Using neurofeedback to augment meditation practice: A critical assessment

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Abstract

Meditation practices such as mindfulness meditation have been shown to lead to a range of positive life outcomes and are now used in treatment approaches to several psychological disorders. Neurofeedback, the act of making a measure of brain activity available to an individual, allowing them to act upon it, has been proposed to augment meditation practice. This essay aims to assess whether positive outcomes of neurofeedback-assisted meditation surpass outcomes of regular meditation. Several neural processes, such as activity of the posterior cingulate cortex, frontal-midline theta oscillations and combinations of alpha and theta oscillations have been investigated as candidate measures for neurofeedback. While studies employing meditation neurofeedback find improvements across measures such as heart rate variability, resting-state EEG band power, cognitive assessments and self-report questionnaires, these improvements do not systematically exceed improvements resulting from regular meditation control conditions. We conclude that more standardization in regards to the measured neural correlates and employed outcome variables, as well as more transparency concerning neurofeedback implementations are needed to accurately assess the benefits of meditation neurofeedback.

1 Introduction

The number of scientific studies reporting the potential benefits of meditation and, in particular, mindfulness meditation have increased exponentially over the last decades. Originating from Buddhist teachings ranging back more than two millennia, meditation concepts have now been incorporated into evidence-based programs such as mindfulness-based stress reduction (MBSR) and feature prominently in a large number of therapeutical approaches to common psychological disorders (Kabat-Zinn, 2003; Baer, 2003). As such, meditation-based techniques have shown to lead to improved therapeutic outcomes for, among others, stress, depression, anxiety, addiction and chronic pain (Shonin, Van Gordon, Compare, Zangeneh, & Griffiths, 2015; Wielgosz, Goldberg, Kral, Dunne, & Davidson, 2019).

Concurrent with the large number of both scientific and popular attention to the topics of meditation and mindfulness, a conceptual ambiguity of what is being investigated has become apparent. For mindfulness alone, Vago and Silbersweig (2012) note that the term is used interchangeably to describe, among other things: ”(1) A temporary state of non-judgmental, non-reactive, present-centered attention and awareness that is cultivated during meditation practice (2) An enduring trait that can be described as a dispositional pattern of cognition, emotion, or behavioral tendency; (3) A meditation practice;(4) An intervention.”. Furthermore, within the scientific literature, several types of meditation have been distinguished, such as focused attention, open-monitoring, transcendental and loving-kindness meditation (Lee, Kulubya, Goldin, Goodarzi, & Girgis, 2018). Meditation traditions also often combine several of these meditation types. Mindfulness, for example, is thought to involve both focused attention as well as open-monitoring, depending on the specific mindfulness tradition. Consequently, this heterogeneity in meditation practices needs too be considered when integrating results across studies and a major challenge to the scientific investigation of meditation benefits is the lack of agreed-upon frameworks and consistent methodologies (Van Dam et al., 2018).

The observed association of meditation practices with positive life outcomes and the growing awareness of meditation within the public conscience have also led to a large number of proposed tools and learning resources. Books, podcasts, mobile applications and virtual reality experiences all claim to facilitate the learning process for novice practitioners. An additional proposed tool for furthering meditation practice is neurofeedback, the act of making a measure of brain activity available to a user in real time, allowing for adaption of the underlying brain processes in response. Neurofeedback applications for meditation have evolved concurrently with research into the underlying neural mechanisms, and different neurofeedback applications focus on different neural correlates of mindfulness meditation. This essay contrasts different neurofeedback paradigms for mindfulness meditation and critically assesses whether they lead to systematic improvements in meditation practice. Additional emphasis will be placed on whether the introduced neurofeedback approaches actually employ the neural correlates thought to underlie mindfulness meditation and whether the extent of potential benefits to one’s practice justify the acquisition and use of brain activity measurement devices.

1.1 Neural Correlates of Meditation

In order to assess the usefulness of neurofeedback-assisted meditation, it is important to consider whether currently employed neurofeedback measures correspond to the neural correlates of meditation identified by the literature. Over the last decades, a large number of mechanisms and neural correlates have been proposed. Additionally, while there are several neural correlates which are found consistently across different types of meditations, correlates also often differ between types of meditation. Identified correlates include neural oscillation patterns, i.e. specific frequency bands, individual brain areas, as well as larger brain networks. This essay briefly introduces the correlates most consistently found in studies of meditation, for a more detailed treatment refer to Fox et al. (2016); Lee et al. (2018); Tang, Hölzel, and Posner (2015).

Studies employing electroencephalography (EEG) and magnetoencephalography (MEG) have reported several oscillatory features which consistently vary between meditation and control conditions, or show differences between novice and expert practitioners. Lee et al. (2018) summarize and integrate findings for commonly reported frequency bands in the neuroscience literature. Overall, the theta (3.5-7 Hz) and alpha (8-13 Hz) frequency bands are most consistently associated with meditation. Theta band power is found to increase during meditation, across different meditation practices such as focused attention and open monitoring. Additionally, the extent to which theta activity increases also correlates with the level of expertise, where expert practitioners show larger theta power increases (Baijal & Srinivasan, 2010). Similarly, alpha band power is also found to increase in frontal, parietal and occipital areas during meditation and persistent increases in alpha activity for experienced practitioners are also observed during sleep (Dentico et al., 2016; Cahn, Delorme, & Polich, 2013). Results for the delta (0.5-3 Hz) and beta (13-30 Hz) bands are less clear and there is conflicting evidence regarding their role during meditation (Lee et al., 2018). An increase in parieto-occipital gamma band power (30-100 Hz) is found specifically for expert practitioners across several types of meditation.

In addition to oscillatory correlates, studies using magnetic resonance imaging (MRI) have also found specific brain areas associated with meditation. MRI studies have been used to identify functional changes in brain activity during meditation, as well as structural changes as a result of long-term meditation practice. Tang et al. (2015) review and group commonly reported brain areas in meditation research, specifically mindfulness, by three core components of meditation, namely attentional control, emotion regulation and self-awareness. Figure 1 gives an overview of these areas. Among others, the anterior cingulate cortex (ACC), the dorsolateral prefrontal cortex and parts of the striatum have been consistently linked to functional changes related to attention in meditation. In regards to emotion regulation, tested by presenting participants with emotional stimuli, the amygdala, insula, parts of the striatum and several prefrontal areas generally show functional differences between novice and expert practitioners. The posterior cingulate cortex (PCC), medial prefrontal cortex and the precuneus, in turn, have been associated with aspects of self awareness in meditation. In a large meta-analysis, Fox et al. (2016) similarly identified structures such the insula, frontopolar cortex, cingulate cortex and parts of the motor cortices as being associated with meditation across different types of meditations. However, the authors caution that these brain areas represent a minority and that the majority of neural correlates found in the literature are specific to a particular type of meditation.

Evidently, a large number of brain areas are involved in different aspects of meditation and few work in isolation. Several well-known brain networks have also been associated with meditation. The default mode network (DMN), made up of several of the brain structures previously mentioned as involved with aspects of self awareness, has been found to be less active in experienced meditators which has been interpreted as a reduced extent of self-referential mind wandering during meditation (Brewer et al., 2011). Additionally, the dorsal attention network (DAN), comprised of areas such as the intraparietal sulcus and the frontal eye fields, has also been found to show increased connectivity as a result of meditation (Froeliger et al., 2012).

As a consequence of the multitude of neural correlates identified to underlie meditation, neurofeedback applications vary widely in regards to which correlate they target. Often this choice depends heavily on the measurement device used, as MRI allows for the monitoring of specific brain areas with high spatial resolution, whereas the high temporal resolution of EEG affords the monitoring of oscillatory features.

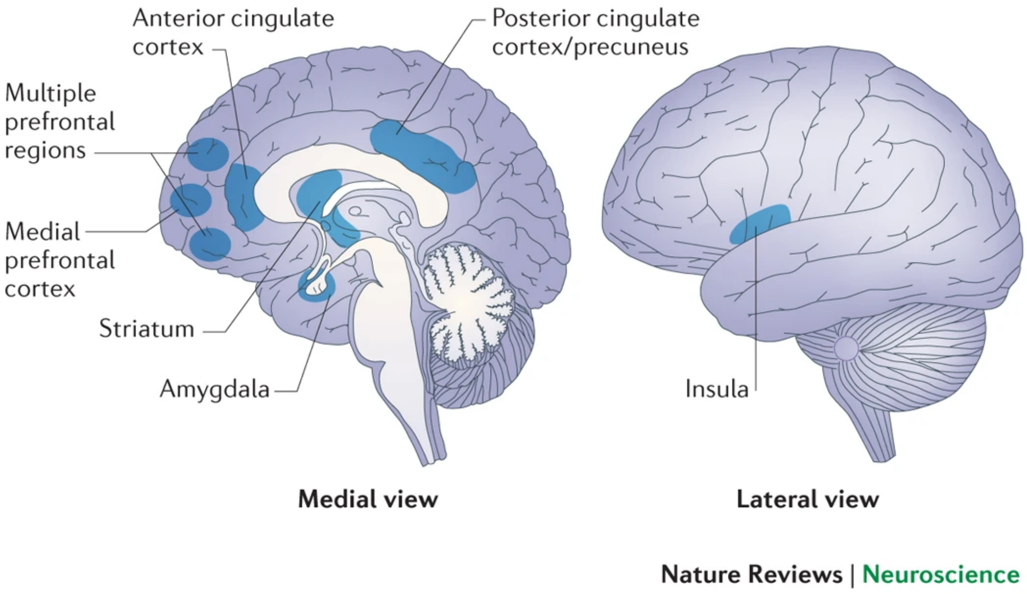

Figure 1: ”Schematic view of some of the brain regions involved in attention control (the anterior cingulate cortex and the striatum), emotion regulation (multiple prefrontal regions, limbic regions and the striatum) and self-awareness (the insula, medial prefrontal cortex and posterior cingulate cortex and precuneus)”. Figure and caption reproduced from Tang et al. (2015).

1.2 Neurofeedback

Neurofeedback can be seen as a specific case of biofeedback, where a measured body signal is used to learn to control the underlying body function. For neurofeedback, sensors capture brain activity related to a specific cognitive process. For the majority of neurofeedback paradigms, users receive either auditory or visual feedback, such as a tone changing in pitch or a bar changing in size based on measured brain activity. Many paradigms visualize frequency band power. For the treatment of psychological disorders where specific frequency bands are known to be abnormal, users can be instructed to up- or downregulate these bands by observing the presented feedback. Within the treatment of ADHD, for example, neurofeedback has been used to teach the downregulation of the theta band and upregulation of the beta band in fronto-central locations, resulting in long-lasting treatment outcomes comparable to medication approaches (Arns, Heinrich, & Strehl, 2014; Monastra, Monastra, & George, 2002). Frequency band neurofeedback approaches have been investigated and used for the treatment of, among others, learning disabilities, depression, anxiety, addiction, epilepsy, schizophrenia and PTSD (Hammond, 2011; Brandmeyer & Delorme, 2013).

Several approaches have also incorporated neurofeedback in relation to brain activity observed in reference populations. Z-score neurofeedback, for example, uses a measure of deviation between the user’s live brain activity and averaged values of a reference population as a feedback signal (Thatcher & Lubar, 2014). The general idea is then for someone undergoing treatment to regulate their brain activity in a way that brings it closer to activity observed in healthy control groups. While this approach is intuitively appealing, its efficacy has yet to be sufficiently established (Coben, Hammond, & Arns, 2019).

When comparing the range of previously mentioned psychological disorders which benefit from meditation practice to those for which neurofeedback treatment has been shown to be effective, one observes considerable overlap (Brandmeyer & Delorme, 2013). Additionally, many neurofeedback practices target frequency bands such as alpha and theta, which have also been found to be associated with meditation experience. As such, it is unclear whether neurofeedback and meditation yield positive benefits by the same mechanisms or whether there are qualitative differences. Similarly, it is interesting to consider whether their combined use leads to an interaction and a greater net outcome, or whether the use of both is equivalent to using either one of them in isolation.

Several studies have investigated the benefits of combining meditation and neurofeedback (MNF). However, not all studies compare MNF to a condition of meditation in isolation, but rather a control condition involving no treatment. As such, it is not always clear whether reported improvements are due to the addition of neurofeedback per se. Furthermore, many different MNF approaches and paradigms have been proposed and investigated, increasing the difficulty of assessing aggregated results. The following sections describe and contrast studies involving MNF grouped into four categories. As the type of measurement device for MNF heavily influences which neural correlate is used for feedback, we report studies employing MRI and EEG separately. Whereas MNF studies using MRI focus mostly on changes in activation of specific brain areas such as the PCC, EEG-based MNF studies largely employ frequency bands as their feedback signal. Additionally, several applications of MNF using commercially available brain recording devices have been investigated and a number of authors proposed combining MNF with augmented or virtual reality. This essay aims to critically assess whether the positive outcomes of MNF surpass those of regular meditation and whether the use of technologies such as medical EEG, MRI, commercial EEG devices and AR/VR for neurofeedback is justified. While positive outcomes of meditation are not fully characterized by quantifiable measures, we limit our assessment to outcome variables such as changes in heart rate variability, resting-state EEG band power, cognitive assessments and self-report questionnaire scores.

2 Results and Discussion

2.1 MRI Neurofeedback

While MRI is, overall, not well suited for regular neurofeedback practice, due to the expensiveness of individual measurement sessions and the measurement device, several studies have investigated MNF using functional MRI (fMRI) in the context of researching neural correlates of meditation. The high spatial resolution of fMRI especially allows for feedback signals based on activation of very specific brain areas, whereas EEG-based neurofeedback is generally more coarse and reflects activity in broader brain networks. However, the high spatial resolution of fMRI comes at the cost of lower temporal resolution. Whereas EEG allows for neurofeedback updates in the order of milliseconds, fMRI-based feedback has latencies in the order of seconds. As such, real-time neurofeedback using fMRI is possible, but might not represent minute temporal changes as accurately as EEG.

Garrison et al. (2013) employed fMRI to investigate the role of the posterior cingulate cortex (PCC) during focused attention meditation as well as to assess whether its activation corresponded to self-reports of subjective experience by practitioners. The PCC is a central part of the default mode network and thought to be involved in self-referential processing related to mind wandering during meditation. PCC activity could, therefore, be a valuable feedback signal during meditation. In their study, both experienced meditation practitioners as well as novice practitioners engaged in meditation focused on the breath while activation of the PCC was presented to them as a graph. Positive percent changes in PCC activation in comparison to a baseline were presented as an upward-sloping red graph and decreases in activation as a downward-sloping blue graph. When informed that the red graph corresponded to self-referential mind wandering and the blue graph to focused attention, both experienced and novice meditators reported that their subjective experience corresponded highly with the PCC activity graph. To rule out confirmation bias, a follow up study did not inform participants of what the graph represented. Still, meditators found the PCC activity to more directly correspond to their subjective meditative experience compared to the activity graph of another control brain region. Interestingly, when asked to increase the blue graph (i.e. decrease PCC activation) only experienced meditators were able to do so to a significant extent. As such, it appears that while PCC activity correlates with subjective meditation experience regardless of overall experience, only experienced practitioners were able to successfully act on the graph as a neurofeedback signal. A potential difficulty for novice practitioners could have been the mode of presenting neurofeedback. Participants were instructed to primarily engage in breath-based focused attention, letting the activity graph rest at the corners of their awareness, and from time to time check how well the current graph corresponded to their subjective experience. Potentially, the simultaneous focus on the breath and a visual stimulus was more effortful for novices, whereas experienced practitioners would likely need fewer cognitive resources to focus on the breath.

A potential adaption to the neurofeedback scheme used in Garrison et al. (2013) could be to communicate PCC activation as an auditory signal, for example, by modulating white noise. Additionally, a more minimal neurofeedback scheme, such as a single tone when PCC activity exceeds a certain threshold, communicating current mind wandering, could be less distracting to novice meditators. While novices were not able to quantitatively affect their meditation neurofeedback, it appears that some did benefit qualitatively from it. Brewer and Garrison (2014) report that several novices described unique insights about meditation which they gained through the presented feedback, such as the difference between thinking about the breath and feeling the breath. As a central challenge for meditation beginners is the uncertainty of whether one is meditating ”correctly”, the unique advantage of MRI-based neurofeedback could be to visualize qualitative aspects of meditation which are otherwise hard to communicate. As the set of studies reported in Garrison et al. (2013); Brewer and Garrison (2014) focus only on the PCC as a correlate of meditation, future studies should also investigate other brain areas. Investigating MRI neurofeedback based on areas related to attentional control in meditation, such as the anterior cingular cortex, areas related to emotional processing, such as the amygdala and insula, or networks of brain areas might provide a more complete representation of meditation and further benefit novice practitioners.

2.2 EEG Neurofeedback

In addition to PCC-based neurofeedback using MRI, several studies have also investigated EEG neurofeedback involving the PCC. Van Lutterveld et al. (2017) employed gamma band power in the 40-57 Hz range and targeted the PCC using a beamformer source localization approach. Their experimental design was similar to Garrison et al. (2013) in that participants were presented with a real-time graph of PCC activity which showed increases and decreases in relation to a previously established baseline. Participants again consisted of both novice and experienced practitioners of effortless awareness meditation. Whereas experienced practitioners engaged in the effortless awareness practice they were accustomed to, novices were instructed to engage in a ”noting practice”, that is ”to silently label the sensory experience that was most predominant from moment-to moment (i.e. seeing, hearing, feeling or thinking)” (Van Lutterveld et al., 2017). Whether PCC deactivation corresponded to increases or decreases in the graph was randomized between participants. For both groups, participants identified whether effortful awareness was related to graph increases or decreases with high accuracy. In contrast to the preceding MRI studies, both groups were able to volitionally increase the graph components associate with effortless awareness (i.e. PCC deactivation). Potentially, using a noting practice came easier to novice practitioners compared to the breath-based instructions of the MRI paradigm. However, the authors also note that the overall calmer recording situation of EEG could have been less distracting for novices compared to the noise and confined space associated with MRI recordings.

While this study showed that PCC activity also reflects meditation experience when measured through EEG, there are caveats to approximating activity in small, deep brain structures such as the PCC using EEG source localization. The current study used a 128-channel EEG recording device and the authors note that fewer channels would likely decrease the efficacy of the utilized beamformer algorithm. As such, it is questionable whether PCC activity could be used as a neurofeedback metric for EEG devices with significantly fewer channels, which is the case for the majority of consumer-grade EEG devices. Additionally, the previously introduced PCC-focused studies act to show that PCC activity corresponds to subjective meditation experience and that practitioners can use a visualization to volitionally decrease activity. However, there is still a lack of research on whether PCC-based neurofeedback leads to long-term positive outcomes, and whether these outcomes outweigh measures achieved through meditation alone. As it stands, the largest practical advantage of PCC neurofeedback appear to be the possibility of qualitative insights into one's meditation practice.

Outside of using PCC-based neurofeedback, several studies employed frontal-midline theta (FMT) band power in the 3-7 Hz range as a metric for neurofeedback during meditation (Brandmeyer & Delorme, 2020; Prestel, Riedl, Stark, & Ott, 2019). FMT power was shown to negatively correlate with activity in the default mode network and increases in FMT were observed during episodes of focused attention meditation (Scheeringa et al., 2008; Brandmeyer & Delorme, 2018). Brandmeyer and Delorme (2020) investigated the use of FMT neurofeedback by having two groups of meditation novices engage in breath-focused meditation with concurrent neurofeedback. For one group, this feedback consisted of real-time FMT band power, whereas the other group, acting as a control, was shown a recording of uncorrelated neurofeedback from a matched participant. Neurofeedback was visualized through a blue square which changed its color gradient (ranging from black to light blue) based on FMT power in relation to a baseline. Overall, participants engaged in eight sessions of neurofeedback during which they engaged in breath-based focused attention meditation. They were further instructed to attempt to keep the visualization at a light-blue shade (indicating increased FMT). Participants in the real neurofeedback group showed consistent increases in FMT across the eight sessions compared to the control group, which did not show significant changes. Crucially, this allows for the disentanglement of neurofeedback benefits and those gained from meditation alone. As increased FMT power is a characteristic of experienced meditators, it can be argued that this increase in FMT for the treatment group constitutes a unique benefit attributable to the use of neurofeedback (Brandmeyer & Delorme, 2018). Conceivably, classic meditation also leads to increases in FMT, albeit over a longer time course, explaining why no effect was visible for the control group. In addition, it has to be noted that the current study only used eight channels for their neurofeedback, significantly increasing the possibility of the introduced neurofeedback paradigm being used with commercial EEG devices.

Prestel et al. (2019) used a similar design, where six participants with little meditation experience engaged in neurofeedback-assisted meditation across eight sessions. FMT was again used as neurofeedback metric, but communicated as a grey circle changing in size based on changes in FMT power. In contrast to Brandmeyer and Delorme (2020), results in regard to FMT increases after the eight sessions were mixed. Of the six participants, two showed increases in FMT, two showed no significant changes and two actually showed decreases. The authors also collected qualitative data on how participants perceived the neurofeedback meditation. Several participants reported that the conscious goal of increasing the visualized circle actually led to the opposite result, at first a frustrating experience. As such, the type of neurofeedback used in this study might be best suited for practitioners with moderate experience, where the feedback signal augments the meditation, but is not its central focus, as practitioners have already developed a practice routine.

Overall, additional studies with larger samples are necessary to assess the use of FMT neurofeedback for meditation definitely. However, initial evidence of its efficacy compared to a control condition as shown by Brandmeyer and Delorme (2020) and the possibility of measuring FMT using low-channel EEG make FMT a prime target for investigation compared to other paradigms such as PCC-based neurofeedback.

2.3 Commercial Neurofeedback

Compared to the relatively few studies investigating the benefits of neurofeedback for meditation using research-grade EEG and MRI, a larger number of studies have investigated consumer-grade EEG for neurofeedback meditation. A majority employed the Muse EEG headset manufactured by Interaxxon, consisting of four frontotemporal measurement locations, that is two electrodes placed on the forehead and two electrodes close to the ears (Krigolson et al., 2021). A companion mobile application is available to provide meditation neurofeedback, which the majority of studies employing a Muse headset used as their implementation for neurofeedback. While the precise algorithm is proprietary, the involved measure is thought to combine regulation of the alpha and theta band (Polich, Gray, Tran, Morales-Quezada, & Glenn, 2020). The neurofeedback implementation being unknown poses several challenges to the assessment of consumer-grade EEG devices for MNF. First, it is unclear whether the used metric actually represents the neural correlates thought to underlie meditation. Second, changes to the algorithm might have been made between different studies employing the Muse MNF implementation, decreasing their comparability. Third, replication or assessment of the MNF implementation using different devices, such as research-grade EEG, is not possible.

In regards to studies investigating the efficacy of the Muse provided MNF implementation, results have been mixed. Svetlov, Nelson, Antonenko, McNamara, and Bussing (2019) compared changes in heart-rate variability (HRV) and a Muse specific metric of calmness termed ”calm percent” between two groups engaging in a mindfulness-based relaxation exercise, one with additional neurofeedback and one without. Both metrics showed improvements compared to a pre-test measure, but no differences between groups. Similarly, in a sample of participants recently diagnosed with breast cancer, no differences in measures of stress and fatigue improvements were found between a group using Muse neurofeedback and a group receiving a stress reduction control intervention (Millstine et al., 2019). Polich et al. (2020) investigated changes in neurobehavioral symptoms in a sample of participants having experienced traumatic brain injury. Again, no differences were found when comparing outcome differences between a Muse group and a focused attention meditation control group. Acabchuk, Simon, Low, Brisson, and Johnson (2021) measured both mindfulness self-report scores (MINDSENS) as well as Muse metrics in before and after several sessions of meditation. Two groups were asked to use a meditation app, with the treatment group additionally using Muse MNF. While both groups improved in MINDSENS scores, neither showed increases on Muse metrics at the post-test measurement session. The researchers also noted that Muse metrics were not correlated with MINDSENS scores across participants, further indicating that the Muse specific metrics might not be an accurate operationalization of meditation experience.

While the previous studies generally showed improvements in various outcome variables as a result of continued Muse MNF, they were largely equivalent to improvements in control conditions employing meditation without neurofeedback or a comparable intervention. However, a number of studies also found Muse interventions to outperform control conditions. Hunkin, King, and Zajac (2021) reported greater state mindfulness as measured through a breath counting exercise for participants engaging in Muse-delivered aural feedback compared to a control group. However, this effect was rather small and only marginally significant. Episodes of mind wandering as measured by the Muse app were also reported to be fewer compared to the control group. Balconi, Fronda, and Crivelli (2019) found differences in psychophysiological measures including HRV, perceived stress, anxiety and mood states for a condition of Muse meditation compared to a meditation control group. Using a similar experimental group setup, Crivelli, Fronda, Venturella, and Balconi (2019) found improved cognitive performance and attention regulation for a group employing Muse meditation.

While the vast majority of studies on consumer-grade MNF used the Muse headset, Sas and Chopra (2015) introduced a system based on the Emotiv Epoc consumer EEG headset, which features 14 channels. No control group was used in their study, but the authors report that participants were able to achieve deeper meditative states when provided with aural neurofeedback (where deepness of meditative states was based on an internal metric by Emotiv).

Overall, the majority of studies on consumer-grade MNF show that its use leads to improvements across a a large numbers of outcomes variables, both self-report and physiological. However, these improvements seldom exceed improvements due to control interventions such as meditation or stress reduction programs. As such, it is doubtful whether the acquisition of a consumer-grade EEG device for meditation is justified for the majority of practitioners. Additionally, the majority of studies employ a Muse neurofeedback metric for which the underlying neural correlates are not precisely known. Comparisons to effective neural measures of meditation as identified by the literature, therefore, remain difficult.

2.4 Neurofeedback in Virtual and Augmented Reality

A small number of studies also proposed the use of virtual or augmented reality (VR/AR) devices as an extension to neurofeedback-assisted meditation (Kosunen et al., 2016; Potts et al., 2019; Viczko, Tarrant, & Jackson, 2021; Järvelä et al., 2021). While these technologies hold the potential to deliver neurofeedback in novel and less intrusive ways, the majority of studies introduce prototype systems which have not yet been systematically validated. Potts et al. (2019) proposed an AR system using a Muse headset where alpha band power was communicated through the color of plants in a virtual garden. While participants in a pilot study reported enjoying the system, no quantitative assessment or comparison to a meditation control condition was performed. Viczko et al. (2021) compared two groups which engaged in an AR meditation experience, one also receiving neurofeedback through a Muse headset. For both groups, improvements in mood states were observed, with no difference between the groups. Using research-grade EEG, Kosunen et al. (2016) observed deeper levels of meditation, as assessed through self-report questionnaires, for a group engaging in a neurofeedback-assisted VR meditation compared to two groups not receiving neurofeedback (one meditating in VR, one using a screen). Lastly, Järvelä et al. (2021) implemented a social meditation experience in VR, where users engaged in compassion meditation in pairs and received feedback on the shared synchrony of measures such as breathing rate and EEG band power. The presence of these shared biological feedback signals resulted in greater self-reported social presence and empathy. While there is a need for a more rigorous exploration of the benefits of MNF in VR, especially the possibility of social meditation using neurofeedback affords several unique opportunities. Novice practitioners could, for example, engage in a shared meditation with a more experienced teacher and aim to bring their meditation experience closer together through the use of biofeedback synchrony signals.

3 Conclusion

This essay aimed to assess whether the addition of neurofeedback to meditation leads to increases in the positive outcomes of meditation as indicated by a range of outcome variables such as physiological, behavioral and self-report measures of meditation. While there is a significant body of literature on neurofeedback, often involving components relevant to meditation such as alpha and theta frequency bands, there are relatively few studies which specifically investigate the use of meditation with neurofeedback in a systematic way. A number of studies identified the posterior cingulate cortex (PCC) as a target region for delivering neurofeedback, as its deactivation was found to correspond highly to the subjective experience of meditators. However, no assessments were made in regards to how PCC-based neurofeedback outcomes might compare to meditation practice without neurofeedback. Additionally, as the accurate measurement of PCC activity requires either fMRI or high-channel EEG, the PCC is likely not a good candidate for MNF outside the laboratory.

A second potential target for MNF, investigated using research-grade EEG, is frontal-midline theta (FMT). While Brandmeyer (2017) found increases in resting-state EEG theta band power for a group using FMT-neurofeedback compared to a control without neurofeedback assistance, Prestel et al. (2019) did not manage to replicate these findings. As FMT can be measured using relatively low-channel EEG, it represents a potential candidate for real-life MNF applications. However, additional studies are needed to establish to what extent FMT-neurofeedback yields positive outcomes above those gained by a regular meditation practice.

Outside of investigations into MNF using research-grade equipment, several studies employed a Muse EEG device and a companion application for neurofeedback. A central problem underlying these studies is that the specific neurofeedback implementation and neural correlate being measured by Muse have not been made public. The frontal position of two Muse electrodes combined with evidence that the Muse algorithm involves a combination of alpha and theta modulation indicates that what is being measured at least in part overlaps with FMT. However, the lack in transparency make comparisons across devices and replication attempts difficult. Studies investigating the positive outcomes of Muse MNF across measures such as HRV, self-report questionnaires, cognitive assessments and internal Muse metrics also did not consistently find significant improvements compared to control conditions of regular meditation or equivalent programs. As such, there is a need to move towards open source practices both in regards to commercial EEG hardware and neurofeedback delivery applications to allow for transparent comparisons between paradigms. EEG devices manufactured by OpenBCI constitute a step into the right direction, but their higher price point and moderate difficulty of recording EEG do not yet make them a viable candidate for consumer-ready MNF.

While the investigation of VR and AR applications in combination with neurofeedback is still in its infancy, early results indicate that their combination can have positive outcomes surpassing regular meditation (Kosunen et al., 2016; Viczko et al., 2021). Especially attempts to leverage VR for the social aspects of meditation hold promise for users who are not able to engage in communal meditation physically (Järvelä et al., 2021). Using synchrony measures of different bio- and neurofeedback markers between a teacher and a novice could potentially facilitate learning for novice practitioners.

Overall, MNF is consistently shown to yield positive outcomes across a range of different measures. However, there is no systematic evidence that MNF outcomes surpass those gained through regular meditation. Standardization in the field is needed both in terms of what neural correlates are employed for neurofeedback measures as well what outcome variables are chosen to assess the comparisons of MNF with control conditions. Most importantly, more studies are needed which employ transparent and open source implementations of neurofeedback, instead of relying on proprietary hardware and software. Steps in this direction should make a more reliable assessment of the relative benefits of MNF possible. As it stands, some practitioners might benefit from the additional feedback provided by MNF, but the majority might be better served by investing into a comfortable sitting cushion.

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