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Mindfulness-based Neurofeedback: A Systematic Review of EEG and fMRI studies

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Abstract

Neurofeedback concurrent with mindfulness meditation may reveal meditation effects on the brain and facilitate improved mental health outcomes. Here, we systematically reviewed EEG and fMRI studies of mindfulness meditation with neurofeedback (mbNF) and followed PRISMA guidelines. We identified 10 fMRI reports, consisting of 177 unique participants, and 9 EEG reports, consisting of 242 participants. Studies of fMRI focused primarily on downregulating the default-mode network (DMN). Although studies found decreases in DMN activations during neurofeedback, there is a lack of evidence for transfer effects, and the majority of studies did not employ adequate controls, e.g. sham neurofeedback. Accordingly, DMN decreases may have been confounded by general task-related deactivation. EEG studies typically examined alpha, gamma, and theta frequency bands, with the most robust evidence supporting the modulation of theta band activity. Both EEG and fMRI mbNF have been implemented with high fidelity in clinical populations. However, the mental health benefits of mbNF have not been established. In general, mbNF studies would benefit from sham-controlled RCTs, as well as clear reporting (e.g. CRED-NF).

Keywords: Neurofeedback, mindfulness, EEG, fMRI, DMN, theta

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1 Introduction

Mindfulness meditation involves cultivating an accepting, open-minded attention to the present moment (Creswell, 2017). The word mindfulness originated from Eastern contemplative traditions, specifically, as a translation of the term *sati* from Pali or *smrti* from Sanskrit, which mean remembering or being aware. Mindfulness was largely introduced to Western medicine with the advent of mindfulness-based stress reduction (MBSR) in the 1980s (Kabat-Zinn, 1982, 2003). MBSR and its adaptations have been used to treat chronic pain (Goyal et al., 2014; Kabat-Zinn, 1982), anxiety (Goldin et al., 2013; Hoge et al., 2022; Hölzel et al., 2013), addiction (Black, 2014; Garland et al., 2015; Vallejo & Amaro, 2009), and depression (Kuyken et al., 2016). Indeed, mindfulness has been documented to be equally effective as pharmacological treatment for anxiety disorders (Hoge et al., 2022) and potentially more effective than cognitive behavioral therapy (CBT) for treatment of mild-to-moderate depression (Strauss et al., 2023). Mindfulness is now a central component of leading psychotherapeutic approaches like dialectical behavioral therapy (DBT) (Linehan, 1993; McCauley et al., 2018) and acceptance and commitment therapy (ACT) (Hayes et al., 1999).

Mindfulness meditations include practices like *breath awareness*, which involves orienting attention to one's breath and practicing returning to the breath every time one's attention wanders away, and *body scans*, involving moving the spotlight of attention from body part to body part with a curious and non-judgmental attitude towards the sensations one encounters. Another practice is *open monitoring*, where one notices transient thoughts and sensations in an open state without attaching to them. Breath awareness and body scans are often called *focused attention* (FA) practices, aiming to cultivate a stable and precise attention, which contrasts with *open monitoring* (OM) practices, cultivating receptivity to experience (Lutz et al., 2008).

There are several theories regarding the neurobiological mechanisms behind mindfulness meditation. One influential account suggests that large-scale brain networks are involved (Hasenkamp et al., 2012; Mooneyham et al., 2016). Specifically, this account implicates the default-mode network (DMN), with core regions of the posterior cingulate cortex (PCC) and medial prefrontal cortex (mPFC) as well as the central executive network (CEN), with core regions of the dorsolateral prefrontal cortex (DLPFC) and parietal cortex, and the salience network (SN), with core regions of the anterior cingulate cortex (ACC) and insula **(Figure 1**). In this account, the DMN is involved in mind-wandering away from the object of meditation, the CEN is

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involved in goal-directed maintenance of the object, and the SN is involved in switching between the two (Hasenkamp et al., 2012). This is based largely on functional magnetic resonance imaging (fMRI) during focused attention meditation (Fox et al., 2016; Ganesan et al., 2022), changes observed in networks after mindfulness training (Rahrig et al., 2022; Sezer et al., 2022), in addition to a robust cognitive neuroscience literature on these networks (Menon, 2011). In tandem, researchers have examined changes in brain rhythms or oscillations during meditation using electroencephalography (EEG) (**Figure 2**). Brain oscillations represent information processing across wide-ranging brain regions, and change with attention (Herrmann et al., 2016). There is evidence of power increases in alpha, theta and gamma waves during meditation (Chiesa & Serretti, 2010; Lee et al., 2018; Lomas et al., 2015; Stapleton et al., 2020). Alpha and theta power may correspond to inwardly focused attention (Lomas et al., 2015), whereas gamma power may reflect broad awareness (Lomas et al., 2015; Lutz et al., 2004; Stapleton et al., 2020). Despite this meaningful work, the field still lacks a complete mechanistic account of mindfulness meditation. Take, for example, the assertion that mindfulness decreases DMN activation (Brewer et al., 2011; Ganesan et al., 2022). This particular assertion is largely founded on comparisons of meditation to control conditions, which do not directly imply mechanistic involvement. For example, neural changes associated with mindfulness may be caused by decreases in stress accompanying meditation, rather than the voluntary and directed actions of meditation. In addition, the choice of control condition can lead to differing results. For example, Ganesan and colleagues (2022), found that the DMN was less activated during meditation than control conditions in only 60% of the studies reviewed, with the controls including rest, intentional instructions to mind wander, and other functional tasks. A final concern is that reverse inferences from brain areas to psychological processes may be implausible (Poldrack, 2006). To test theories about mindfulness meditation and uncover a more complete mechanistic account, researchers need to manipulate brain function, and neurofeedback affords one opportunity to manipulate brain functions directly implicated in mindfulness meditation.

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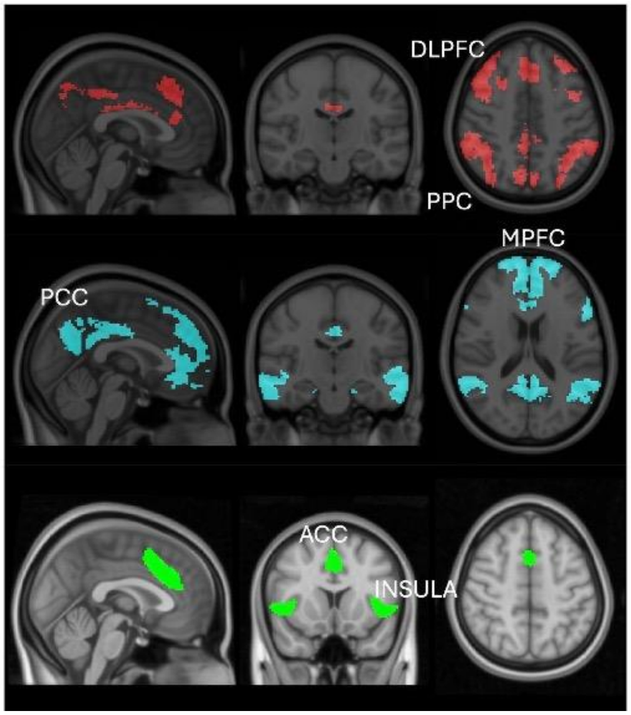

Figure 1: Brain networks involved in mindfulness meditation. Central executive network, in red; Default-mode network, in blue; Salience network, in green. DLPFC: dorsolateral prefrontal cortex; PPC: posterior parietal cortex; PCC: posterior cingulate cortex; MPFC: medial prefrontal cortex; ACC: anterior cingulate cortex; Insula: insular cortex. Adapted with permission from Treves et al., in press.

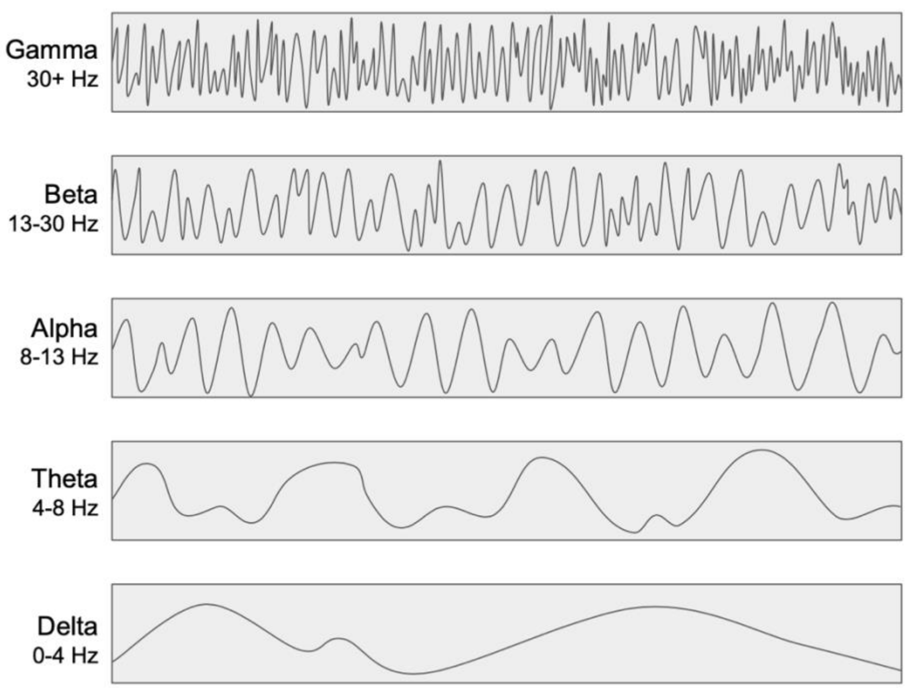

Figure 2: EEG Frequency Bands. This visualization demonstrates the differing frequencies of the various EEG bands. Created in google slides.

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Neurofeedback originated in the 1960s for EEG (Kamiya, 2011), and early 2000s for fMRI (e.g., DeCharms et al., 2004; Yoo & Jolesz, 2002). Similar to biofeedback, it consists of relaying brain data (i.e., the target measure) to a participant while they perform a task. The participant may be given instructions to modulate the target by any number of strategies, or they may be given a specific strategy and told that correct application will be indicated by changes in their brain data. This neurofeedback condition may be compared to control conditions, wherein participants are presented with data from other brain regions not affected by the strategy ('alternative ROI control'), or from other participants ('yoked' sham). Given well-designed controls (Sorger et al., 2019), neurofeedback can provide more substantive evidence that a brain region or network is involved in a process (for a complete account, neurostimulation methods may be most optimal). In addition to providing mechanistic insights into mental processes (Kvamme et al., 2022), neurofeedback allows participants to manipulate those processes. Neurofeedback has been used in many different applications, from the regulation of chronic pain (deCharms et al., 2005), to attentional training (typically involving prefrontal regions) (DeBettencourt et al., 2015; Wang & Hsieh, 2013), to stress reduction (typically involving the amygdala) (Hellrung et al., 2018; Nicholson et al., 2017; Young et al., 2017). It is often considered to 'enhance' learning, leading to improved outcomes (Haugg et al., 2021; Kadosh & Staunton, 2019). Researchers often conduct a single session of neurofeedback and then evaluate behavioral outcomes days, weeks or months later ((Pamplona et al., 2023; Ros et al., 2013); though, several studies have leveraged repeated sessions (Dekker et al., 2014; Mehler et al., 2018). Overall, there is promising evidence for the clinical mental health benefits of EEG and fMRI neurofeedback (Roy et al., 2020; Trambaiolli et al., 2021; Van Doren et al., 2019; c.f. Thibault et al., 2018). Thus researchers have proposed that the clinical benefits of mindfulness (as well as cognitive benefits) could be enhanced or facilitated by neurofeedback (Brandmeyer & Delorme, 2013; Brandmeyer & Reggente, 2023).

Starting in the early 2010s, neurofeedback concurrent with mindfulness meditation has been gaining popularity, and it is often referred to as mindfulness-based neurofeedback (mbNF). The purpose of this paper is to systematically review the literature and thus answer two main questions. First, can participants learn to modulate brain targets through mindfulness meditation practice, providing evidence of their involvement in meditation? Second, what are the behavioral and brain outcomes of mbNF? By reviewing the literature, there

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also are opportunities to discuss methodological limitations. The CRED-NF checklist (Ros et al., 2020), could be a crucial initial step towards standardizing current methodological and outcome reporting practices. The CRED-NF checklist includes preregistration, sample size justification, control group, double-blinding, whether or not participants used a strategy, artifact removal, feedback specification, regulation success (target engagement), brain and behavioral outcomes, and more. We evaluate the quality of studies herein based on the CRED-NF checklist. The present review only examines controlled lab-based EEG and fMRI studies (consumer-grade EEG studies are not reviewed, see Methods).

2 Methods

PRISMA guidelines were followed in this review (**Supplement 2**) (Page et al., 2021).

2.1 Inclusion and Exclusion Criteria

Studies that employed EEG or fMRI neurofeedback concurrently with mindfulness meditation were included. Specifically, studies were selected that claimed to employ mindfulness meditation, and we then evaluated whether the meditation met our definition of mindfulness. For the purposes of this review, mindfulness meditation is defined as meditation practice with the aim of cultivating non-judgmental attention to the present moment, including both focused attention (FA) and open monitoring (OM) practices (Lutz et al., 2008). FA and OM are distinct practices, but both are taught in mindfulness interventions like MBSR (Santorelli, 2014) and involve purposeful redirection of attention to the present moment (Britton et al., 2019; Dahl et al., 2015). Other meditation (e.g. transcendental, compassion) was not included. Exclusion criteria included lack of EEG or fMRI neurofeedback, lack of mindfulness meditation, lack of concurrent neurofeedback and mindfulness meditation, and non-empirical status (e.g., reviews). Studies with consumer-grade EEG devices were considered beyond the scope of this review, as there were substantial such studies (33), and consumer-grade devices don't allow sufficient insight into brain mechanisms. No relevant conference papers or dissertations were identified.

2.2 Systematic Search

A search of PubMed, Web of Science, PsycInfo, and Scopus, was completed on November 11, 2023. Databases were identified based on previous mindfulness systematic reviews and meta-analyses (Goldberg et

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al., 2018; Treves et al., 2019). Search terms were "(mindfulness OR meditation) AND (neurofeedback OR neural feedback OR neuro feedback)". We additionally searched reference sections of included papers.

2.3 Study Selection

All studies were first screened for duplicate publications. Next, all abstracts were screened, including studies based on two main criteria: full report of an empirical study (examples of excluded articles were review papers, protocol papers, book chapters, and conference proceedings) and content relevance (based on above stated inclusion/exclusion criteria). Then remaining studies were screened by reviewing the methods section and full paper to further evaluate the presence of inclusion criteria. Determination of inclusion was established in cases of disagreement by consulting with the first author.

2.4 Coding

Records were grouped according to neuroimaging technique (i.e., EEG or fMRI). Two reviewers (KDG & EW) independently evaluated each EEG study and its characteristics, and two reviewers (INT & ZB) independently evaluated each fMRI study and its characteristics. The studies were coded for sample, targets, neurofeedback details, control conditions, target engagement, neural outcomes and behavioral outcomes (**Tables 1** and **2**). Target engagement was defined as 'whether or not the neurofeedback target was modulated', whereas neural outcomes are changes in other neural measures not targeted in the study neurofeedback protocol. Behavioral outcomes may consist of outcomes like state mindfulness reported after the scan, or more distal but related outcomes (e.g. cognitive performance on a separate task).

2.5 Bias and quality coding

No automation tools were used. Papers were coded independently to limit reviewer bias. Risk of bias in the studies was not quantified given the limited number of RCTs. Instead, we coded studies based on the CRED-NF checklist (Ros et al., 2020), reporting whether recommended items were present in the studies (**Table S1**).

Box 1: Neurofeedback Terms

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Bidirectional control: Testing whether participants may modulate a neurofeedback target in both directions. For example, decreasing the DMN by meditating, and increasing the DMN by ruminating.
Calibration: A preceding block of non-neurofeedback data used for the neurofeedback target estimates, typically eyes-open rest.
Control, Alternate ROI: Typically, feedback is given from a region or network that is not related to the task.
Control, Yoked Sham: Feedback is presented to a control participant from an experimental participant. This feedback is controlled for in terms of perceived reward but not contingent on a control participant's performance.
Functional/individual localization: Determining a brain area or network based on data from the participant. An example is conducting resting-state fMRI before the neurofeedback task, which can be used to extract intrinsic networks that are correlated at rest.
Intermittent vs continuous: Intermittent, or delayed, feedback is feedback presented after regular intervals, not concurrently with task. Continuous, or real-time, feedback is feedback presented throughout the task (e.g. every second). May involve different attentional demands (Hellrung et al., 2018).
Offline artifact correction: Estimates of motion or physiology are corrected for or tested for in post-processing.
Online artifact correction: Estimates of motion or physiology are included in real-time models (e.g. GLMs), so feedback is not presented based on those artifacts.
Target: The brain measure relayed to participants.
Target engagement: A test of whether participants successfully learned to modulate the target brain measure, may consist of examining overall levels of target, change in target, or target performance in transfer runs.
Transfer run: A neuroimaging run where participants perform the neurofeedback task without any feedback presented. Transfer tasks after feedback can be used to assess whether learning has occurred.

3 Results

3.1 Search Results

A Prisma flow diagram is shown in **Figure 3**. The search yielded 676 records across four databases. After removing duplicates and excluding based on title and abstract, full texts were reviewed for the remaining 114 studies. The final sample included 19 studies with 15 independent samples representing 419 participants.

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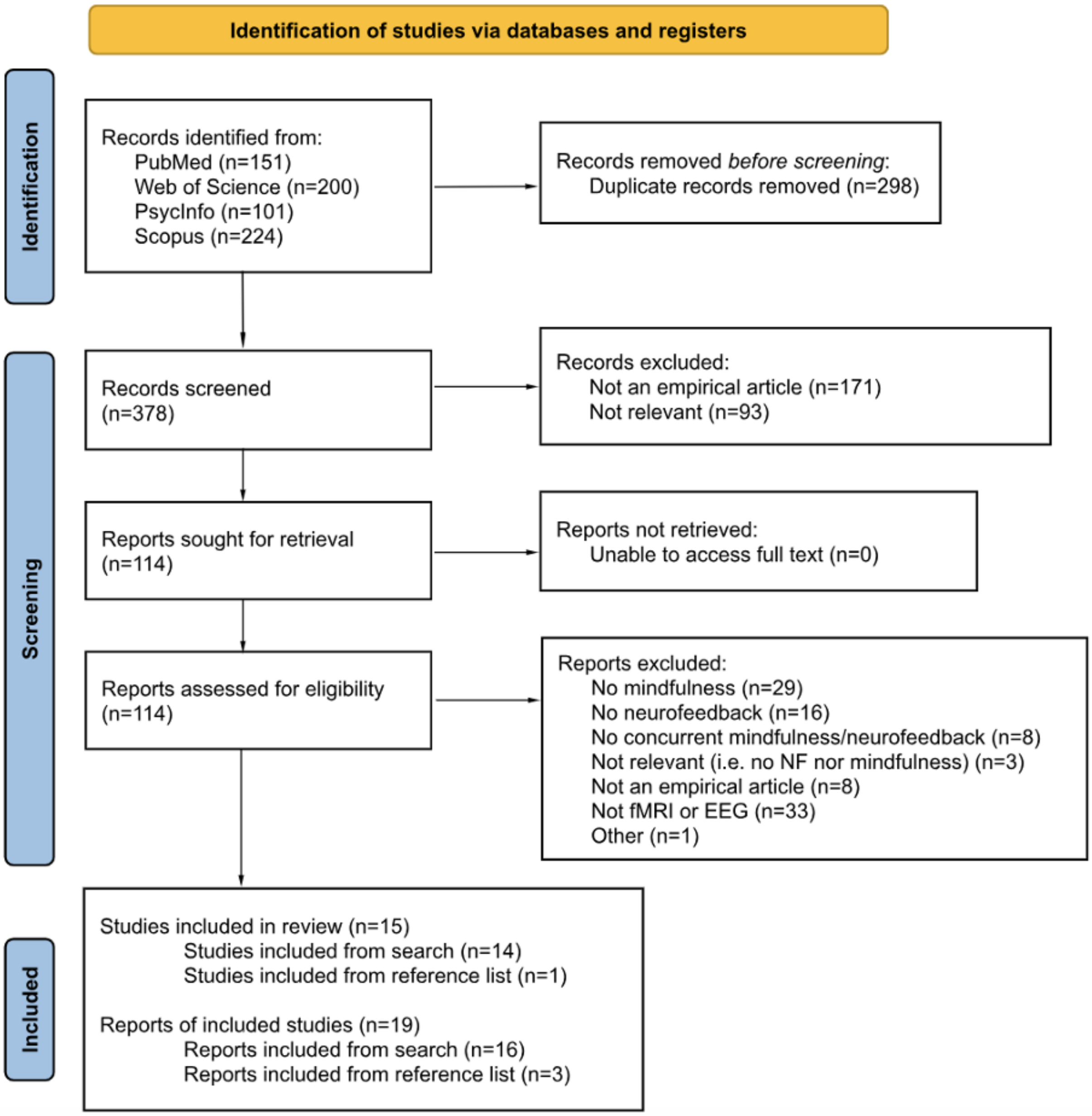

Figure 3: PRISMA flow diagram depicting number of identified and evaluated articles for concurrent mindfulness and fMRI or EEG neurofeedback procedures.
Note. Studies refer to unique samples, while reports refer to publications on said samples. Our review identified four samples which corresponded to more than one published report, as indicated in this flowchart and in the study summary tables (Tables 1 and 2).

Author/ Date	Sample	Mindfulness Meditation	Control Condition	Neural Target	Feedback presentation	fMRI session details	Target Engagement	Neural Outcomes	Behavioral Outcomes
Garrison, Scheinost, et al., 2013	Exp1: 9 meditators (variety of traditions, M= 9.5 yrs, 8803 hrs), 11 non-meditators Exp2: 10 meditators (variety of traditions, M=18.4 yrs, 10567 hrs)	Focused attention/ breath practice	None[a]	PCC activation	Bar graph: blue upwards bar for activation increases, red downwards bar for activation decrease. Full graph with past feedback shown.	Exp1 : 3-min NF scan. Exp2: three 1-min NF scans.	Exp 1: More negative PCC activations during NF in meditators compared to controls. Exp 2: significant deactivation of PCC compared to self-reference.	Not reported	Effortless awareness was associated with decreased PCC activity.
Garrison, Santoyo, et al., 2013	Same sample as Exp2 from Garrison, Scheinost et al., 2013, 10 meditators	"	Within-subject no feedback	"	"	Six 1-min feedback scans	Not reported	"	Qualitative report: PCC deactivation was associated with experience of focused attention and effortless awareness, PCC activation was associated with opposite.
Kim et al., 2019	60 adults[b]	Focused attention/ breath practice	Yoked sham group	Individually localized DMN, CEN, and SN. Mediation slope excluding CEN from DMN and SN relationship.	Thermometer where higher bar reflects higher mediation slope. Calculated using windowed brain activity from 50 sec prior.	Two 5-min NF runs, one transfer fMRI run.	Mediation effect not significantly larger in experimental group. However, correlation between mediation effect and mindfulness/target performance feedback (TPF, self-report) only in experimental group.	Activations in DMN negatively correlated with mindfulness/TPF in experimental group.	No group X time effects on mood, state mindfulness, TPF, or stress. No reported changes in cognitive tasks.
Bauer et al., 2020	11 participants with schizophrenia or schizoaffective disorder	Open awareness (noting)	Alternative ROI control: from somatomotor cortex during finger tapping in same participants (7 completed)	Individually localized CEN and DMN networks. Increase CEN relative to DMN (PDA).	A moving ball. The ball moves relative to the difference between CEN and DMN. If CEN > DMN, ball moves up. If DMN > CEN, ball moves down. Activations from 30 sec prior.	Two no-feedback transfer runs (2.5-mins each), four feedback scans (2.5-mins each).	Participants showed significant CEN > DMN (more than chance) on average during NF. Unclear whether control condition also engaged target.	Decreased DMN connectivity (mPFC-PCC), decreased CEN-DMN connectivity (dlPFC-mPFC) from pre- to post-resting-state, not present in control condition.	AHs decreased 1-wk after, returning to baseline after >12-wks. AHs were not affected by control neurofeedback task.
Okano et al., 2020	Same sample as Bauer et al., 10 participants with schizophrenia or schizoaffective disorder	Open awareness (ignoring auditory stimuli)	"	Functionally localized STG activation	Thermometer, where height is activation in STG.	2 transfer runs and four NF runs (~ 1-min). Each run had 2 "listen" blocks and 2 "ignore" blocks (16-sec each).	Anatomically defined STG activation was less post-feedback transfer than pre-feedback. No differences after control condition.	Not reported	AHs decreased, not affected by control task. Correlation between right STG decrease and AH decrease. AHs returned to baseline after 12-wks.

Author/ Date	Sample	Mindfulness Meditation	Control Condition	Neural Target	Feedback presentation	fMRI session details	Target Engagement	Neural Outcomes	Behavioral Outcomes
Pamplona et al., 2020	30 adults	Focused attention[c]	No-feedback control group	SAN activation (composite of DAN and FPN) minus subject-specific DMN (core hubs and angular gyrus). Compared to baseline blocks.	Intermittent feedback with thermometer (red is high SAN-DMN, blue is low SAN-DMN) every 40 sec (with monetary rewards at end of run).	Two NF runs (6-mins each), two transfer runs.	Decreased DMN activations over training (specifically mPFC and PCC) and in post-transfer runs (compared to pre-transfer). Increased attentional network (specifically mid-cingulate and pre-SMA) activations during training and in transfer runs (specifically IPS).	Not reported	Control group improved more on multiple attention tests, but NF group improved in RTs for vigilance test, specifically during early trials. No changes in attentiveness and stress. No relationship between changes in self-report/behavior changes and target engagement.
Pamplona et al., 2023	Same sample as Pamplona et al. (2020), 15 adults	"	None	"	"	"	"	Transfer at 2 months: DMN deactivation present (PCC/mPFC), not present in SAN. DMN visual area correlations increased and maintained at follow-up, related to degree of psychomotor vigilance changes.	No behavioral effects persist at two months.
Kirlic et al., 2022	34 adolescents (ages 13-17)	Focused attention/ breath practice	None	PCC activation	Bar graph: blue upwards bar for activation increases ("focused attention"), red downwards bar for activation decreases ("mind-wandering"). Tasked to match blue bar with green target bar.	Three 7-min NF runs, two transfer fMRI runs (OBS and TRS).	PCC deactivation during NF, consistent when compared to rest or self-referential processing. Not observed during post-transfer. Widespread deactivations in other regions. Limited evidence of correlations between PCC activation and self-reports (e.g. mindfulness) - doesn't survive MC.	Not reported	No changes in PSS or negative affect. State mindfulness increase maintained at 1-wk.
Yu et al., 2022	Same sample as Kirlic, 37 adolescents (ages 13-17)	"	"	"	"	"	"	Posterior insula activations decrease. Anterior insula activations increase. No transfer effects.	Self-report state mindfulness increased. No change for mind-wandering.
Zhang et al., 2023	9 adolescents (ages 17-19) with lifetime history of major depressive disorder/anxiety disorders	Open awareness (noting)	None	Individually localized CEN and DMN networks. Increase CEN relative to DMN (PDA).	A moving ball. The ball moves relative to the difference between CEN and DMN. If CEN > DMN, ball moves up. If DMN > CEN, ball moves down. Activations from 30 sec prior.	Five 2.5-min NF sessions. No transfer.	More overall time in CEN > DMN state. Marginally lower DMN activation.	sgACC -DMN (mPFC/PCC) connectivity decreased. Target performance (PDA) correlated with decrease (only in last NF block).	State mindfulness increased, correlated with target performance and connectivity decrease.

1

Table 1. Summary of studies of fMRI-based neurofeedback with concurrent mindfulness practice.

Note. AH = auditory hallucinations; CEN = Central executive network; DAN = Dorsal attention network; dlPFC = dorsolateral prefrontal cortex. DMN = Default mode network; FPN = frontoparietal network; Hrs = hours. M = mean; MC = Multiple comparisons; Mdn = median; Min = minute; mPFC = medial prefrontal cortex; OBS = Observe runs; PACE = prospective acquisition correction; PCC = posterior cingulate cortex; PDA = Positive diametric activity; PSS = Perceived Stress Scale; RT = Reaction time; SAN = Sustained attention network; SD = standard deviation; Sec = second; SN = Salience network; STG = superior temporal gyrus; TPF = task-performance feedback; TRS = Transfer runs; Wk = week; Yr = year.

[a] Feedback from parietal cortex only used during monitoring phase.
[b] All male participants.
[c] Participants allowed to use any strategy that works for them.

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3.2 fMRI Studies

3.2.1 Summary

We identified 10 reports of fMRI neurofeedback including 7 unique samples (**Table 1**). There were two studies that used different neurofeedback protocols with the same sample, patients with schizoaffective disorders (Bauer et al., 2020; Okano et al., 2020). In total, there were 177 unique participants, and most samples were at or below 30 participants (**Figure S1 & S2**). Studies employed focused attention and open monitoring meditations. The first study published was Garrison et al. (2013a), a breath-focused attention study, which was also the only study to involve experienced meditators. Garrison et al. (2013b) examined qualitative reports from meditators who were asked to explore correspondence between brain signals and meditation experiences. A typical open monitoring protocol asked participants to label thoughts and feelings as they came up (Bauer et al., 2020). Only one study reported participants' actual mental strategies during neurofeedback regulation (Pamplona et al., 2020), and found a variety of strategies employed, some of which weren't typical mindfulness. Control conditions encapsulated yoked sham, alternate ROI, and mindfulness meditation without feedback, but many studies did not include controls (**Figure S3 & S4)**. Only two studies examined between-subjects controls (**Figure S5**) (Kim et al., 2019; Pamplona et al., 2020), and transfer runs (**Box 1**) were inconsistently used across studies. Zhang et al. (2023) was the only study to examine adolescents. Qualitative assessments of the mbNF experience are found in **Table S3.**

3.2.2 fMRI Targets

The majority of studies employed activation-based, default-mode network targets (**Figure 4**). There was some variety in the specification of the DMN. Two studies targeted PCC activity (Garrison et al., 2013; Kirlic et al., 2022, Yu et al., 2022). Multiple studies used individualized networks generated from independent component analysis of resting-state scans (Bauer et al., 2020; Kim et al., 2019; Pamplona et al., 2020, 2023). These studies combined network activations from not only the DMN but also attentional networks like the dorsal attention network (Pamplona et al., 2020, 2023), the salience network (Kim et al., 2019), and the CEN (Bauer et al., 2020). One study used a task to functionally localize the superior temporal gyrus (STG) in order to modulate auditory processing (Okano et al., 2021). Kim et al. (2019) was the only study which used a

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connectivity-like target, and they examined the direct effect from DMN-SN, excluding the influence of the CEN (as the CEN was proposed to be involved with the visual feedback monitoring and not the meditation). Target measures did not appear to depend on whether participants performed focused attention vs open monitoring.

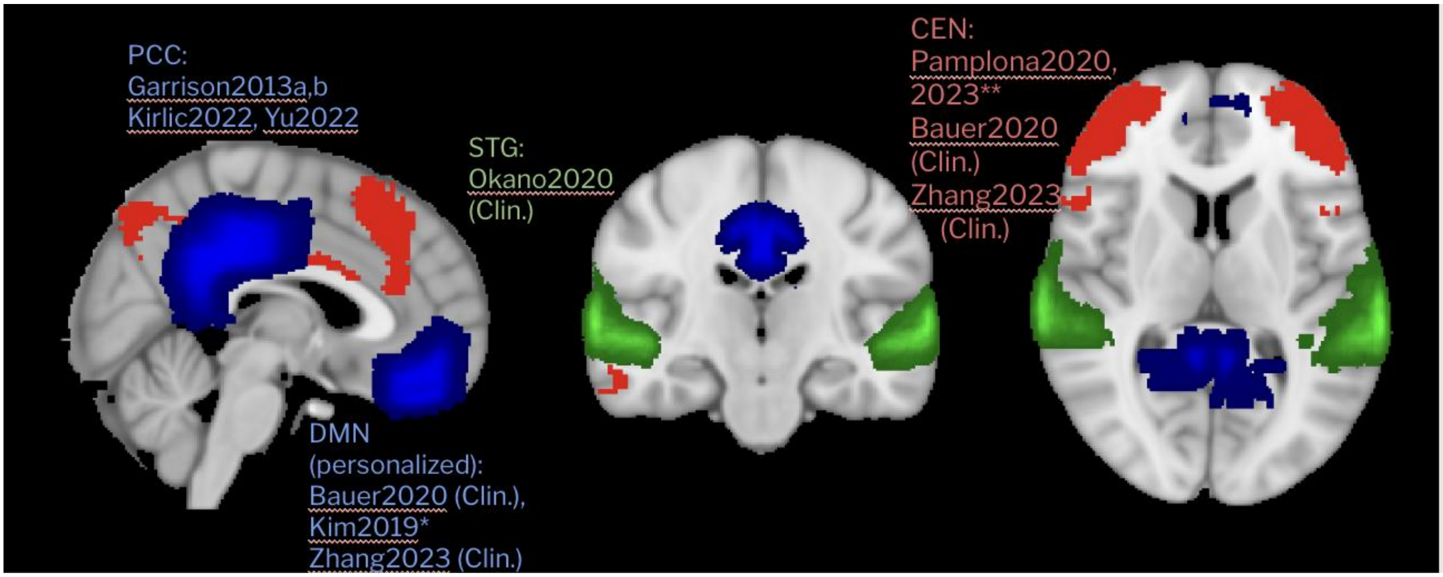

Figure 4: fMRI targets for neurofeedback. In blue, default-mode network (DMN) regions. In green, the superior temporal gyrus (STG). In red, the central executive network (CEN). Networks are taken from the Yeo atlas (Yeo et al., 2011), and STG was extracted from the Harvard-Oxford cortical atlas. *Kim used DMN-SN slope **Pamplona used sustained attention network.

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There were different approaches to computing the target measure. Multiple studies used baseline periods in the same fMRI scan to scale and baseline the neurofeedback target measure (e.g., 30 seconds of rest ;Bauer et al., 2020; Okano et al., 2020; Zhang et al., 2023). Garrison et al., 2013a, 2013b used a self-reference task. Some studies used online motion artifact correction, and two studies additionally conducted online correction for physiological signals like breathing and heart rate (Kirlic et al., 2022; Yu et al., 2022). No differences were observed between neurofeedback and rest in terms of motion or physiological signals.

Feedback was displayed visually to participants during fMRI in all cases. Some studies used delayed feedback, e.g. continuous feedback but with a time lag (Bauer et al., 2020; Kim et al., 2019), and one used intermittent feedback (Pamplona et al., 2020). One study displayed a continuously updating graph containing past values of the measure (Garrison et al., 2013). Negative and positive feedback was shown. One study incorporated rewards for target engagement (Pamplona et al., 2020).

3.2.3 fMRI Target Engagement

All studies evaluated target engagement. Garrison et al. (2013) found that meditators showed more negative PCC (the target) activation than controls. Two studies examined the amount of time spent in a 'correct' brain state (CEN > DMN), and found above chance engagement for the group (Bauer et al., 2020; Zhang et al., 2023). Another study examined change over neurofeedback blocks in activation, and found significant decreases in the DMN (Pamplona et al., 2020), but no increases in their individually defined attentional networks. Transfer runs can also be used to assess whether target engagement or learning has taken place. Kirlic et al. (2022) observed decreased PCC activation during neurofeedback compared to control tasks, but not in the post-transfer run. Although there seems to be consistent evidence of DMN deactivation during neurofeedback, the only study to use a sham control and a large (n~60) sample did not find evidence for target engagement (mediation slope between the DMN-SN) (Kim et al., 2019). This and the transfer results from Kirlic and colleagues make it unclear whether participants have learned to modulate their brain networks.

3.2.4 Neural Outcomes

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Many studies examined the possibility of neural changes due to neurofeedback. Some reports focused on DMN-based connectivity assessed during resting-state fMRI before and after neurofeedback. There are indications of reduced within-DMN connectivity (e.g. between the MPFC and PCC), as well as more negative correlations between DMN and CEN (Bauer et al., 2020). Other studies found reduced DMN connectivity with the sgACC (sometimes considered part of the DMN; Zhang et al., 2023), reduced DMN connectivity with the STG (Okano et al., 2020), and increased DMN-visual area connectivity (Pamplona et al., 2023) even at a 2-month follow-up assessment. Of the findings, only the DMN-STG finding was established as specific to the mindfulness-based neurofeedback, as Okano and colleagues did not find DMN-STG changes in an alternative ROI control session (finger tapping). However, Zhang et al. (2023) found associations between DMN-sgACC connectivity decreases and target engagement and state mindfulness in their small sample.

Researchers also examined activations in non-target and target brain regions. Yu et al. (2022) found that neurofeedback increased anterior insula activations, and decreased posterior insula activations, without any transfer effects. This could reflect changes in interoceptive processing during mbNF. Kim et al. (2019) found that activations in the DMN negatively correlated with state mindfulness, but only in the experimental group and not the sham feedback group.

3.2.5 State Mindfulness

To assess whether participants are learning from neurofeedback, studies also tested whether they experienced increases in state (or momentary) mindfulness, as reported after the scans. State mindfulness assessments typically involved questions about present-focused awareness of the mind and body (Tanay & Bernstein, 2013). Kim et al. (2019) found no mbNF vs control group effects on state mindfulness or self-report target efficacy. However, two uncontrolled studies found increases in state mindfulness after neurofeedback (Kirlic et al., 2022; Zhang et al., 2023).

3.2.6 Behavioral Outcomes

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A central motivation for many of the studies was the possibility of beneficial behavioral or self-reported outcomes. Pamplona et al., (2020) observed improvements in reaction time on a vigilance test, but this was not maintained at the 2-month follow-up (Pamplona et al., 2023). They also did not observe a correlation between target engagement and vigilance reaction time. Kirlic et al. (2022) did not observe any changes in perceived stress or negative affect after neurofeedback. Bauer et al. and Okano et al. observed decreases in auditory hallucinations that were not present after a control neurofeedback task, however, the protocols were conducted on the same sample and the same baseline was used for both. Overall, there is limited evidence for mindfulness-based fMRI neurofeedback benefits as yet.

3.2.7 Clinical Applications

Three studies conducted neurofeedback with small clinical samples (Bauer et al., 2020; Okano et al., 2020; Zhang et al., 2023). Bauer and Okano et al. examined neurofeedback in the same 10 individuals with schizophrenia, and found decreases in auditory hallucinations - although these changes were not sustained at 12 weeks. Zhang et al. examined neurofeedback in 9 adolescents with affective disorder history, and found decreases in sgACC-DMN connectivity which is heavily implicated in adolescent depression (Chai et al., 2016); though symptom changes were not assessed. These studies can be considered pilots–focused mostly on establishing feasibility of the neurofeedback protocols in clinical samples.

3.2.8 Quality (CRED-NF)

In general, the control conditions in fMRI studies (within and across-subjects) were lacking, with only one study involving adequate controls and reporting. Reporting of feedback specifications, target engagement (in the feedback condition), data processing methods, etc. was present across the vast majority of studies. Few studies conducted preregistration, power analyses, or made their data/code open access. A full table may be found in **Table S2.**

Author/ Date	Sample	Mindfulness Meditation	Control Condition	Neural Target	Feedback presentation	EEG session details	Target Engagement	Neural Outcomes	Behavioral Outcomes
Hinterberger & Fürnrohr, 2016	26 meditators (M 8.2 yrs practicing), 10 non-meditators	Focused attention and body scan[a]	Within-person control. Focused attention meditation only, body scan meditation only, and yoked sham.	EEG frequency bands (USP, SCP, delta1, delta2, theta, alpha, beta, gamma, wide) amplitude and time from peak-to-peak of a wave cycle.	Sensorium (multimodal NF environment using sound and light changes)	Two 20-min sessions on two separate days.	Compared to the aggregate of non-Sensorium conditions, the aggregate of all Sensorium conditions showed a stronger increase in power in the theta2, alpha1, and alpha2 bands.[b]	Not reported	Subjective feedback ratings show Sensorium was not inferior to meditation alone, and was rated as a more extraordinary experience. The Pseudo-Sensorium was found to be inferior to Sensorium3.
Kosunen et al., 2016	43 adults	Focused attention and body scan	Within-person controls. Followed both meditation exercises (1) using a computer screen with no VR headset or NF and (2) using the VR headset with no NF.	Increase in power of alpha band and theta band	VR headset. Users begin on a platform. Increases in theta band power correspond to platform levitating, while increases in alpha band power correspond to increases in opacity of energy bubble surrounding user.	Two 10-min NF sessions in one day.	Not reported	Not reported	On a meditation depth questionnaire, the VR+NF condition performed significantly better than the Screen only condition, but not the VR+no NF condition.
Salminen et al., 2023	Same sample as Kosunen et al. 2016, 43 adults	"	"	"	"	"	No significant effect for alpha. Significantly greater frontal theta activation during NF sessions versus no-NF conditions.	Significantly more gamma power during VR vs. computer screen. Significantly more gamma power during NF vs. no-NF. Significantly more gamma power during body scans than focused attention.	Higher self-reported sense of presence during NF vs. no-NF. Higher self-reported sense of presence was reported in VR vs. computer screen conditions.
van Lutterveld et al., 2017	16 novice meditators, 16 experienced meditators (Mdn 6164 hrs, minimum 5 yrs experience)	Noting practice (for novices), and effortless awareness (for experienced meditators)	Within-person control. Bidirectional control	Decreased gamma band PCC activity	Bar graph: upward bar for increases in PCC power and downward bar for decreases in PCC power. Full graph with past feedback shown.	Three 1.5-min runs of concurrent meditation and NF.	Novice meditators were able to decrease PCC power in noting practice runs only. Experienced meditators were able to for all runs. Neither group was able to upregulate PCC (bidirectional control)	Not reported	Both groups associated effortless awareness with decreased PCC activity.
Dunham et al., 2018	10 adults	Open awareness	None	BIS value (higher value correlates with higher power in high-frequency bands)	Continuous display of raw EEG and a BIS value (0–100). Participants were told a BIS value more than 94 indicates fast brainwave activity, which might denote stress.	Up to 4 days over a 21 day period. Each day has two 12-min blocks.	BIS value significantly decreased compared to baseline. For the one participant who completed 4 days, mean BIS score significantly decreased from day 1 to day 4.	Not reported	For the one participant who completed 4 days, wellbeing score increased from day 1 to day 4.

Author/ Date	Sample	Mindfulness Meditation	Control Condition	Neural Target	Feedback presentation	EEG session details	Target Engagement	Neural Outcomes	Behavioral Outcomes
Dunham et al., 2019	57 adults	Open awareness	None	“	“	4 days over a 21 day period. Each day has two 12-min blocks.	Mean BIS and minimum BIS lower than baseline BIS for each of 4 training days, but no significant change in values across days.	Not reported	Wellbeing scores significantly increased from day 1 to day 4, and were significantly higher than the single time point comparison sample.
Prestel et al., 2019	6 meditators (Mdn 70 hrs experience)	Focused attention and open monitoring[c]	Within-person control. Final session was meditation only with no NF.	Increase frontal midline theta (FMT)	Grayscale sphere, increases in FMT power correspond to sphere becoming larger, decreases in FMT power correspond to sphere becoming smaller.	Eight sessions over 2 weeks. Each session has five 5-min training blocks.	Number of sessions was significantly positively associated with greater FMT power. However, this was mostly due to 2 subjects who had a strong significant positive correlation, while the other 4 subjects had nonsignificant effects. Mixed results for control condition.	Not reported	In post-session interviews, some participants reported negative experiences with NF (e.g. distraction, pressure to perform). Subjective appraisal of performance did not always align with one’s FMT power values.
Brandmeyer & Delorme, 2020	24 adults	Focused attention/breath practice	Between-person control. Yoked sham NF (from gender-matched pair in the experimental group)	Increase frontal midline theta (FMT)	Colored square, color was updated 4X per sec, with a gradient from black (low FMT amplitude) to light blue (high FMT amplitude).	Eight sessions over 2 weeks. Each session has six 5-min training blocks.	NF group had significant increase in FMT activity across sessions. No significant differences in FMT across sessions among sham control group.	Significant increase in gamma power in frontal midline and left temporal parietal areas during N-2 back task pre to post NF for NF group only. No significant differences in EEG activity for SART or local-global task (attention).	Faster reaction times post-NF on correct trials during the N-2 back working memory task for NF group only. No significant results for SART or local-global task (attention).
Chen et al., 2021	34 meditation-naive participants (17 with anxiety disorder; 17 healthy)	Mindfulness recording therapy[d]	None	Alpha band power of right and left frontal lobes	Bar graph with two bars representing alpha power on the left (colored red) and right (colored green) sides of the frontal lobe.	One 8-min session	Not reported	Significant increase in alpha, gamma, and theta power pre-post mindfulness NF for both groups. An ANOVA revealed a significant main effect of condition (anxiety vs healthy), condition × brain region, condition x hemisphere, and condition x region x hemisphere.	Not reported

Table 2. Summary of studies of EEG-based neurofeedback with concurrent mindfulness practice.

Note. BIS = Bispectral Index^{TM}; EEG = Electroencephalography; FMT = frontal midline theta; Hrs = hours; M = Mean; Mdn = Median; Min = minutes; NF = neurofeedback; PCC = Posterior Cingulate Cortex; SART = Sustained attention to response task; SCP = Slow Cortical Potentials; Sec = seconds; USP = Ultra-Slow Potentials; VR = Virtual Reality; Wide = 1–40 Hz. Yrs = years.

[a] Mindfulness instructions for control conditions were different than instructions for Sensorium conditions, which were more general
[b] Two of the three Sensorium conditions utilized neurofeedback (Sensorium 1 condition did not)
[c] Participants allowed to use any strategy that works for them
[d] Details of mindfulness task were not further specified

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3.3 EEG studies

3.3.1 Summary

Nine reports of EEG neurofeedback during mindfulness meditation were identified, corresponding to eight unique samples (**Figure S1 & S2**). In total, there were 242 unique participants, and all samples were adults. Multiple samples looked at meditators, or compared meditators to non-meditators (Hinterberger & Fürnrohr, 2016; Prestel et al., 2019; van Lutterveld et al., 2017). Only one sample included a clinical population (anxiety disorders; Chen et al., 2021) and only two samples did not include a control condition (Chen et al., 2021; Dunham et al., 2018; Dunham et al., 2019). All control conditions were within-subject with the exception of Brandmeyer and Delorme (2020) (**Figure S5)**. However, the control conditions varied; most were compared to some form of meditation without neurofeedback and others included yoked shams (**Figure S3 & S4**) (Hinterberger & Fürnrohr, 2016; Brandmeyer & Delorme, 2020). The most common types of meditation were focused attention, body scan, and open monitoring. The terminology for the type of meditation was not always consistent, and we used specific reporting from studies to classify meditation types. That said, reporting on specific mindfulness instructions was not always clear (Chen et al., 2021) and participants were sometimes allowed to use various strategies (Prestel et al., 2019). It is also important to note that even within a single study, the instructions of the control condition mindfulness did not always match the instructions of the active NF session (Hinterberger & Fürnrohr, 2016). Qualitative assessments of the mbNF experience are found in **Supplement Table 2.**

3.3.2 EEG Targets

Almost all studies used changes in frequency band power as their neural target (**Figure 5**); the most common was alpha and theta, though some studies used gamma (van Lutterveld et al., 2017) or Bispectral Index™ (BIS) value, which is an EEG technique most commonly used to measure depth of consciousness for patients under general anesthesia (Dunham et al., 2018; Dunham et al., 2019). Multiple studies focused on more than one frequency band (Hinterberger & Fürnrohr, 2016; Kosunen et al., 2016; Salminen et al., 2023). Some studies focused on whole brain frequency band power, while others looked at frontal midline sites (Brandmeyer & Delorme, 2020; Prestel et al., 2019) or source localized areas like the PCC (van Lutterveld et al., 2017). The

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density of EEG ranged from high density 128-channel (van Lutterveld et al., 2017) to extremely low density Bispectral Index, which generally has 2-4 channels though the exact number of channels was not reported in this case (Dunham et al., 2018; Dunham et al., 2019). Notably, the way the target was calculated varied, even within a sample. For example, Salminen et al. (2023) calculated theta power from an average of two electrodes (F3 and F4) and alpha power from an average of all electrodes (F3, F4, C3, C4, P3, and P4). Other studies used an independent component analysis (ICA) to calculate the target (Chen et al., 2021; Prestel et al., 2019). Interestingly, the only two samples that had the same neural target (frontal midline theta) calculated the feedback differently, with Brandmeyer & Delorme (2020) using the signal from a single frontal electrode (Fz) while Prestel et al. (2019) used an ICA to determine frontal midline theta. Almost all feedback was displayed visually, most commonly on some sort of screen, though virtual reality was also used (Kosunen et al., 2016; Salminen et al., 2023). One study used both sounds and light changes as their feedback presentation (Hinterberger & Fürnrohr, 2016). Positive and negative feedback was shown for all studies.

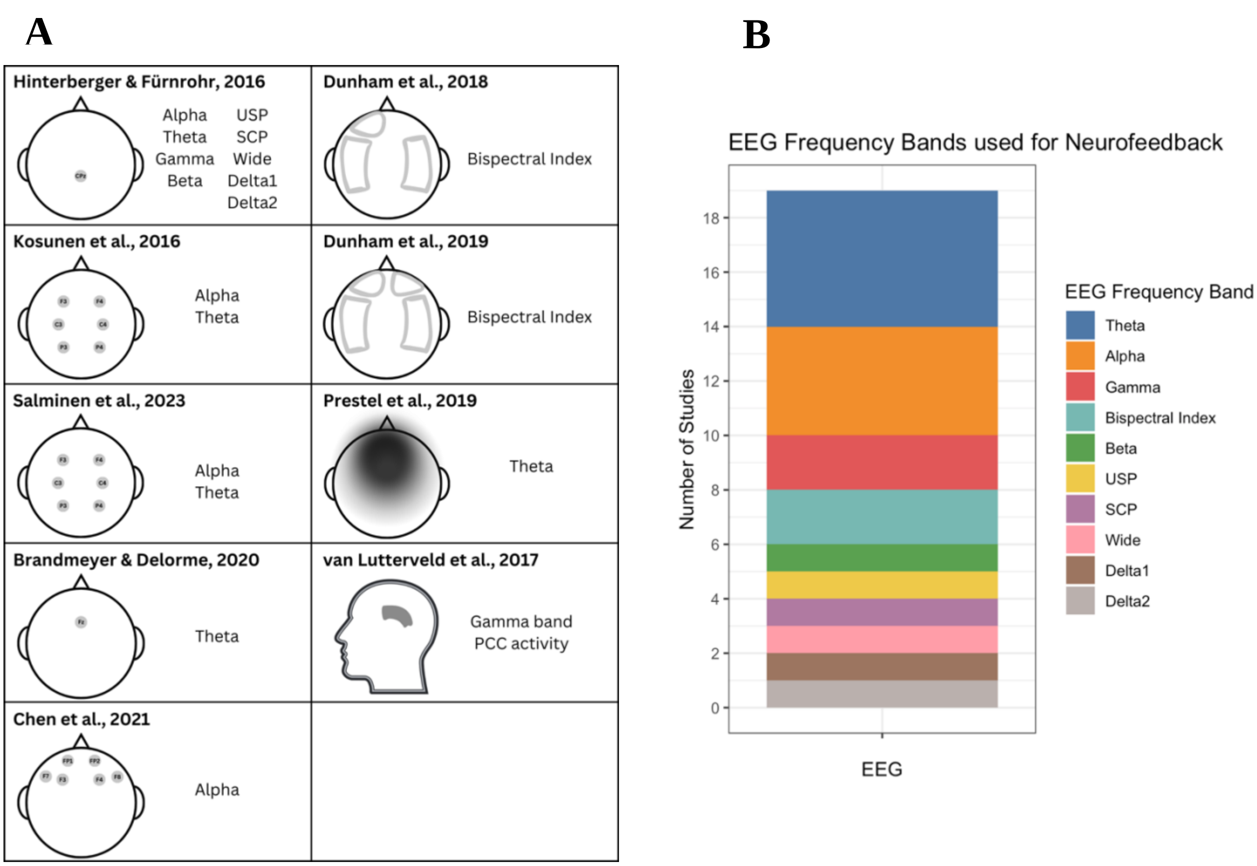

Figure 5. This figure displays the variety in methods of calculating EEG-neurofeedback. In **A),** the spatial layouts of the neurofeedback targets are displayed. Hinterberger & Fürnrohr, 2016 calculated alpha, theta, beta, gamma, USP, SCP, wide, delta1, and delta2 from CPz. Kosunen et al., 2016 calculated theta and alpha

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using an average from F3, F4, C3, C4, P3, and P4. Salminen et al., 2023 calculated theta power using an average F3 and F4, while alpha power was calculated as an average of F3, F4, C3, C4, P3, and P4. Brandmeyer & Delorme, 2020 used Fz to calculate frontal midline theta. Chen et al., 2021 used FP1, F3, F7 and FP2, F4, F8 to calculate alpha of the left and right frontal lobes, respectively. Dunham et al., 2018 placed the BIS sensor on the left forehead and the temporal fossa. Dunham et al., 2019 placed the BIS sensor on the left or right forehead and the temporal fossa. Prestel et al., 2019 used independent component analysis (ICA) with a 32-channel setup to calculate frontal midline theta. van Lutterveld et al., 2017 used source estimation with a 128-channel setup to determine Gamma band PCC activity. In **B),** the frequency bands used by each study are displayed. Theta was used the most by five studies, closely followed by alpha, which was used in four studies.

3.3.3 EEG Target Engagement

Not all papers reported on target engagement (Kosunen et al., 2016; Chen et al., 2021). For those that did, the way the target engagement was reported differed. For example, some studies looked at activation compared to baseline (Dunham et al., 2018; Dunham et al., 2019; van Lutterveld et al., 2017), compared to no NF conditions (Salminen et al., 2023), or across sessions using different linear models (Prestel et al., 2019; Brandmeyer & Delorme, 2020). The difference in reporting and measures used makes synthesizing results difficult, as well as the fact that support for target engagement was mixed. The strongest support was for an impact on theta (Brandmeyer & Delorme, 2020; Hinterberger & Fürnrohr, 2016; Salminen et al., 2023; Prestel et al., 2019), while alpha had both significant and null results (Hinterberger & Fürnrohr, 2016; Salminen et al., 2023). However, it is important to note Hinterberger and Fürnrohr's (2016) significant results were collapsed across multiple experimental conditions, one of which did not include NF. Others found significant changes in BIS values compared to baseline (Dunham et al., 2018; Dunham et al., 2019), but the significant decrease from day one to day four (Dunham et al., 2018) did not hold up in a larger sample (Dunham et al., 2019). For those who did find significant results across days, the significant effect was in one case driven by two participants (Prestel et al., 2019), and was stronger when certain "non-responders" were excluded (Brandmeyer & Delorme, 2020). It is also important to note the spatial limitations of neural targets using EEG, given that spatial resolution of EEG is limited even when using source localization. For example, the one study that used source localization of the PCC found that over 80% of runs examined had significant correlations between the right lateral occipital cortex and the PCC, though less than 36% of runs showed significant correlation between the left supplementary motor area and the PCC (van Lutterveld et al., 2017). Correlations between 40-57Hz PCC time series and delta, theta, alpha, and beta were calculated, but never surpassed

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more than 40% of runs showing significant correlations. The frequency specific to the PCC may be more accurate than the source localization, which may be capturing signals from occipital regions of the brain more broadly.

3.3.4 Neural Outcomes

Only four studies out of nine reported on other neural outcomes. All four studies examined EEG bands beyond the bands of the neural target, focusing on: (a) other frequency bands during NF and/or control (Salminen et al., 2023; van Lutterveld et al., 2017), (b) frequency bands at rest before and after NF (Chen et al., 2021), and (c) frequency bands in tasks before and after NF (Brandmeyer & Delorme, 2020). The following results discuss frequency bands that were not the target of NF. There is support that alpha, theta, and gamma power significantly increase from pre to post mindfulness NF (Chen et al. 2021), as well as support for gamma increases during NF compared to no-NF (Salminen et al., 2023). The delivery of NF (Virtual Reality (VR) > computer screen) and the type of meditation (body scan > focused attention) can also have an impact on the level of gamma (Salminen et al., 2023). There is mixed support for NF's effect on cognitive tasks, with no significant changes found for attentional tasks, but a significant increase in gamma power during a working memory task done before and after NF for those that received NF (Brandmeyer & Delorme, 2020).

3.3.5 Behavioral Outcomes

All but one study reported on some sort of behavioral outcome. Most focused on how individuals felt doing the mbNF (Hinterberger & Fürnrohr, 2016; Kosunen et al., 2016; Prestel et al., 2019; Salminen et al., 2023), while others looked at changes in well-being (Dunham et al., 2018; Dunham et al., 2019) or even performance on cognitive and attentional tasks (Brandmeyer & Delorme, 2020). When looking at immersive ways to deliver neurofeedback, such as the Sensorium or VR, findings suggest participants find these types of modalities more extraordinary, more engaging, have more positive experiences and less negative experiences compared to audio/visual guided meditations without VR or Sensorium enhancements (Hinterberger & Fürnrohr, 2016; Kosunen et al., 2016; Salminen et al., 2023). However, this difference is not always due to the addition of neurofeedback, as control conditions with these enhancements with yoked sham or no NF did not always show

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significant differences (Hinterberger & Fürnrohr, 2016; Kosunen et al., 2016). Accordingly, some participants report that too much focus on the NF can be distracting and lead to poorer performance; however, it is interesting to note that subjective experience of performance did not always align with objective performance, as measured by frontal midline theta (Prestel et al., 2019). Beyond experiences during mbNF, studies have found that wellbeing scores increase from baseline to completion of all sessions, and are significantly higher at completion than a control group who received no mbNF (Dunham et al., 2018; Dunham et al., 2019). There is also some evidence to suggest NF may help improve performance on memory tasks (NF group compared to sham control had faster reaction times post-NF for correct trials during the N-2 back working memory task) (Brandmeyer & Delorme, 2020). However no significant effects were found for attention tasks.

3.3.6 Clinical Applications

Only one study examined EEG neurofeedback in a clinical sample of 17 individuals with anxiety disorders (Chen et al., 2021). Compared to healthy controls, anxious subjects exhibited initial lower power in alpha, theta, and gamma. After NF, anxious subjects significantly increased power across all bands in all brain areas. Chen et al. (2021) suggest that the increase in gamma power indicated a reduction in anxiety symptoms, though they did not report on changes in subjective measures of anxiety. ANOVAs revealed interactions of condition vs brain region/hemisphere, but the direction of differences were not reported. Although the remaining studies reported on non-clinical samples, Dunham et al., 2018 and Dunham et al., 2019 examined well-being as a target for mindfulness neurofeedback among physicians/nurses, a group within which stress and emotional exhaustion are common (Dunham et al., 2018). Participants' subjective well-being was found to improve following the mbNF, suggesting that even in non-clinical samples, NF may be a promising avenue to increase well-being.

3.2.8 Quality (CRED-NF)

There were control conditions in the majority of the EEG studies, but they typically lacked blinding (sham). Reporting of feedback specifications and target engagement was common. Few studies reported artifact

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correction. Few studies conducted preregistration, justified their sample sizes or made their data/code open access. A full table may be found in **Table S3.**

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4. Discussion

Mindfulness meditation consists of purposefully bringing one's attention back to the present moment, and cultivating an open-minded and non-judgmental attitude (Creswell et al., 2017). Though mindfulness meditation is increasingly used for promoting mental health, there are many open questions about its neural bases. In this review, we investigate a promising tool for understanding the neural mechanisms of mindfulness, neurofeedback. Neurofeedback consists of relaying neural signals (the target) to the participant and examining if they can learn to modulate the signals (target engagement). Successful modulation provides evidence that a target brain region is involved in meditation. In addition, given the right targets, neurofeedback may help participants practice correctly and lead to better attention, deeper mindfulness, and positive behavioral outcomes. In this systematic review, we assess whether participants can modulate brain targets (insight into neural mechanisms) and whether participants benefit from the practice (behavioral outcomes). We included studies utilizing mindfulness meditation with concurrent EEG or fMRI feedback (i.e., mindfulness-based neurofeedback [mbNF]).

The search yielded 19 reports, with 15 independent samples. The earliest study was published in 2013, underscoring the nascency of the mbNF field (systematic inquiry of neurofeedback more generally extends back to the early 2000s for fMRIs and the 1960s for EEG). Studies used a wide range of targets across brain areas and frequency bands, and often reported different metrics of target engagement. Neurofeedback duration and number of runs varied (from single 15-min sessions to multiple weeks of training). Sample sizes were generally small, given the resource-intensive nature of neurofeedback. Few studies were RCTs, which are critical for establishing mbNF efficacy and testing mechanisms.

4.1 Brain Targets

One of the prominent neuroscientific theories of mindfulness posits that successful practice leads to downregulation of the DMN, perhaps most robustly the core hubs of the PCC and mPFC (Ganesan et al., 2022). The DMN has a well-established role in internally-generated, self-referential thought (Andrews-Hanna, 2012; Buckner et al., 2008). Mindfulness meditation involves recognizing self-referential thoughts, disengaging from them, and engaging in attention on an object like the breath. Thus, mindfulness may involve downregulating DMN activity. Accordingly, many fMRI studies of mbNF chose to target the DMN. Some studies

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calculated and displayed anatomically defined PCC activations compared to a control self-reference condition (Garrison, Santoyo, et al., 2013; Garrison, Scheinost, et al., 2013), whereas others used subject-specific, functionally derived maps of the DMN (Bauer et al., 2020; Kim et al., 2019; Okano et al., 2020; Pamplona et al., 2020; Zhang et al., 2023). Consistent downregulation of the DMN was found. Neurofeedback studies often included other networks like the central executive network (CEN) and salience network (SN). There is extensive reason to believe that DMN and other network interactions may be involved in mindfulness meditation, specifically in the switching between external and internal modes of attention (Hasenkamp et al., 2012; Mooneyham et al., 2016; Rahrig et al., 2022). Accordingly, studies relayed the participants' difference between CEN and DMN (Bauer et al., 2020; Zhang et al., 2023), sustained attention networks and DMN (Pamplona et al., 2020, 2023), and the slope of the DMN-SN connectivity excluding the CEN (Kim et al., 2019). It is unclear when participants are given these multivariate measures which variable is being trained –one study found that the DMN was modulated and not the sustained attention network (Pamplona et al., 2020).

Researchers also examined neuroplastic changes dependent on their DMN-based neurofeedback, finding changes in DMN region connectivity with other brain areas like the anterior cingulate cortex (Zhang et al., 2023). These changes suggest that neurofeedback may modulate intrinsic features of the DMN, offering a key inroad to mitigate ruminative and depressogenic perseveration tendencies (Zhang et al., 2021).

Mindfulness meditation has been associated with power increases in alpha, theta and gamma waves during meditation (Chiesa & Serretti, 2010; Lee et al., 2018; Lomas et al., 2015; Stapleton et al., 2020). Alpha and theta power may correspond to shifting attention to internal sensations and thoughts (Lomas et al., 2015), whereas gamma power may reflect wider awareness (Lomas et al., 2015; Lutz et al., 2004; Stapleton et al., 2020). There is considerable evidence that gamma EEG activity can be contaminated by muscle activity (Muthukumaraswamy, 2013; Whitham et al., 2007). However, it is not necessary to disregard gamma power altogether, as long as multiple precautions are taken to remove muscle artifacts and confirm they are not correlated with data (e.g., van Lutterveld et al., 2017). Accordingly, the 9 EEG studies of mbNF selected alpha, theta and gamma targets. The most consistent evidence was for theta increases, specifically frontal midline theta, which is often an indicator of cognitive control (Cavanagh & Frank, 2014). Results were mixed when probing alpha and gamma power.

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The study of EEG and fMRI have often been conducted in isolation, and each has advantages and disadvantages. EEG-neurofeedback is useful for precise temporal modulation as well as cost-effective application but lacks spatial specificity and may be susceptible to motor artifacts (Muthukumaraswamy, 2013; Whitham et al., 2007). fMRI-neurofeedback is useful for targeting specific brain regions with specificity, however, it is expensive and the underlying signals are slow to change. There have been meaningful efforts to develop EEG measures with spatial specificity. Frontal midline theta may be negatively correlated with DMN activation (Scheeringa et al., 2008; Prestel et al., 2018), while gamma may be positively correlated with DMN activation (Berkovich-Ohana et al., 2012). One neurofeedback study included, Van Lutterveld et al. (2017), specifically targeted activity in the PCC by using source localization. Yet, they did find that occipital cortex activity correlated heavily with localized PCC activity. It may be necessary to conduct EEG-fMRI fusion experiments to develop better measures. In a seminal paper, Keynan et al. (2019) created an EEG target measure of amygdala activity derived from machine learning based on simultaneous EEG-fMRI and showed that participants could modulate the target. The amygdala-EEG neurofeedback led to increases in emotional awareness and regulation and decreases in amygdala activation as measured by fMRI.

4.3 Brain Target Summary and Limitations

Extant research has, at times, corroborated neuroscientific theories of mindfulness; however, the majority of research did not include robust control conditions, which results in a lack of specificity. For example, decreases in DMN activation during neurofeedback does not indicate that participants are learning or that DMN deactivation is linked to mindful states. One possibility is that focusing on the display of the feedback itself may lead to DMN decreases. There is substantial evidence that engaging in external tasks leads to decreases in DMN activations (Raichle, 2015; Whitfield-Gabrieli & Ford, 2012), and likely changes in power as well (Fitzgibbon et al., 2004; Khader & Rösler, 2011). Another possibility is that mindfulness meditation leads to decreases in DMN activation, but that this process is implicit and beyond conscious control (thus, neurofeedback would not make a difference). To obviate these concerns, researchers need to employ blinded control conditions or/and transfer tasks. Gold-standard control conditions involve delivering participants feedback that should be unaffected by meditation (e.g. activations from another brain area, from another subject, or reversed activation) (Sorger et al., 2019; Thibault et al., 2016). A weaker control condition is

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mindfulness-as-usual, which is effective for examining general neurofeedback mechanisms, and neurofeedback benefits, but not target-specific mechanisms (Ros et al., 2020). Transfer tasks involve asking participants to meditate but removing the influence of neurofeedback- and one can examine differences in transfer tasks assessed before and after neurofeedback. Notably, the fMRI studies that employed sham controls or transfer tasks did not find significant differential evidence for target engagement (Kim et al., 2019; Kirlic et al., 2022). EEG studies did not employ transfer tasks, and only one study employed sham (Brandmeyer & Delorme 2020). Brandmeyer and Delorme (2020) found evidence of increased target engagement of frontal midline theta in mbNF, while the sham group showed no significant changes. Comparisons of EEG-neurofeedback to mindfulness-as-usual also resulted in improved target engagement (Hinterberger & Fürnrohr, 2016; Salminen et al., 2023). In summary, there is not currently evidence from the strongest designs supporting mbNF-specific mechanisms of DMN activation control, while there are some indications of control over frontal midline theta.

4.4 State Mindfulness

It is critical to identify whether neural feedback can engage the proposed target mechanism, but this is insufficient if it does not yield greater mindfulness and associated mental health benefits. Ideally, target engagement also leads to increases in state mindfulness, or deeper mindfulness during practice. There is only limited evidence in our included studies for increased state mindfulness (Hinterberger & Fürnrohr, 2016; Kim et al., 2019; Kirlic et al., 2022; Zhang et al., 2023 c.f., Kim et al., 2019, Prestel et al., 2019). One concern is that monitoring of the feedback may cause distraction during meditation. For this reason, some studies provided feedback intermittently after blocks of meditation (Pamplona et al., 2020, 2023), or allowed practitioners to close their eyes during meditation (van Lutterveld et al, 2017). The studies mostly used visual feedback, which may be distracting. Future research could examine the impact of design choices on state mindfulness during mbNF, including visual/auditory modality, continuous vs intermittent feedback, etc. It may also be useful to collect data throughout the course of mbNF to assess inattention.

4.5 Behavioral Outcomes

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Of note, mbNF has often been proposed to enhance mindfulness acquisition (Brandmeyer & Delorme, 2013). A prime motivation for many of the studies reviewed was the possibility of beneficial outcomes in cognition and affect. An fMRI study observed some improvements in reaction times on a cognitive task beyond a control condition (Pamplona et al., 2020), but it wasn't maintained at follow-up. An EEG study identified memory improvements but not RT improvements (Brandmeyer & Delorme, 2020). Another fMRI study tested perceived stress and negative affect, and didn't observe any improvements (Kirlic et al., 2022), whereas an EEG study identified improvements beyond a waitlist control (Dunham et al., 2018). Two fMRI studies observed decreases in auditory hallucinations (Bauer et al., 2020; Okano et al., 2020), a striking finding with implications for deleterious psychosis symptoms, however the findings were extracted from two protocols on the same sample. Of course, studies may have measured cognitive and affective outcomes but not reported them (many EEG studies did not report behavioral outcomes). Preregistration of measures and analyses was scarce. Overall, there is limited existing evidence for mindfulness-based neurofeedback benefits in terms of behavioral or clinical outcomes.

4.6 Clinical Relevance

Clinical populations may benefit from adaptations of mindfulness instruction. Individuals with histories of trauma may experience traumatic re-experiencing and distress due to meditation (Treleaven, 2018; Zhu et al., 2019). Ruminative individuals with a tendency to engage in repetitive negative thoughts may particularly have trouble learning meditation (Alleva et al., 2014; Crane & Williams, 2010; Hilton et al., 2017). It may be especially helpful for these clinical populations to have scaffolds while they meditate. Mindfulness-based NF may be such a scaffold, providing an engaging external locus of attention plus the same essential components of mindfulness - redirection of attention and non-judgement. Studies on mbNF included here involved clinical participants (Bauer et al., 2020, Okano et al., 2020, Zhang et al., 2023) but none involved healthy control groups. Future studies should assess directly whether the benefits of mbNF are more pronounced in clinical groups. Of course, mbNF should not be considered a replacement for more traditional mindfulness training (e.g.,with in-person teaching). There is a rich psychotherapeutic literature on developing mindfulness adaptations for clinical groups (e.g. mindfulness-based cognitive therapy; Segal et al., 2004) and acceptance

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and commitment therapy; (Hayes et al., 1999), and mbNF requires more validation before joining these frontline treatments.

4.7 Summary

This systematic review of mindfulness meditation concurrent with EEG or fMRI neurofeedback suggests that participants can learn to downregulate the DMN and increase power in the theta band. However, the lack of adequate control conditions limits mechanistic assertions. In addition, the downstream benefits of mindfulness-based neurofeedback require systematic examination. There is evidence for the feasibility of neurofeedback with clinical populations, and future work should directly compare the effects of mbNF between clinical and non-clinical populations.

4.7 Limitations

Our conclusions should be tempered in light of the heterogeneity of the studies. Targets, outcomes, and sample characteristics varied widely across the studies. These differences are well-known to affect neural outcomes (e.g. neuromaturation in adolescents, Fan et al., 2021; Norbom et al., 2021). Mindfulness training may be more effective for reducing psychological distress than for improving cognitive function ((Gill et al., 2020; Whitfield et al., 2022), and it is unclear whether this applies to mbNF. Reporting was also variable, which we assessed using the CRED-NF checklist (Ros et al., 2020). The vast majority of studies lacked blinded control conditions, reported brain target engagement as a single outcome instead of comprehensively, and did not engage in open science practices. In the future, full reporting of targets and outcomes could help identify why some studies may see effects and others do not, and it could lead to possible quantitative synthesis of effects.

Another limitation is the scope of the review. We chose not to review all meditation based neurofeedback, restricting our selection to studies that employed mindfulness practices. There are multiple families of meditations, including attentional, constructive and deconstructive practices (Dahl et al., 2015). The studies included here involved attentional practices. Future work should examine the effects of neurofeedback on other practices, perhaps targeting different brain processes.

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4.8 Future Directions

To study the mechanisms of mbNF and associated effects, the field would benefit from adopting best practices. Chief among these may be a confirmatory-exploratory distinction. Exploratory studies may examine multiple targets, multiple modalities of feedback, qualitative as well as quantitative feedback – all with the aim of establishing preliminary hypotheses about neural targets. These studies are necessary and important given the nascency of the field. Three studies reviewed provide a sound roadmap for this type of work (Garrison et al., 2013ab, Van Lutterveld et al., 2017). One innovation in particular is working with experienced meditators, who have detailed awareness of mental phenomena during meditation. Another innovation is developing individualized targets - one method could be monitoring neural data during meditation for a given participant, with self-report probes (experience samples), and then in a subsequent task delivering feedback that was trained on that initial period. This personalization may be more effective than using 'one-size-fits-all' brain signals (Brandmeyer & Reggente, 2023).

It is critically important, however, to build on this work using RCTs with carefully designed sham control conditions. Such confirmatory work, through tests of clear and a priori hypotheses, can help the field evaluate whether participants learn to modulate a neural signal, and whether it leads to higher state mindfulness and positive mental health or cognitive outcomes. Sham or alternative ROI controls are preferred, given their ability to control for effects of placebo as well as feedback monitoring, but mindfulness-as-usual controls are useful and easier to implement. Researchers may even choose to examine different dosages of mbNF (Bloom et al., 2023). Clinical trial registration and/or preregistration is useful, and when deviations emerge as they always do during empirical research, they should be reported. As mentioned previously, the CRED-NF checklist should be used for standardized reporting.

A final aim is real-world translation. In contrast to fMRI, which is costly and largely only accessible via academic medical centers, there is burgeoning interest in consumer-grade EEG tools like MUSE (Hashemi et al., 2016; Sawangjai et al., 2019), which are relatively cheap (~$250) and easy to use. We believe that this interest should be tempered given the limited knowledge base in lab settings. EEG tools like MUSE may rely on the potent influence of *neurosuggestion* (Schönenberg et al., 2017), which is a cultural emphasis and trust

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in Western society for neuroscientific technology. Speculatively, *neurosuggestion* effects may not be sustainable in supporting a habit of meditation, and may obscure the self-insight that comes with meditation (Vago & David, 2012).

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References

Alleva, J., Roelofs, J., Voncken, M., Meevissen, Y., & Alberts, H. (2014). On the Relation Between Mindfulness and Depressive Symptoms: Rumination as a Possible Mediator. *Mindfulness*, *5*(1), 72–79. https://doi.org/10.1007/s12671-012-0153-y

Andrews-Hanna, J. R. (2012). The Brain's Default Network and Its Adaptive Role in Internal Mentation. *The Neuroscientist*, *18*(3), 251–270. https://doi.org/10.1177/1073858411403316

Bauer, C. C. C., Okano, K., Ghosh, S. S., Lee, Y. J., Melero, H., Angeles, C. L., Nestor, P. G., Del Re, E. C., Northoff, G., Niznikiewicz, M. A., & Whitfield-Gabrieli, S. (2020). Real-time fMRI neurofeedback reduces auditory hallucinations and modulates resting state connectivity of involved brain regions: Part 2: Default mode network -preliminary evidence. *Psychiatry research*, *284*, 112770. https://doi.org/10.1016/j.psychres.2020.112770

Berkovich-Ohana, A., Glicksohn, J., & Goldstein, A. (2012). Mindfulness-induced changes in gamma band activity – Implications for the default mode network, self-reference and attention. *Clinical Neurophysiology*, *123*(4), 700–710. https://doi.org/10.1016/j.clinph.2011.07.048

Black, D. S. (2014). Mindfulness-based interventions: An antidote to suffering in the context of substance use, misuse, and addiction. *Substance Use and Misuse*, *49*(5), 487–491. https://doi.org/10.3109/10826084.2014.860749

Bloom, P. A., Pagliaccio, D., Zhang, J., Bauer, C. C. C., Kyler, M., Greene, K. D., Treves, I., Morfini, F., Durham, K., Cherner, R., Bajwa, Z., Wool, E., Olafsson, V., Lee, R. F., Bidmead, F., Cardona, J., Kirshenbaum, J. S., Ghosh, S., Hinds, O., … Auerbach, R. P. (2023). Mindfulness-based real-time fMRI neurofeedback: A randomized controlled trial to optimize dosing for depressed adolescents. *BMC Psychiatry*, *23*(1), 757. https://doi.org/10.1186/s12888-023-05223-8

Brandmeyer, T., & Delorme, A. (2013). Meditation and neurofeedback. *Frontiers in Psychology*, *4*. https://www.frontiersin.org/articles/10.3389/fpsyg.2013.00688

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Brandmeyer, T., & Delorme, A. (2020). Closed-Loop Frontal Midlineθ Neurofeedback: A Novel Approach for Training Focused-Attention Meditation. *Frontiers in human neuroscience*, *14*, 246. https://doi.org/10.3389/fnhum.2020.00246

Brandmeyer, T., & Reggente, N. (2023). *Navigating the "Zen Zeitgeist": The Potential of Personalized Neurofeedback for Meditation* [Preprint]. PsyArXiv. https://doi.org/10.31234/osf.io/x23me

Buckner, R. L., Andrews-Hanna, J. R., & Schacter, D. L. (2008). The brain's default network: Anatomy, function, and relevance to disease. *Annals of the New York Academy of Sciences*, *1124*, 1–38. https://doi.org/10.1196/annals.1440.011

Chen, C., Xiao, X., Belkacem, A. N., Lu, L., Wang, X., Yi, W., Li, P., Wang, C., Sha, S., Zhao, X., & Ming, D. (2021). Efficacy Evaluation of Neurofeedback-Based Anxiety Relief. *Frontiers in neuroscience*, *15*, 758068. https://doi.org/10.3389/fnins.2021.758068

Chiesa, A., & Serretti, A. (2010). A systematic review of neurobiological and clinical features of mindfulness meditations. *Psychological Medicine*, *40*(8), 1239–1252.

Crane, C., & Williams, J. M. G. (2010). Factors Associated with Attrition from Mindfulness-Based Cognitive Therapy in Patients with a History of Suicidal Depression. *Mindfulness*, *1*(1), 10–20. https://doi.org/10.1007/s12671-010-0003-8

Creswell, J. D. (2017). Mindfulness Interventions. *Annual Review of Psychology*, *68*(1), 491–516. https://doi.org/10.1146/annurev-psych-042716-051139

DeBettencourt, M. T., Cohen, J. D., Lee, R. F., Norman, K. A., & Turk-Browne, N. B. (2015). Closed-loop training of attention with real-time brain imaging. *Nature Neuroscience*, *18*(3), 470–478. https://doi.org/10.1038/nn.3940

DeCharms, R. C., Christoff, K., Glover, G. H., Pauly, J. M., Whitfield, S., & Gabrieli, J. D. (2004). Learned regulation of spatially localized brain activation using real-time fMRI. *Neuroimage*, *21*(1), 436–443.

deCharms, R. C., Maeda, F., Glover, G. H., Ludlow, D., Pauly, J. M., Soneji, D., Gabrieli, J. D. E., & Mackey, S. C. (2005). Control over brain activation and pain learned by using real-time functional MRI. *Proceedings of the National Academy of Sciences*, *102*(51), 18626–18631. https://doi.org/10.1073/pnas.0505210102

Dekker, M. K. J., Sitskoorn, M. M., Denissen, A. J. M., & van Boxtel, G. J. M. (2014). The time-course of alpha neurofeedback training effects in healthy participants. *Biological Psychology*, *95*, 70–73. https://doi.org/10.1016/j.biopsycho.2013.11.014

Dunham, C. M., Burger, A. L., Hileman, B. M., & Chance, E. A. (2018). Learning receptive awareness via neurofeedback in stressed healthcare providers: a prospective pilot investigation. *BMC research notes*, *11*(1), 645. https://doi.org/10.1186/s13104-018-3756-0

Dunham, C. M., Burger, A. L., Hileman, B. M., Chance, E. A., Hutchinson, A. E., Kohli, C. M., DeNiro, L., Tall, J. M., & Lisko, P. (2019). Brainwave Self-Regulation During Bispectral IndexTM Neurofeedback in Trauma Center Nurses and Physicians After Receiving Mindfulness Instructions. *Frontiers in psychology*, *10*, 2153. https://doi.org/10.3389/fpsyg.2019.02153

Fitzgibbon, S. P., Pope, K. J., Mackenzie, L., Clark, C. R., & Willoughby, J. O. (2004). Cognitive tasks augment gamma EEG power. *Clinical neurophysiology*, 115(8), 1802-1809. https://doi.org/10.1016/j.clinph.2004.03.009

Fox, K. C. R., Dixon, M. L., Nijeboer, S., Girn, M., Floman, J. L., Lifshitz, M., Ellamil, M., Sedlmeier, P., & Christoff, K. (2016). Functional neuroanatomy of meditation: A review and meta-analysis of 78 functional neuroimaging investigations. *Neuroscience and Biobehavioral Reviews*, *65*, 208–228. https://doi.org/10.1016/j.neubiorev.2016.03.021

Ganesan, S., Beyer, E., Moffat, B., Van Dam, N. T., Lorenzetti, V., & Zalesky, A. (2022). Focused attention meditation in healthy adults: A systematic review and meta-analysis of cross-sectional functional MRI studies. *Neuroscience and Biobehavioral Reviews*, *141*. https://doi.org/10.1016/j.neubiorev.2022.104846

Garrison, K. A., Santoyo, J. F., Davis, J. H., Thornhill, T. A., 4th, Kerr, C. E., & Brewer, J. A. (2013). Effortless awareness: using real time neurofeedback to investigate correlates of posterior cingulate cortex activity in meditators' self-report. *Frontiers in human neuroscience*, *7*, 440. https://doi.org/10.3389/fnhum.2013.00440

Garrison, K. A., Scheinost, D., Worhunsky, P. D., Elwafi, H. M., Thornhill, T. A., 4th, Thompson, E., Saron, C., Desbordes, G., Kober, H., Hampson, M., Gray, J. R., Constable, R. T., Papademetris, X., & Brewer, J.

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A. (2013). Real-time fMRI links subjective experience with brain activity during focused attention. *NeuroImage*, *81*, 110–118. https://doi.org/10.1016/j.neuroimage.2013.05.030

Garland, E. L., Froeliger, B., & Howard, M. O. (2015). Neurophysiological evidence for remediation of reward processing deficits in chronic pain and opioid misuse following treatment with Mindfulness-Oriented Recovery Enhancement: Exploratory ERP findings from a pilot RCT. *Journal of Behavioral Medicine*, *38*(2), 327–336. https://doi.org/10.1007/s10865-014-9607-0

Goldberg, S. B., Tucker, R. P., Greene, P. A., Davidson, R. J., Wampold, B. E., Kearney, D. J., & Simpson, T. L. (2018). Mindfulness-based interventions for psychiatric disorders: A systematic review and meta-analysis. *Clinical Psychology Review*. https://doi.org/10.1016/j.cpr.2017.10.011

Goldin, P., Ziv, M., Jazaieri, H., Hahn, K., & Gross, J. J. (2013). MBSR vs aerobic exercise in social anxiety: fMRI of emotion regulation of negative self-beliefs. *Social Cognitive and Affective Neuroscience*, *8*(1), 65–72. https://doi.org/10.1093/scan/nss054

Goyal, M., Singh, S., Sibinga, E. M. S., Gould, N. F., Rowland-Seymour, A., Sharma, R., Berger, Z., Sleicher, D., Maron, D. D., Shihab, H. M., Ranasinghe, P. D., Linn, S., Saha, S., Bass, E. B., & Haythornthwaite, J. A. (2014). Meditation Programs for Psychological Stress and Well-being: A Systematic Review and Meta-analysis. *JAMA Internal Medicine*, *174*(3), 357–368. https://doi.org/10.1001/jamainternmed.2013.13018

Hasenkamp, W., Wilson-Mendenhall, C. D., Duncan, E., & Barsalou, L. W. (2012). Mind wandering and attention during focused meditation: A fine-grained temporal analysis of fluctuating cognitive states. *NeuroImage*, *59*(1), 750–760. https://doi.org/10.1016/j.neuroimage.2011.07.008

Haugg, A., Renz, F. M., Nicholson, A. A., Lor, C., Götzendorfer, S. J., Sladky, R., Skouras, S., McDonald, A., Craddock, C., Hellrung, L., Kirschner, M., Herdener, M., Koush, Y., Papoutsi, M., Keynan, J., Hendler, T., Cohen Kadosh, K., Zich, C., Kohl, S. H., … Steyrl, D. (2021). Predictors of real-time fMRI neurofeedback performance and improvement – A machine learning mega-analysis. *NeuroImage*, *237*(May), 118207. https://doi.org/10.1016/j.neuroimage.2021.118207

Hayes, S. C., Strosahl, K. D., & Wilson, K. G. (1999). *Acceptance and commitment therapy* (Vol. 6). Guilford press New York. http://www.ava-edu.net/biblioteca/wp-content/uploads/2020/08/Encyclopedia-of-Cognitive-Behavior-Therapy-Springer-US-200.pdf#page=8

Hellrung, L., Dietrich, A., Hollmann, M., Pleger, B., Kalberlah, C., Roggenhofer, E., Villringer, A., & Horstmann, A. (2018). Intermittent compared to continuous real-time fMRI neurofeedback boosts control over amygdala activation. *Neuroimage*, *166*, 198–208.

Herrmann, C. S., Strüber, D., Helfrich, R. F., & Engel, A. K. (2016). EEG oscillations: From correlation to causality. *International Journal of Psychophysiology*, *103*, 12–21. https://doi.org/10.1016/j.ijpsycho.2015.02.003

Hilton, L., Hempel, S., Ewing, B. A., Apaydin, E., Xenakis, L., Newberry, S., Colaiaco, B., Maher, A. R., Shanman, R. M., Sorbero, M. E., & Maglione, M. A. (2017). Mindfulness Meditation for Chronic Pain: Systematic Review and Meta-analysis. *Annals of Behavioral Medicine*, *51*(2), 199–213. https://doi.org/10.1007/s12160-016-9844-2

Hinterberger, T., & Fürnrohr, E. (2016). The Sensorium: Psychophysiological Evaluation of Responses to a Multimodal Neurofeedback Environment. *Applied psychophysiology and biofeedback*, *41*(3), 315–329. https://doi.org/10.1007/s10484-016-9332-2

Hoge, E. A., Bui, E., Mete, M., Dutton, M. A., Baker, A. W., & Simon, N. M. (2022). Mindfulness-Based Stress Reduction vs Escitalopram for the Treatment of Adults With Anxiety Disorders. *JAMA Psychiatry*, *20007*(1), 13–21. https://doi.org/10.1001/jamapsychiatry.2022.3679

Hölzel, B. K., Hoge, E. A., Greve, D. N., Gard, T., Creswell, J. D., Brown, K. W., Barrett, L. F., Schwartz, C., Vaitl, D., & Lazar, S. W. (2013). Neural mechanisms of symptom improvements in generalized anxiety disorder following mindfulness training. *NeuroImage: Clinical*, *2*(1), 448–458. https://doi.org/10.1016/j.nicl.2013.03.011

Kabat-Zinn, J. (1982). An outpatient program in behavioral medicine for chronic pain patients based on the practice of mindfulness meditation: Theoretical considerations and preliminary results. *General Hospital Psychiatry*, *4*(1), 33–47. https://doi.org/10.1016/0163-8343(82)90026-3

Kabat-Zinn, J. (2003). *Mindfulness-based interventions in context: Past, present, and future.* https://psycnet.apa.org/record/2003-03824-002

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Kadosh, K. C., & Staunton, G. (2019). A systematic review of the psychological factors that influence neurofeedback learning outcomes. *Neuroimage*, *185*, 545–555.

Kamiya, J. (2011). The First Communications About Operant Conditioning of the EEG. *Journal of Neurotherapy*, *15*(1), 65–73. https://doi.org/10.1080/10874208.2011.545764

Keynan, J. N., Cohen, A., Jackont, G., Green, N., Goldway, N., Davidov, A., Meir-Hasson, Y., Raz, G., Intrator, N., Fruchter, E., Ginat, K., Laska, E., Cavazza, M., & Hendler, T. (2019). Electrical fingerprint of the amygdala guides neurofeedback training for stress resilience. *Nature Human Behaviour*, *3*(1), Article 1. https://doi.org/10.1038/s41562-018-0484-3

Khader, P. H., & Rösler, F. (2011). EEG power changes reflect distinct mechanisms during long-term memory retrieval. *Psychophysiology*, 48(3), 362-369. **https://doi.org/10.1111/j.1469-8986.2010.01063.x**

Kim, H. C., Tegethoff, M., Meinlschmidt, G., Stalujanis, E., Belardi, A., Jo, S., Lee, J., Kim, D. Y., Yoo, S. S., & Lee, J. H. (2019). Mediation analysis of triple networks revealed functional feature of mindfulness from real-time fMRI neurofeedback. *NeuroImage*, *195*, 409–432. https://doi.org/10.1016/j.neuroimage.2019.03.066

Kirlic, N., Cohen, Z. P., Tsuchiyagaito, A., Misaki, M., McDermott, T. J., Aupperle, R. L., Stewart, J. L., Singh, M. K., Paulus, M. P., & Bodurka, J. (2022). Self-regulation of the posterior cingulate cortex with real-time fMRI neurofeedback augmented mindfulness training in healthy adolescents: A nonrandomized feasibility study. *Cognitive, affective & behavioral neuroscience*, *22*(4), 849–867. https://doi.org/10.3758/s13415-022-00991-4

Kosunen, I., Salminen, M., Jarvela, S., Ruonala, A., Ravaja, N., Jacucci, G. (2016). RelaWorld: Neuroadaptive and Immersive Virtual Reality Meditation System. *Proceedings of the 21st International Conference on Intelligent User Interfaces, 208-217. https://doi.org/10.1145/2856767.2856796*

Kuyken, W., Warren, F. C., Taylor, R. S., Whalley, B., Crane, C., Bondolfi, G., Hayes, R., Huijbers, M., Ma, H., Schweizer, S., Segal, Z., Speckens, A., Teasdale, J. D., Van Heeringen, K., Williams, M., Byford, S., Byng, R., & Dalgleish, T. (2016). Efficacy of mindfulness-based cognitive therapy in prevention of depressive relapse an individual patient data meta-analysis from randomized trials. *JAMA Psychiatry*. https://doi.org/10.1001/jamapsychiatry.2016.0076

Lee, D. J., Kulubya, E., Goldin, P., Goodarzi, A., & Girgis, F. (2018). Review of the Neural Oscillations Underlying Meditation. *Frontiers in Neuroscience*, *12*. https://www.frontiersin.org/articles/10.3389/fnins.2018.00178

Linehan, M. M. (1993). *Skills training manual for treating borderline personality disorder.* Guilford press. https://psycnet.apa.org/record/1995-98090-000

Lomas, T., Ivtzan, I., & Fu, C. H. Y. (2015). A systematic review of the neurophysiology of mindfulness on EEG oscillations. *Neuroscience and Biobehavioral Reviews*, *57*, 401–410. https://doi.org/10.1016/j.neubiorev.2015.09.018

Lutz, A., Greischar, L. L., Rawlings, N. B., Ricard, M., & Davidson, R. J. (2004). Long-term meditators self-induce high-amplitude gamma synchrony during mental practice. *Proceedings of the National Academy of Sciences of the United States of America*, *101*(46), 16369–16373. https://doi.org/10.1073/pnas.0407401101

Lutz, A., Slagter, H. A., Dunne, J. D., & Davidson, R. J. (2008). Attention regulation and monitoring in meditation. *Trends in Cognitive Sciences*, *12*(4), 163–169. https://doi.org/10.1016/j.tics.2008.01.005

McCauley, E., Berk, M. S., Asarnow, J. R., Adrian, M., Cohen, J., Korslund, K., Avina, C., Hughes, J., Harned, M., Gallop, R., & Linehan, M. M. (2018). Efficacy of Dialectical Behavior Therapy for Adolescents at High Risk for Suicide: A Randomized Clinical Trial. *JAMA Psychiatry*, *75*(8), 777–785. https://doi.org/10.1001/jamapsychiatry.2018.1109

Mehler, D. M. A., Sokunbi, M. O., Habes, I., Barawi, K., Subramanian, L., Range, M., Evans, J., Hood, K., Lührs, M., Keedwell, P., Goebel, R., & Linden, D. E. J. (2018). Targeting the affective brain—A randomized controlled trial of real-time fMRI neurofeedback in patients with depression. *Neuropsychopharmacology*, *43*(13), 2578–2585. https://doi.org/10.1038/s41386-018-0126-5

Menon, V. (2011). Large-scale brain networks and psychopathology: A unifying triple network model. *Trends in Cognitive Sciences*, *15*(10), 483–506. https://doi.org/10.1016/j.tics.2011.08.003

Mooneyham, B. W., Mrazek, M. D., Mrazek, A. J., & Schooler, J. W. (2016). Signal or noise: Brain network interactions underlying the experience and training of mindfulness. *Annals of the New York Academy of Sciences*, *1369*(1), 240–256. https://doi.org/10.1111/nyas.13044

bioRxiv preprint doi: https://doi.org/10.1101/2024.09.12.612669; this version posted September 15, 2024. The copyright holder for this preprint (which was not certified by peer review) is the author/funder, who has granted bioRxiv a license to display the preprint in perpetuity. It is made available under aCC-BY-NC-ND 4.0 International license.

Muthukumaraswamy, S. D. (2013). High-frequency brain activity and muscle artifacts in MEG/EEG: a review and recommendations. *Frontiers in human neuroscience*, *7*, 138.

Nicholson, A. A., Rabellino, D., Densmore, M., Frewen, P. A., Paret, C., Kluetsch, R., & Lanius, R. A. (2017). The neurobiology of emotion regulation in posttraumatic stress disorder: Amygdala downregulation via real-time fMRI neurofeedback. *Human Brain Mapping*, *38*(1), 541–560.

Okano, K., Bauer, C. C. C., Ghosh, S. S., Lee, Y. J., Melero, H., de Los Angeles, C., Nestor, P. G., Del Re, E. C., Northoff, G., Whitfield-Gabrieli, S., & Niznikiewicz, M. A. (2020). Real-time fMRI feedback impacts brain activation, results in auditory hallucinations reduction: Part 1: Superior temporal gyrus - Preliminary evidence. *Psychiatry research*, *286*, 112862. Advance online publication. https://doi.org/10.1016/j.psychres.2020.112862

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, n71. https://doi.org/10.1136/bmj.n71

Pamplona, G. S. P., Heldner, J., Langner, R., Koush, Y., Michels, L., Ionta, S., Salmon, C. E. G., & Scharnowski, F. (2023). Preliminary findings on long-term effects of fMRI neurofeedback training on functional networks involved in sustained attention. *Brain and Behavior*. https://doi.org/10.1002/brb3.3217

Pamplona, G. S. P., Heldner, J., Langner, R., Koush, Y., Michels, L., Ionta, S., Scharnowski, F., & Salmon, C. E. G. (2020). Network-based fMRI-neurofeedback training of sustained attention. *NeuroImage*, *221*(July), 117194. https://doi.org/10.1016/j.neuroimage.2020.117194

Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in Cognitive Sciences*, *10*(2), 59–63.

Prestel, M., Steinfath, T. P., Tremmel, M., Stark, R., & Ott, U. (2018). fMRI BOLD correlates of EEG independent components: Spatial correspondence with the default mode network. *Frontiers in Human Neuroscience*, *12*, 478.

Prestel, M., Riedl, R., Stark, R., & Ott, U. (2019). Enhancing mindfulness by combining neurofeedback with meditation. *Journal of Consciousness Studies, 26*(7-8), 268–293.

Rahrig, H., Vago, D. R., Passarelli, M., Auten, A., Lynn, N. A., & Brown, K. W. (2022). Disrupting The Resting State: Meta-Analytic Evidence That Mindfulness Training Alters Default Mode Network Connectivity. *Scientific Reports*, *0123456789*, 1–21. https://doi.org/10.1038/s41598-022-15195-6

Raichle, M. E. (2015). The Brain's Default Mode Network. *Annual Review of Neuroscience*, *38*(1), 433–447. https://doi.org/10.1146/annurev-neuro-071013-014030

Ros, T., Enriquez-Geppert, S., Zotev, V., Young, K. D., Wood, G., Whitfield-Gabrieli, S., Wan, F., Vuilleumier, P., Vialatte, F., Van De Ville, D., Todder, D., Surmeli, T., Sulzer, J. S., Strehl, U., Sterman, M. B., Steiner, N. J., Sorger, B., Soekadar, S. R., Sitaram, R., … Thibault, R. T. (2020). Consensus on the reporting and experimental design of clinical and cognitive-behavioural neurofeedback studies (CRED-nf checklist). *Brain*, *143*(6), 1674–1685. https://doi.org/10.1093/brain/awaa009

Ros, T., Théberge, J., Frewen, P. A., Kluetsch, R., Densmore, M., Calhoun, V. D., & Lanius, R. A. (2013). Mind over chatter: Plastic up-regulation of the fMRI salience network directly after EEG neurofeedback. *Neuroimage*, *65*, 324–335.

Salminen, M., Järvelä, S., Kosunen, I., Ruonala, A., Hamari, J., Ravaja, N., & Jacucci, G. (2023). Meditating in a neurofeedback virtual reality: effects on sense of presence, meditation depth and brain oscillations. *Behaviour & Information Technology*, 1–15. https://doi.org/10.1080/0144929X.2023.2258231

Sawangjai, P., Hompoonsup, S., Leelaarporn, P., Kongwudhikunakorn, S., & Wilaiprasitporn, T. (2019). Consumer grade EEG measuring sensors as research tools: A review. *IEEE Sensors Journal*, *20*(8), 3996–4024.

Scheeringa, R., Bastiaansen, M. C., Petersson, K. M., Oostenveld, R., Norris, D. G., & Hagoort, P. (2008). Frontal theta EEG activity correlates negatively with the default mode network in resting state. International Journal of Psychophysiology, 67(3), 242–251.

Schönenberg, M., Wiedemann, E., Schneidt, A., Scheeff, J., Logemann, A., Keune, P. M., & Hautzinger, M. (2017). Neurofeedback, sham neurofeedback, and cognitive-behavioural group therapy in adults with

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attention-deficit hyperactivity disorder: A triple-blind, randomised, controlled trial. *The Lancet Psychiatry*, *4*(9), 673–684.

Segal, Z. V., Teasdale, J. D., & Williams, J. M. G. (2004). *Mindfulness-Based Cognitive Therapy: Theoretical Rationale and Empirical Status.* https://psycnet.apa.org/record/2005-02461-003

Sorger, B., Scharnowski, F., Linden, D. E., Hampson, M., & Young, K. D. (2019). Control freaks: Towards optimal selection of control conditions for fMRI neurofeedback studies. *Neuroimage*, *186*, 256–265.

Stapleton, P., Dispenza, J., McGill, S., Sabot, D., Peach, M., & Raynor, D. (2020). Large effects of brief meditation intervention on EEG spectra in meditation novices. *IBRO Reports*, *9*, 290–301. https://doi.org/10.1016/j.ibror.2020.10.006

Strauss, C., Bibby-Jones, A.-M., Jones, F., Byford, S., Heslin, M., Parry, G., Barkham, M., Lea, L., Crane, R., de Visser, R., Arbon, A., Rosten, C., & Cavanagh, K. (2023). Clinical Effectiveness and Cost-Effectiveness of Supported Mindfulness-Based Cognitive Therapy Self-help Compared With Supported Cognitive Behavioral Therapy Self-help for Adults Experiencing Depression. *JAMA Psychiatry*. https://doi.org/10.1001/jamapsychiatry.2023.0222

Thibault, R., Lifshitz, M., & Raz, A. (2016). The Self-Regulating Brain and Neurofeedback: Experimental Science and Clinical Promise. *Cortex*.

Treleaven, D. A. (2018). *Trauma-sensitive mindfulness: Practices for safe and transformative healing*. WW Norton & Company.

Treves I.N., Bauer, C.C.C, Sacchet. M.D., Greene, K.D, Berkovich-Ohana, A., Whitfield-Gabrieli. S. (in press): Toward a Brain Network Science of Mindfulness. *The Handbook of Mindfulness and Self-Regulation: Cognitive Neuroscience, Social Personality, Clinical, and Applied Perspectives.* New York, NY, US: Springer.

Treves, I. N., Tello, L. Y., Davidson, R. J., & Goldberg, S. B. (2019). The relationship between mindfulness and objective measures of body awareness: A meta-analysis. *Scientific Reports*, *9*(1), 1–12. https://doi.org/10.1038/s41598-019-53978-6

Vago, D. R., & David, S. A. (2012). Self-awareness, self-regulation, and self-transcendence (S-ART): A framework for understanding the neurobiological mechanisms of mindfulness. *Frontiers in Human Neuroscience*, *6*(OCTOBER 2012), 1–30. https://doi.org/10.3389/fnhum.2012.00296

van Lutterveld, R., Houlihan, S. D., Pal, P., Sacchet, M. D., McFarlane-Blake, C., Patel, P. R., Sullivan, J. S., Ossadtchi, A., Druker, S., Bauer, C., & Brewer, J. A. (2017). Source-space EEG neurofeedback links subjective experience with brain activity during effortless awareness meditation. *NeuroImage*, *151*, 117–127. https://doi.org/10.1016/j.neuroimage.2016.02.047

Vallejo, Z., & Amaro, H. (2009). Adaptation of mindfulness-based stress reduction program for addiction relapse prevention. *Humanistic Psychologist*, *37*(2), 192–206. https://doi.org/10.1080/08873260902892287

Wang, J.-R., & Hsieh, S. (2013). Neurofeedback training improves attention and working memory performance. *Clinical Neurophysiology*, *124*(12), 2406–2420. https://doi.org/10.1016/j.clinph.2013.05.020

Whitfield-Gabrieli, S., & Ford, J. M. (2012). Default Mode Network Activity and Connectivity in Psychopathology. *Annual Review of Clinical Psychology*, *8*(1), 49–76. https://doi.org/10.1146/annurev-clinpsy-032511-143049

Whitham, E. M., Pope, K. J., Fitzgibbon, S. P., Lewis, T., Clark, C. R., Loveless, S., Broberg, M.,Wallace,A., DeLosAngeles,D., Lillie,P., Hardy, A., Fronsko, R.,Pulbrook,A.,&Willoughby, J.O. (2007). Scalp electrical recording during paralysis: Quantitative evidence that EEG frequencies above 20 Hz are contaminated by EMG. Clinical neurophysiology: official journal of the International Federation of Clinical Neurophysiology, 118(8), 1877–1888.

Yoo, S.-S., & Jolesz, F. A. (2002). Functional MRI for neurofeedback: Feasibility study on a hand motor task. *Neuroreport*, *13*(11), 1377–1381.

Young, K. D., Misaki, M., Harmer, C. J., Victor, T., Zotev, V., Phillips, R., Siegle, G. J., Drevets, W. C., & Bodurka, J. (2017). Real-time functional magnetic resonance imaging amygdala neurofeedback changes positive information processing in major depressive disorder. *Biological Psychiatry*, *82*(8), 578–586.

Yu, X., Cohen, Z. P., Tsuchiyagaito, A., Cochran, G., Aupperle, R. L., Stewart, J. L., Singh, M. K., Misaki, M., Bodurka, J., Paulus, M. P., & Kirlic, N. (2022). Neurofeedback-Augmented Mindfulness Training Elicits

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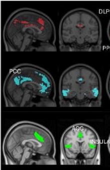
Distinct Responses in the Subregions of the Insular Cortex in Healthy Adolescents. *Brain sciences*, *12*(3), 363. https://doi.org/10.3390/brainsci12030363

Zhang, J., Kucyi, A., Raya, J., Nielsen, A. N., Nomi, J. S., Damoiseaux, J. S., Greene, D. J., Horovitz, S. G., Uddin, L. Q., & Whitfield-Gabrieli, S. (2021). What have we really learned from functional connectivity in clinical populations? *NeuroImage*, *242*(July), 118466. https://doi.org/10.1016/j.neuroimage.2021.118466

Zhang, J., Raya, J., Morfini, F., Urban, Z., Pagliaccio, D., Yendiki, A., Auerbach, R. P., Bauer, C. C. C., & Whitfield-Gabrieli, S. (2023). Reducing default mode network connectivity with mindfulness-based fMRI neurofeedback: a pilot study among adolescents with affective disorder history. *Molecular psychiatry*, *28*(6), 2540–2548. https://doi.org/10.1038/s41380-023-02032-z

Zhu, J., Wekerle, C., Lanius, R., & Frewen, P. (2019). Trauma-and stressor-related history and symptoms predict distress experienced during a brief mindfulness meditation sitting: Moving toward trauma-informed care in mindfulness-based therapy. *Mindfulness*, *10*, 1985–1996.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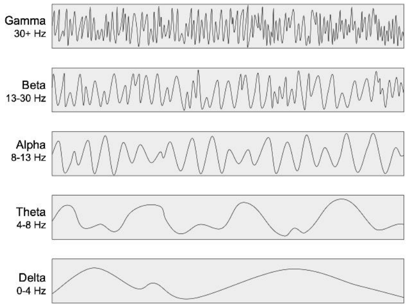
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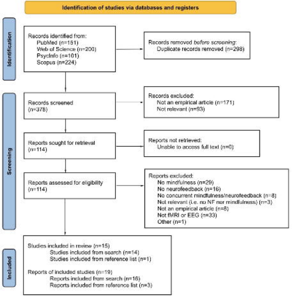
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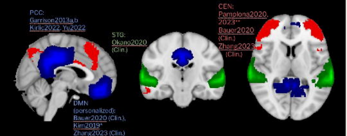
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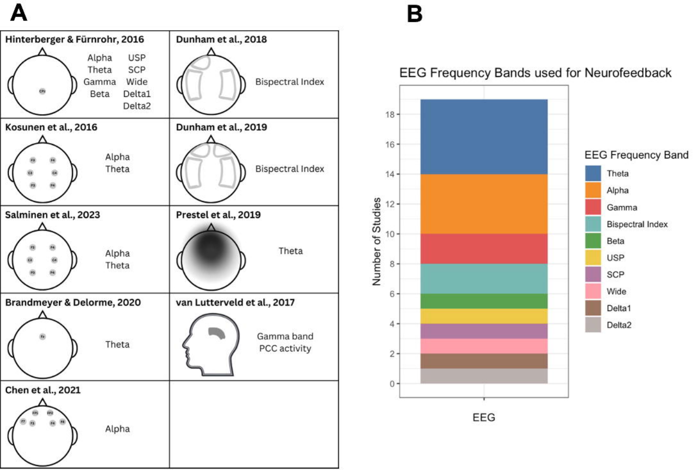

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