have been shown to have differences in sleep architecture, although sleep time did not differ between meditator and non-meditator groups [78-80]. These studies also broke up their subjects into different age groups [78, 79]. Middle aged Vipassana meditators (31-55 years) had enhanced amounts of REM sleep as compared to age matched controls [78]. These meditators also didn't show the reduced amount of SWS seen in middle aged controls [78]. These effects seem to continue with more advanced aging, with a follow up study showing that older [50-60 years old] Vipassana meditators also had longer SWS duration and longer REM duration than age matched controls [79].

Sleep undergoes organizational changes and qualitative declines while aging. Reports show that older individuals are likely to have decreases in amount of SWS and REM sleep, and have increases in stage 1 sleep, wake after sleep onset, and sleep fragmentation [84-86]. Aging is also associated with lesser amplitude of delta power in SWS and lessened amplitudes of circadian rhythms [87, 88]. The causes of these sleep phenomena over the lifespan are poorly understood. This may partially be due to the increased prevalence of sleep disorders such as insomnia, restless leg syndrome, nocturia, and other ailments [89-91]. Meditation has been found effective in reducing the severity of insomnia and restless leg syndrome [92-94]. If meditation is also able to protect against changes in sleep architecture and sleep duration, then meditation should be investigated to see if it prevents the cognitive decline seen with decreased sleep amounts [95]. Sleep issues are starting to be shown to be predictors of cognitive decline [86] and other disorders. There is a need for more longitudinal studies of experienced meditators and how their sleep and health changes over their lifespan, with special considerations when they are elderly.

Our current knowledge on meditation's effect on sleep is skewed based on the few types of meditation that have been studied thus far. Detailed sleep of long-term Theravada or Tibetan Buddhism meditators has been directly investigated [71]. These traditions include components of both OM and FA (with focus on the breath) [71]. It was found that gamma power (25-42 Hz) during nREM sleep is strongest in the frontal and prefrontal areas and weakest in temporal [71]. In experienced meditators there was significantly higher gamma activity in parietal-occipital regions than naïve meditators. This did not take place during the first episode of nREM, but during the later three nREM episodes across their night. This nREM gamma power is correlated to amount of daily meditation practice [71]. Higher gamma during sleep could be reflecting that long term meditators are able to still maintain some activation in the sensory regions and Default Mode Network allowing them to maintain some level of awareness during sleep [71].

This potential increase of awareness during sleep has yet to be tested directly. Gamma power increases have also been recorded in the third nREM episode of LK and FA, which may indicate the traits of meditation in later sleep [80]. Gamma power increases may not be unique to meditators, as a subset of novices show this, but Lutz and colleagues stated that all experienced LK meditators in their study had the same increase in gamma power [96]. This may also be a result of this LK meditation as compared to the changes seen in FA. The literature on gamma power is growing, since historically gamma power has been filtered from different meditation EEG studies, but more recent analysis methods have allowed researchers to be able to distinguish gamma activity from muscular artifacts and other EEG noise.

EEG theta and alpha frequency oscillations have also been linked to maintenance of transcendental consciousness or awareness during sleep in TM practitioners, a process called witnessing sleep [77, 97]. These experienced TM practitioners showed greater theta2 (6-8 Hz)–alpha1 (8-10 Hz) relative power during nREM sleep [77]. This amount of power shows a graded effect related to meditation experience, showing a trait of meditation in sleep [77]. More recently, Dentico and colleagues reported the same greater theta and alpha power in experienced meditators of both mindfulness and loving-compassion traditions [80]. The increase in theta and alpha power was visible after 8 hours of meditation during nREM sleep and was considered to be state changes as a "reactivation of the neuronal activity" during meditation [80]. This brings up the question if concentrative traditions may interplay with sleep differently than mindfulness or compassion based meditations. Reported results thus far may be skewed due to the few studies done on sleep, meditation, and performance.

3.2 Meditation and Sleep Loss

Reaction time and attention tasks are very susceptible to improvements via meditation. But after sleep loss, reaction time decreases due to fatigue and decreased maintenance of attention. The PVT, psychomotor vigilance task, measures reaction time and sustained attention in response to a visual stimulus [98]. Sleep restriction to 5 hours of sleep significantly worsens PVT performance and PVT lapses [63]. Those who underwent a 21-day meditation training had a performance boost after a session of meditation, which resulted in reaction times similar to pre-sleep restriction values, and a reduced number of lapses. The non-meditation controls did not get a performance boost nor a reduction in lapses [63]. Self-reported sleepiness after the sleep restrictions was reduced due to meditation, but not due to the control condition [63]. Self-reported fatigue or having low energy was also measured and subjects had no difference in amount of fatigue after meditation or their controls [63].

This same performance enhancing effect have been noted even after a whole night of sleep deprivation. Novice meditators, with no prior meditation training, underwent a whole night of sleep deprivation. The sleep deprivation significantly worsened PVT reaction time, but a single session of FA meditation was able to return reaction times close to baseline values [57]. Because of this strong effect in novices, meditation's state changes can overcome some of the deficits due to sleep loss.

Due to the limited number of studies that looked at sleep deprivation in meditators, limited conclusions can be drawn. Meditation may be able to return PVT performance close to non-sleep deprived levels, even in novices. Other performance measures need to be tested. There are no data on how expert meditators respond to sleep deprivation. Also data need to be gathered on the neuronal dynamics of these processes after sleep deprivation or restriction.

4. Interactions with Stress

Although anxiety and cognitive performance are not believed to be directly correlated [99], stress can impact performance and memory [100]. Stress' impact on performance has conflicting literature and multiple hypotheses have been posited on this topic [101].

Those with high anxiety are more prone to distractions and require more effort to complete a task [102, 103]. Those with higher anxiety have been found to have longer reaction times, but comparable accuracy relative to those with low anxiety [100]. The attentional control theory states that stress may impair attentional control by shifting mental resources from the task at hand and reduces the influence of the goal-directed attentional system [100]. Meditation experience lowers basal levels of anxiety [104-106] and decreases the response to stress [107-109]. Meditation also has been shown to activate areas involved in the relaxation response [110]. If proven, the attention control theory would fit into the meditation and performance paradigm well, with meditation reducing stress and allowing more attentional resources to be utilized on task performance, but more research is needed.

Anxiety and sleep have a bidirectional relationship. Stress levels can directly impact sleep, and the amount and quality of sleep can impact anxiety. András and colleagues [111] found that higher levels of anxiety can increase sleep latency, reduce amounts of slow wave sleep, and decrease the amount of REM sleep. Since anxiety negatively impacts sleep, meditation may reduce anxiety therefore improving sleep and performance. Even one meditation session can increase the amount of mindfulness and positively affected mood [58, 112]. The next step is for research to determine if this stress reduction caused by meditation can positively impact sleep as well.

Fragmented circadian rhythms have been associated with increased anxiety disorders in middle aged and elderly people [113]. As stated earlier, there is a lack of studies on meditation and circadian rhythms, so further circadian meditation research should also consider anxiety as part of that equation. At this point, we can say there appears to be multiple interactions between stress, meditation, sleep and performance. Future work in these areas should investigate causal interactions more directly.

5. Limits of Meditation and Future Directions

This literature review details the relationship between meditation, sleep, and performance, but most of these findings are based on very few papers that have limited conclusions. There is much work that needs to be done to conclusively describe these relationships between meditation, sleep, and performance.

Meditation can improve attention and emotional wellbeing, but has limitations on its enhancements, and a dedicated “fan” base that may exaggerate the benefits, or have a vested interest in positive results. The specific focus of meditation trains the associated regions in the brain, and may not help processes taking place primarily in unrelated regions. For example, the ability to improve cardiac interoception (the conscious perception of heart rate) was found to not be associated with meditation training, although regions associated with interoception are found to be increased during meditation [61, 114, 115]. Since cardiac interoception tasks are different than what is practiced during meditation, this may explain the negative results seen. Kohler and colleagues showed no difference in the Go/No-Go task between meditation and control activity groups [63]. These subjects practiced FA, Nidra yoga, meditation which is distinct from the response inhibition to a stimulus that is measured with the Go/No-Go task [116]. These results are heavily based on the type of meditation, as other meditation practices may impact cardiac interoception or the Go/No-Go task. The effects of meditation may be very specific and do not improve all performance ubiquitously.

Most of the studies included in this review use different types of meditation. Due to the different neuronal aspects of each meditation subtype, conclusions drawn here are far from conclusive on how meditation interacts with sleep and on subsequent performance. There is a need for more systematic study of sleep from those who practice different meditation techniques. Also, there needs to be more studies that directly compare different meditation types using multiple panels of cognitive tasks.

It is also unknown how long a single meditation session can impact the meditator. No current study has charted out the improvement in performance over time. Because the state effect of meditation is of unknown duration, the trait effects of meditation are difficult to separate from other influences. Beyond that, trait effects are also difficult to study, partly due to the difficulty of finding a comparable control group to long-term meditators. There may be certain traits that predispose someone to successful meditation and getting greater benefits from said meditation [117]. There are also many different covariables that may vary drastically between long-term meditators and non-meditators, such as diet, activity level, drug use, amount of motivation, and the ability to master a task. It is impossible to determine if this is directly due to the meditation training, or to other differences between groups. Performance studies need to be done on subjects with meditation experience, but without recent meditation practice. This would allow for traits to be clearly distinguished from state effects.

As this paper demonstrates sleep, meditation experience, and stress can all impact performance. Many of these studies have found correlations between these variables, but the causal relationship is unclear. The ability to meditate effectively and the subsequent performance boost may depend on stress levels, a previous night's sleep, circadian factors, or other variables. Research on meditation is growing, but still has a long way to go.

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Author Contributions

Both L.E. Guerriero and B.F. O'Hara contributed to the writing and conceptual ideas included in this manuscript.

Competing Interests

The authors have declared that no competing interests exist.

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