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REVIEW

Meta-analysis Provides Weak Evidence for an Effect of Mindfulness on Neural Activity Related to Error-Processing in Healthy Individuals Only

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Abstract

Objectives Research into the effects of mindfulness meditation indicates improvements in mental health and cognitive function. Mechanisms underpinning these improvements include increased attentional function and decreased emotional reactivity. These functions are engaged when an individual reacts to an error. As such, researchers have examined differences in neural activity between mindful and non-mindful groups during tasks that elicit error responses using electroencephalography (EEG). Event-related potentials associated with error-processing are primarily the error-related negativity (ERN) and error positivity (Pe), which occur ~ 0–150 ms and ~ 200–400 ms following an error. This meta-analysis aimed to determine the effects of mindfulness on ERN and Pe amplitudes.

Methods Our literature search revealed 16 studies that examined the ERN (total $N = 887$, 469 mindfulness, 418 controls) and 12 studies that examined the Pe (total $N = 747$, 395 mindfulness, 352 controls).

Results Results showed a weak association between mindfulness and more negative ERN amplitudes at electrode FCz, with inconsequential Bayesian evidence, after the analysis was restricted to studies including healthy participants only ($Q(1) = 4.725$, $p = 0.030$, BF10 = 1.714). The results also provided a preliminary suggestion that mindfulness reduced the Pe amplitude at electrode Pz ($Q(2) = 8.023$, $p = 0.018$), when studying individuals that had weeks to years of mindfulness practice (but not less than weeks of mindfulness practice).

Conclusions The results do not provide good evidence that mindfulness meditation affects EEG measures of error processing. However, our findings are limited by heterogeneity and potential biases, and as such should be interpreted with caution.

Protocol and Registration Systematic Review Registration: PROSPERO CRD42021249775.

Keywords Mindfulness · Error · Error-processing · ERN · Pe · Meta-analysis

Mindfulness meditation is a practice that places focus on training awareness that is non-judgmental and focused on the present moment (Kabat-Zinn, 2005). It is a practice that has surged in popularity in recent decades, as it offers many social and psychological benefits (increased empathic concern, emotion regulation, decreased symptoms of depression, self-compassion, and increased compassion for others) (Chiesa et al., 2011; Donald et al., 2019; Gu et al., 2015; Lykins & Baer, 2009). In contrast to brain training approaches which focus on specific cognitive processes, mindfulness has been reported to improve cognitive function across a range of areas (attentional functioning, memory, executive functioning, and higher-order function) (Chiesa et al., 2011; Gill et al., 2020). Given that mindfulness can be cultivated more robustly with repeated practice (Kabat-Zinn, 2005), it is unsurprising that greater mindfulness experience leads to an even greater degree of improvement in attention (Chiesa et al., 2011).

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One component of attention is error-processing, which allows individuals to maintain their behaviour according to their goals (Smart & Segalowitz, 2017). Research into the effects of mindful awareness on error performance has revealed that mindfulness can positively impact performance-monitoring and, subsequently, self-regulation (Smart & Segalowitz, 2017). This may, in part, be explained by the areas of the brain which are involved in error-processing; the anterior cingulate cortex (ACC; Carter et al., 1998; Garavan et al., 2002; Gehring & Fencsik, 2001; Hester et al., 2009; Kerns et al., 2004; Macdonald et al., 2000) and the dorsolateral prefrontal cortex (DLPFC; Carter et al., 1998; Garavan et al., 2002; Kerns et al., 2004; Macdonald et al., 2000). Both regions are reported to be significantly altered in their activity and connectivity as a result of mindfulness meditation (Tang et al., 2015). This overlap between the areas of the brain affected by meditation and the areas that underpin error processing suggests that error-processing may be influenced by mindfulness practice. The relationship between mindfulness and error processing may be confirmed through electroencephalography (EEG), which can non-invasively measure electrical voltage potentials in the brain. Upon perceiving an error, the ACC generates the error-related negativity component (ERN), a neuro-electrical event that is localized in electrodes over fronto-midline scalp regions (Falkenstein et al., 2000; Gehring et al., 1993; Ridderinkhof et al., 2002). The ERN begins around the time of the error and has been found to reach the most negative amplitude approximately 50–100 ms later (Gehring et al., 1993; Olvet & Hajcak, 2008). The amplitude and timing of the ERN deflection is influenced by the ease of error detection, with easier detections producing greater amplitudes (Falkenstein et al., 2000). There have been several theories regarding the role of the ERN, with some suggesting it is the result of a preconscious error-detection mechanism (Kamarajan, 2019), while others have indicated that it reflects the process of response checking (Falkenstein et al., 2000) or detection of response conflict (Gehring & Fencsik, 2001). ERN-like responses have additionally been reported following correct responses (including where the correct "response" is a non-response), albeit smaller in amplitude (Falkenstein et al., 2000; Vidal et al., 2000). This suggests that the ERN reflects at least partly the process of response checking, rather than only a response to an error.

Following the activation of the ACC, the DLPFC is suggested to be activated to perform the function of increasing cognitive control (Garavan et al., 2002; Kerns et al., 2004). This allows for future behavioural adjustment, resulting in reduced activity in the ACC for following trials (Kerns et al., 2004). The event-related potential generated at least partially from the DLPFC in response to error-processing is referred to as the error positivity (Pe; Falkenstein et al., 2000; Larson et al., 2007) (Table 1). The Pe occurs with a centro-parietal locus, reported between 200 and 500 ms following a response (Falkenstein et al., 2000). It has been theorized to reflect a conscious awareness of the error (Falkenstein et al., 2000), with evidence of a correlation between higher Pe amplitudes and post-error slowing (Hajcak et al., 2003).

While the evidence certainly suggests the possibility that error-processing can be influenced by mindfulness practice, much of the research has produced conflicting results. Several studies on non-clinical populations have reported no significant difference between meditators and controls on either ERN or Pe amplitudes (Bailey et al., 2019; Bing-Canar et al., 2016) while other studies examining both ERN and Pe have presented some significant effects. These effects were additionally inconsistent, with some only reporting differences in the ERN (and not the Pe) for mindfulness meditators when compared with controls (Andreu et al., 2017; Saunders et al., 2016; Smart & Segalowitz, 2017; Teper & Inzlicht, 2013), while Larson et al. (2013) only reported changes in the Pe (and not the ERN) (Table 2). Additionally, different studies have at times reported differences in the meditation group that are in the opposite direction to other studies; for example, Lin et al. (2019) reported an increased Pe amplitude in their mindful group, while Larson et al. (2013) report a decreased Pe amplitude. One possible explanation for the conflicting results is that the effect of mindfulness on error processing is conditional on other factors. Meta-analytic results have identified variability in the effect size and affected brain region of neural activity differences between studies of novice meditators compared to controls, and experienced mindfulness meditators compared to controls (Falcone & Jerram, 2018). This result suggests that the level of mindfulness experience may contribute towards the observed results in error processing studies of the effect of mindfulness.

Additionally, previous research suggests there are notable differences in the amplitudes of the ERN and Pe in clinical groups when compared with controls (Bailey et al., 2015; Kaiser et al., 2020; Lutz et al., 2021a, b; Michael et al., 2021; Pasion & Barbosa, 2019; Perera et al., 2019). These pre-existing effects on the ERN or Pe may interact with the effect of mindfulness on these ERPs. As such, it may be that the effect of mindfulness on measures of error processing is conditional on whether mindfulness is being practiced by a clinical or healthy population. If mindfulness is shown to alter error processing measures in a specific direction, then clinicians could recommend mindfulness as a treatment for clinical conditions that differ from healthy individual brain activity related to error processing. Mindfulness may resolve the pathology represented by the error processing neural biomarker of the condition. This aligns with suggestions for the targeting of biomarkers as an effective treatment approach for clinical conditions (Meyer, 2016; Weinberg et al., 2012).

Table 1 Characteristics of the studies included in the meta-analysis

Study	Age (years)	Population	Intervention description	Length of mindfulness practice	Task	Stimuli
Andreu et al. (2017)	Meditators: range 19–64 years old, $M = 34.22$, $SD = 11.09$; control: range 20–62 years old, $M = 31.88$, $SD = 10.02$	23 Vipassana meditators and 24 healthy control athletes; matched number of hours of practice	None - cross-sectional only	Vipassana meditation practice ($M = 5.1$ years, $SD = 3.73$) with a total of 2500 mean hours of meditation (*range* = 375–12,550, $SD = 2658$)	Flanker task; minimum number of trials for inclusion = 7	Congruent (a row of five letters—SSSSS, HHHHH) or incongruent (central stimulus opposing letter—SSHSS, HHSHH)
Bailey et al. (2019)	Meditators: $M = 35.32$, $SD = 11.82$; control: $M = 35.20$, $SD = 14.66$	22 meditators, 20 healthy controls	None - cross-sectional only	Meditators: $M = 8.72$ years ($SD = 12.25$); $M = 5.74$ h per week of current practice	Go/No-Go, Colour Stroop and Emotional Stroop task	Emotional faces for the Go/No-Go and colour words for the Colour Stroop task
Bailey et al. (2022b)	Meditators: $M = 34.93$, $SD = 12.52$; control: $M = 29.96$, $SD = 11.42$	27 meditators and 27 controls; healthy	None - cross-sectional only	Average of 7.57 years' meditation experience and an average of 7.98 h of practice per week	Go/No-Go task; minimum of 6 epochs for inclusion	Emotional faces; Happy (Go), Sad (No-Go)
Cragun et al. (2020)	Not specified	N = 86 healthy young adults; 38 assigned to a mindfulness condition, 43 to control condition	6-week mindfulness intervention compared to a 6-week control condition listening to TED talks	One hour per week for 6 weeks in total	Modified Flanker task, with a minimum of 10 epochs for inclusion	Not specified
Eichel and Stahl (2020)	Range 18 to 39; $M \pm SD = 24.3 \pm 5.5$; meditation—23.6 ± 4.7; progressive muscle relaxation (PMR)—25.1 ± 6.4	42 female university students; meditation ($n = 22$), PRM ($n = 20$)	Meditation: Smartphone app audio files (3, 5, 15, and 30 min) guided and silent versions; PMR: audio file (17 and 32 min)	Meditation—training at least twice daily, with at least the 15 min of guided meditation for 4 weeks; it was recommended to increase the training amount if possible; PMR—twice daily home practice sessions for 4 weeks; it was recommended to increase the training amount if possible	Modified Simon Task	Two black boxes framed in white (position of the arrow inside) or cyan (direction of the arrow)
Esposito (2015)	$M = 7.86$, $SD = 1.50$	$N = 96$; 69.8% of children spending at least some time in institutional care, 42.7% of the participants receive special ed at school; 14—baseline ADHD; 8—anxiety disorder; 1—depression	Very short mindfulness and relaxation practices adapted for school-aged children; child-friendly games that specifically address inhibitory control, attention, and cognitive flexibility	Mindfulness Training and Executive Function training groups participated in 12 total hours of training, split into hour-long classes that take place twice per week	Color Flanker and Emotion Induction Go/No-Go tasks; computerized delayed gratification task (for points); for "Hot" inhibitory control—the Dinky Toys task	Flanker—congruent (a row of five red/blue circles—RRRRR/BBBBB), incongruent (central target opposite colour—RRBRR/BBRBB); Go/No-Go task—two letters X and Y presenting one at a time, either alternating (Go) or repeated (No-Go)

Table 1 (continued)

Study	Age (years)	Population	Intervention description	Length of mindfulness practice	Task	Stimuli
Fissler et al. (2017)	Depressed: $M = 39.4$, $SD = 12.2$; control: $M = 35.5$, $SD = 13.2$	Depressed Patients; Mindfulness training group ($n = 36$), control condition ($n = 32$), baseline comparison healthy controls ($n = 25$)	Mindfulness group—standard sequence of mindfulness-based interventions using recorded guided meditations; control group—relaxation condition; healthy controls—no intervention	About 25 min twice per day on six out of seven days of each week, for 2 weeks ~ 11 h in total	Sustained-Attention-to-Response task	Array of single digits (1–9) with target number as 3
Larson et al. (2013)	Mindfulness: $M = 19.9$, $SD = 2.0$; control: $M = 20.6$, $SD = 2.3$	Healthy non-meditators ($N = 55$) randomly assigned to mindfulness ($n = 28$; 12 females) and control group ($n = 27$; 14 females)	Both the mindfulness and control exercises from Jon Kabat-Zinn's Mindfulness for Beginners two-disk CD set	Mindfulness group—Breathing exercise from the Mindfulness for Beginners Disk 2 CD (total time = 14:33); control group—Awareness, A Sixth Sense (time = 7:41) and An Ethical Foundation (time = 6:38); (total time = 14:19)	Modified Eriksen Flanker task after intervention only	Arrow stimuli with central arrows facing left or right (congruent or incongruent)
Lin et al. (2019)	*Range* from 18 to 28; $M = 19.22$, $SD = 1.34$	Females; meditation ($n = 103$); control ($n = 103$)	Resting time—5 min; open monitoring meditation vs control group (TED talk)	Meditation group—20 min OM meditation audio; control group—18 min TED talk audio	Emotion picture viewing task and computerized Flanker task	Flanker—congruent (a row of five arrows facing the same direction—> > > > >/< < < < <) or incongruent (central arrow facing opposite direction—> > < > >/< < > < <)
Moadab (2013)	Meditators: $M = 46.78$, $SD = 17.77$; control: $M = 46.43$, $SD = 17.37$	23 meditators (had to practice meditation at least three times a week for at least the last 3 years) and 23 controls	Scripted progressive relaxation for 5 min or focused-attention meditation for 5 min, between blocks of Flanker Task	Meditators: $M = 16.02$ years ($SD = 13.39$)	Modified version of the Eriksen Flanker task	Flanker—congruent (a row of five arrows facing the same direction—> > > > >/< < < < <) or incongruent (central arrow facing opposite direction—> > < > >/< < > < <)

Table 1 (continued)

Study	Age (years)	Population	Intervention description	Length of mindfulness practice	Task	Stimuli
Pozuelos et al. (2019)	$M = 31.5$	Healthy adults; meditation ($n = 21$, 10 male); waitlist control group ($n = 15$, 9 male)	Meditation group participants engaged in 3 weeks of meditation practice from week 2 to week 4	Total of 3 weeks of meditation practice (mindful breath awareness training); 2 h introduction into mindfulness practice + two 1-h follow-up meditation training sessions (one per week) + regular meditation minimum of 10 min per day, at least 5 days per week	Go/No-Go task split into two consecutive blocks	Green light (Go); Red light (No-Go)
Rodeback et al. (2020)	$M = 20.7$, $SD = 2.3$	Undergraduate university students (ERN/Pe—$n = 71$); TSST condition ($n = 36$); control ($n = 35$)	Trier Social Stress Test—prepare and deliver a speech for 5 min + Paced Auditory Serial Addition Task (PASAT)	Control group—relaxing mindfulness listening exercise (14:33 min of mindfulness recordings that includes mindfulness of breathing exercise from Jon Kabat-Zinn's Mindfulness for Beginners Disk 2 CD)	Go/No-Go task	Letter M (Go) or W (No-Go); 70% of trials were Go and 30% of trials were No-Go
Saunders et al. (2016)	$M = 18.9$, $SD = 2.84$	University students; 24 males, 17 females; emotion-focused ($n = 19$); thought-focused ($n = 22$); pre-post comparison	Two induction procedures: one auditory induction for concentrative meditation practice; followed by image task (4 images) focusing on either thought or feeling	13 min of auditory induction for concentrative meditation practice; followed by image task (4 images) focussing on either thought or feeling	Go/No-Go task before and after mindfulness; Induction	Stimulus letters M (Go) and W (No-Go); 80% of trials were Go
Smart and Segalowitz (2017)	*Range* 65 to 80; healthy control: $M = 70.0$, $SD = 3.45$; subjective cognitive decline: $M = 69.60$, $SD = 3.58$	Healthy controls ($n = 23$); subjective cognitive decline ($n = 15$)	Single-blind randomized controlled trial design	Mindfulness training—8-week manualized protocol entitled Wisdom Mind—based on Kabat-Zinn's (2005) MBSR; control condition—psychoeducation on cognitive ageing—5 weeks	Eriksen Flanker task	Congruent (SSSSS, HHHHH) or incongruent (SSHSS, HHSHH) letters

Table 1 (continued)

Study	Age (years)	Population	Intervention description	Length of mindfulness practice	Task	Stimuli
Teper and Inzlicht (2013)	Meditators: $M=33.00$, $SD=11.49$; non-meditators: $M=37.47$, $SD=14.56$	Meditators ($n=20$, 11 females), non-meditators ($n=18$, 16 females); various meditation backgrounds	None - cross-sectional only	At least 1 year ($M=3.19$, $SD=1.39$)	Colour Stroop task	Colour words congruent or incongruent to the semantic meaning of the word

ADHD attention deficit and hyper-activity disorder, *M* mean, *SD* standard deviation, *PMR* progressive muscle relaxation, *TSST* Trier Social Stress Test, *PASAT* Paced Auditory Serial Addition Task

Therefore, in order to resolve the inconsistencies in previous research and determine whether the effects of mindfulness on error processing might be dependent on contextual factors, we aimed to undertake a meta-analysis examining whether mindfulness alters EEG measures of error-processing. The current analysis could subsequently contribute towards informing potentially individualized treatment recommendations if positive results are apparent. In addition, the results may lead into a clearer discernment of the effects of mindfulness meditation on attentive-related neural activity; thus, answering the question of whether mindfulness affects some, but not all, attentional processes.

In addition to our primary analysis of whether mindfulness altered error processing, we aimed to explore whether the effect was dependent upon specific factors that might moderate the effects of mindfulness on error processing. Factors of consideration were the extent of total mindfulness experience and whether the population studied was a clinical or healthy population. Given previous findings, our primary hypothesis was that the ERN and Pe amplitudes would show significantly larger amplitudes in mindfulness meditators when compared with non-meditators. Further, we expected that more mindfulness experience or longer length of mindfulness intervention would produce a stronger effect on the ERN and Pe than less meditation experience and shorter interventions. A third non-directional, exploratory hypothesis was that clinical populations would show a different pattern of effect of mindfulness meditation on their ERN and Pe amplitudes, when compared with non-clinical populations.

Methods

Search Strategy

The team developed a broad electronic search strategy. We conducted systematic search through the Ovid software in PSYCinfo, Embase, Scopus, Web of Science, Pubmed, and CINAHL databases using search term lists under the categories of mindfulness, EEG, and error processing. The search terms included mindful*, meditat*, mindfulness meditation, MBCT, mindfulness based cognitive therapy, MBSR, mindfulness based stress reduction, mindfulness intervention vipassana; EEG, electroencephalography, event-related potential, ERP, brain waves, neural oscillation, ERN, Pe, error processing, error positivity, error related negativity; error processing, Pe, ERN, error positivity, error related positivity, error detection, performance monitoring, error awareness, error monitoring, post-error adjustment, post-error positivity, and action-monitoring. Search terms were adjusted across databases and no date or language limitations were placed on the search. References of the selected

Table 2 ERN and Pe amplitudes, as reported in studies produced from the literature search

Authors	EEG measures reported	Data obtained to calculate effect sizes	ERN *g*	ERN SE	Pz Pe *g*	Pz Pe SE	FCz Pe *g*	FCZ Pe SE
Andreu et al. (2017)	ERN, CRN, Pe	*F*-test	−0.77	0.3	−0.53	0.3	−0.53	0.3
Bailey et al. (2019)	ERN, Pe	*M*, *SD*	0.19	0.30	−0.02	0.31	0.30	0.31
Bailey et al. (2022b)	ERN, Pe	*M*, *SD*	−0.13	0.27	−0.36	0.27	0.58	0.28
Cragun et al. (2020)	ERN, CRN, Pe	*M*, *SD*	0.01	0.22	0.02	0.22	0.02	0.22
Eichel and Stahl (2020)	ERN, Pe	*M*, *SD*	−0.38	0.31	0.12	0.31	0.12	0.31
Esposito (2015)	N2, ERN, FRN	*M*, *SD*	0.53	0.34	-	-	-	-
Fissler et al. (2017)	ERN, CRN, and difference ERN	*M*, *SD*, *F*-test	−0.15	0.24	-	-	-	-
Larson et al. (2013)	Correct-trial and error-trial ERN and Pe	*M*, *SD*	−0.18	0.27	−0.61	0.28	−0.61	0.28
Lin et al. (2019)	ERN, Pe	*M*, *SD*	−0.10	0.14	0.3	0.14	0.3	0.14
Moadab (2013)	ERN, CRN, Pe	*F*-test	0.14	0.33	0.83	0.34	0.83	0.34
Pozuelos et al. (2019)	ERN	*M*, *SD*, *F*-test	−4.01	0.59	-	-	-	-
Rodeback et al. (2020)	ERN, CRN, Pe	*M*, *SD*	−0.14	0.24	0.55	0.24	0.55	0.24
Saunders et al. (2016)	ERN, CRN, Pe	*M*, *SD*, *F*-test	−0.45	0.19	0.07	0.31	0.07	0.31
Saunders et al. (2016)—Thoughts	ERN, CRN, Pe	*M*, *SD*, *F*-test	0.12	0.03	-	-	-	-
Smart and Segalowitz (2017)	ERN, Pe	*M*, *SD*, *F*-test	0.68	0.36	−0.72	0.37	−0.72	0.37
Teper and Inzlicht (2013)	ERN, Pe	*M*, *SD*	−0.58	0.33	−0.41	0.33	−0.41	0.33

EEG electroencephalography, *ERN/Ne* error-related negativity, *CRN* correct-response negativity, *Pe* error positivity, *FRN* feedback-related negativity

studies were then searched manually to identify additional material. The searches were conducted again before final analyses to screen for any new studies. The database search results were imported into Covidence.

In the initial phase of screening, we examined study titles and abstracts to filter studies through the inclusion and exclusion criteria. Studies which were selected for inclusion in the analysis, were subsequently full-text screened to verify eligibility for analysis. Each study was screened independently by two reviewers. Conflicts in screening decisions were resolved via discussion.

Screening and Eligibility

The inclusion criteria could include both clinical and non-clinical populations. Interventions were required to involve a "mindful breathing exercise" that fits the description of mindfulness, provided by the mindfulness-based stress reduction (MBSR) approach. The study needed to have examined the difference between mindfulness meditators and a comparison group (inexperienced meditators, controls, treatment as usual or other groups). Studies which obtained measures of mindfulness intervention outcomes either post-meditation or by pre-post design, were additionally included. The outcome measures were required to consist of error-processing or performance-monitoring ERP data, specifically ERN and/or Pe amplitudes as recorded by EEG. Studies that examined neural responses other than those related to error processing or response monitoring were excluded. Studies that examined yoga, mantra, or chakra meditation were excluded, as were studies that included participants without any experience in mindfulness practice (i.e. studies which only examined the relationship between error processing measures and dispositional mindfulness). Studies that did not analyse EEG activity were not included in the analysis, as were those unavailable in English print, or unavailable through the search databases. The study selection process is depicted in Fig. 1.

Quality Assessment

In reviewing study quality and risk of bias scales, we determined that no single scale was fully appropriate for assessing studies of the kind we were examining. As such, we assessed study quality and risk of bias using multiple scales to provide as much information as possible with which to assess the potential that study quality and risk of bias may affect our results. Study quality was assessed using the adapted version of the Cochrane Collaboration's Tool for Assessing Risk of Bias (CCRBT; Higgins et al., 2011), the PEDro scale (Sherrington et al., 2020), and the Standard Quality Assessment Criteria for

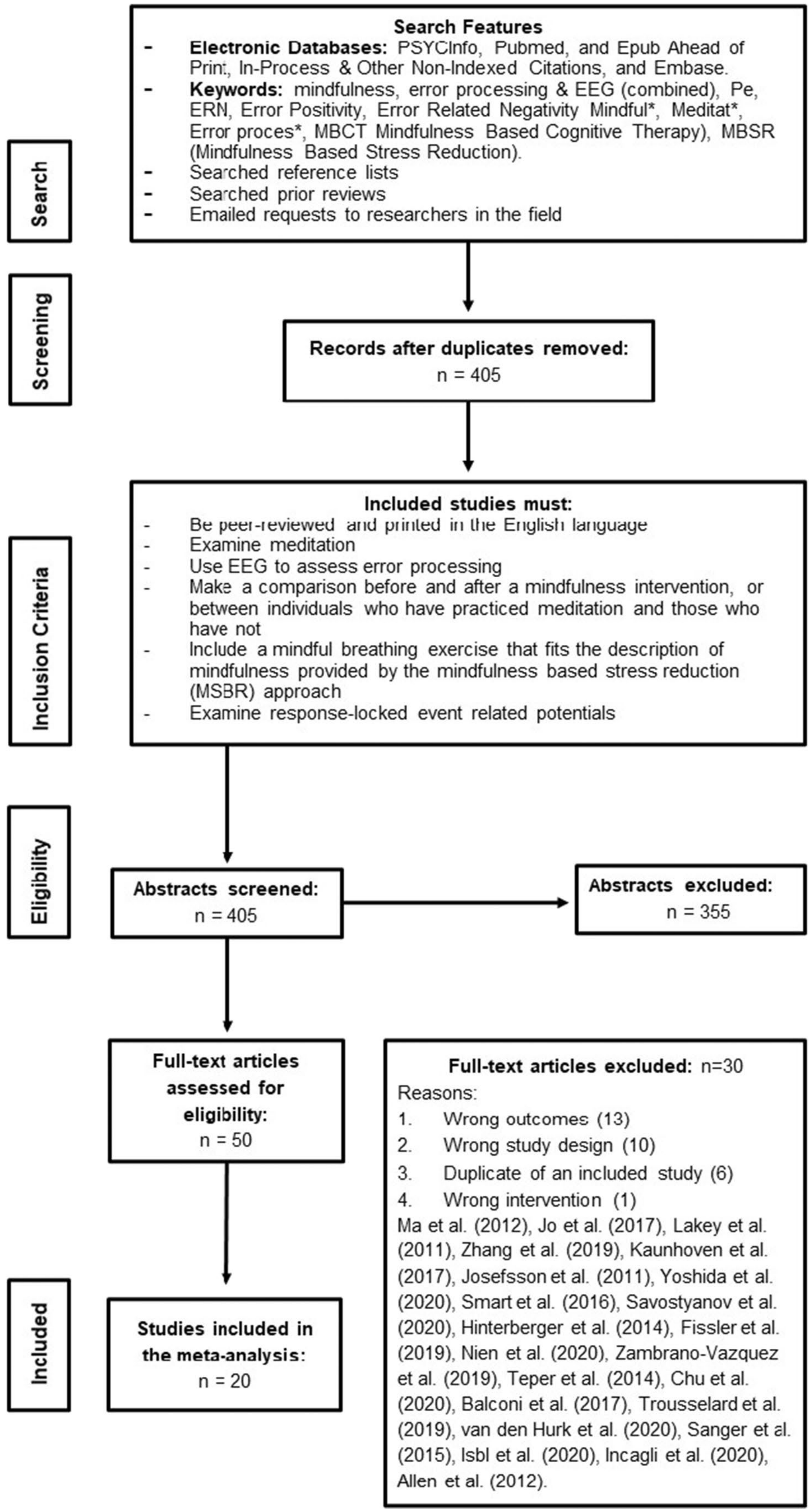

Fig. 1 PRISMA flowchart of review process

Evaluating Primary Research Papers from a Variety of Fields (SQAC; Kmet et al., 2004). Two reviewers (NWB and MO) independently completed the quality assessment for each study, using the full list of criteria from all three scales. A consensus was made and overall scores were produced using the final data from the consensus. The figures included in this analysis were created using the "robvis" risk of bias visualization tool (McGuinness and Higgins, 2021).

The CCRBT (Higgins et al., 2011) is a domain-based evaluation of bias. Assessments of the seven domains were made using a "high", "low", or "unclear" judgement. Guidelines for completing these judgements were sourced from Higgins et al. (2011). An overall judgement of "high", "moderate", or "low" risk of bias was determined for each individual study, using methods outlined by Armijo-Olivo et al. (2010).

The PEDro scale (Sherrington et al., 2000) comprises 11 items, accessed via the Physiotherapy Evidence Database (2021; see Fig. 13). Ratings were provided through a "yes", "no", or "unsure" judgement. The assessment of risk was made using the administration notes provided with the PEDro scale. A "yes" rating was only awarded for a criterion where the process of reducing or eliminating bias was both clearly defined and of a satisfactory standard. Overall assessment of risk for individual studies was calculated using a binary method (Maher et al., 2003). For items 2 to 11, each satisfactory evaluation was awarded a value of "1". Unsatisfactory or unclear bias criteria were awarded "0". An overall score ranging from 0 to 10 was calculated for each study by summing the awarded values. Higher overall scores indicate better study quality.

The SQAC (Kmet et al., 2004) includes two independent sets of criteria, designed for separately assessing quantitative and qualitative studies. In this analysis, the 14 quantitative criteria were used for evaluation (see Fig. 14). The judgements were "yes", "no", "partial", or, where applicable, "N/A". Similar to the PEDro Scale, the scoring system outlined by Kmet et al. (2004) was binary and included a summation of awarded scores ("yes" = 2, "partial" = 1, "no" = 0). Criteria that recorded "N/A" were excluded from the summation. The overall score was determined by calculating the total possible score (e.g. 28 – (N/A × 2)) and dividing the summation by that value. The scoring system is designed to assist researchers to determine a "cut-off" point for study inclusion. In this analysis, studies were not excluded from the meta-analysis based on their overall score. Rather the scores were observed as an indication of strengths and limitations to each study's control for potential bias. Studies that presented fewer "no" or "partial" judgements, recorded higher overall scores.

Data Extraction and Effect Size Calculation

Two studies did not report sufficient data for calculation of effect sizes for the difference between the mindful and control group, and did not reply to emails requesting further details. One of these studies reported a null result (Bing-Canar et al., 2016), while the other reported a positive result (Schoenberg et al., 2014). While research has recommended imputing effect sizes from null results using $p = 0.50$ when further details for calculation of effect sizes are not available (Lipsey & Wilson, 2001), we considered that including only the null result using this approach would bias the meta-analysis towards a null result, and that excluding both studies would be the least biased approach.

While a number of studies assessed correlational relationships between a mindfulness scale and ERN amplitudes in individuals who had not practiced any mindfulness training, we excluded these studies from our analysis (Cary et al., 2020; Dawson, 2020; Eichel & Stahl, 2017). Between-group designs were preferred if reported by the study, but pre-post designs were included if they were the only data reported. This was appropriate as the effect sizes from both study designs reflected the same treatment effect (a condition involving mindfulness training compared to a condition without mindfulness training), and the effect sizes were all scaled in the same metric (microvolts reported for the ERN and Pe), providing the sufficient conditions to enable valid inclusion of both study designs (Morris & DeShon, 2002). However, we considered that dispositional mindfulness may be influenced by different underlying mechanisms and have different effects on the ERN/Pe when compared to mindfulness training, and that this point in combination with the different study design presented more validity risk to our analysis than was desirable. As such, we excluded studies that reported only correlations between dispositional mindfulness and the ERN/Pe.

We computed the standardized mean difference (SMD) and standard errors (SE) from values reported in the studies using the Practical Meta-Analysis Effect Size Calculator (Lipsey & Wilson, 2001) with the following order of preference: (1) between-group comparisons of the means and standard deviations (or standard errors) (12 studies for the ERN, 10 for the Pe); (2) t or F statistics for between-group comparisons (one study for both the ERN and Pe: Andreu et al., 2017; (3) p-values for between-group comparisons (SMD for these approaches were computed using the toolbox for practical meta-analysis provided by Lipsey & Wilson, 2001); (4) pre-post comparisons of means and standard deviations (calculated separately for both the mindfulness of thoughts and mindfulness of emotions samples from Saunders et al. (2016), as this study only reported the results of the two types of mindfulness intervention, and no comparisons with a control group) (SMDs and SEs for this approach were computed following the recommendations for calculating the SD of the pre-post difference provided by Smith and Beretvas (2009), assuming a conservative correlation between pre and post scores of 0.7, as recommended by Rosenthal et al. (1994); (5) pre-post comparisons of the main effect of time using the *F*-value (in a pre-post design where means and SDs were not reported: Saunders et al., 2016). One study (Esposito, 2015) included two control groups, so the SMD was computed by including both of the control groups and sub-groups of a larger control group, with the between subgroup variance pooled to compute the SD (Lipsey & Wilson, 2001). We aimed to select data from absolute ERN/Pe values rather than difference waves between correct and error responses where possible. While some studies did report difference waves, all studies that did also reported absolute ERN or Pe values, so these were used across all studies.

After we had computed the SMD, we converted the effect size values to Hedge's g to provide an estimate of the effect size that was unbiased by sample size (Hedges, 1981) using the approximation equation provided by Moran et al. (2017). We subsequently coded effect sizes so that negative effect sizes reflected less positive (or more negative) values in the mindfulness group, and positive effect sizes reflected more positive (or less negative) values in the mindfulness group.

Analysis

We conducted a random effects analysis on these effect sizes, with a restricted maximum likelihood estimator (REML). This was achieved using the JASP statistical analysis program and was performed separately for the ERN and Pe. Between-study heterogeneity was estimated using Cochran's Q ($p < 0.05$ was deemed heterogeneous) and I^2 (cut-offs of low, moderate, and high heterogeneity were set at 25%, 50%, and 75% respectively [Higgins et al., 2003]). Funnel plots and Egger's regression analysis (Egger et al., 1997) were used to test for publication bias. Where these tests suggested an issue, studies were inspected for potential methodological reasons that might have caused them to produce outlying data, and were excluded if this inspection indicated a likely reason. After this step, if the Funnel plot and Egger's regression analysis (Egger et al., 1997) still indicated an issue, we planned to adjust effect size estimates for funnel plot asymmetry using the trim and fill method (Duval & Tweedie, 2000).

In analysing the ERN, we included the following factors: type of population (Healthy/At Risk/Clinical) and length of mindfulness practice (years/weeks/minutes). We also planned to include study design as a factor (intervention design/cross-sectional design), but this factor mapped perfectly onto the length of mindfulness practice (with all interventions falling into the weeks/minutes categories, and all cross-sectional designs falling into the years category). As such, we did not include this as a factor in our analysis. Additionally, of the studies that analysed the Pe, none examined a clinical population, and only one examined an "at risk" population. As such, we included the "at risk" population with the healthy control studies and did not include clinical/healthy population as a potential moderating factor.

Additionally, because the polarity of the Pe is reversed in parietal electrodes compared to frontal electrodes, and studies reported Pe amplitude results from a range of midline electrodes (from Fz to Pz), we conducted several separate analyses to ensure our meta-analysis of the Pe would not be biased by the electrode reported. Firstly, we conducted an analysis including as many studies as possible, preferencing the Pz electrode if available, but selecting data from the closest electrode reported if data was not available (generally central electrodes such as Cz). Since the polarity of the Pe is typically reversed between frontal and parietal electrodes, we excluded studies that only reported results from frontal electrodes from this analysis. If meditators showed larger Pe amplitudes, these amplitudes (and thus the difference in amplitude between groups) would be reversed in polarity at the frontal electrodes, so inclusion of these electrodes in the same analysis as the posterior electrodes would reduce our potential to detect a significant effect, especially if the studies examining frontal electrodes showed significant results). Secondly, we conducted two separate analyses, one which restricted our analysis to only include studies that reported data from Pz, and the second only including studies that reported data from FCz.

Finally, in order to assess the strength of the evidence in support of each null or alternative hypothesis, we performed a Bayesian meta-analysis. We used the model-averaging setting which avoids a forced decision between testing fixed and random effects, and we have provided the Bayes Factor (BF) value indicating the strength of support for the null (BF01) or alternative hypothesis (BF10) for each fixed and random effect model (Gronau et al., 2021).

Results

ERN Amplitudes

We conducted an analysis of ERN amplitudes across all studies including the factors of practice time and population type in the analysis. The results indicated the omnibus test of model coefficients was not significant, $Q(4) = 5.771$, $p = 0.217$, indicating that overall, there was no significant difference in the ERN between meditators and controls (Fig. 2). The test of residual heterogeneity was high and significant $Q(11) = 53.199$, $I^2 = 89.998$, 95% $CI = [80.432, 97.603]$, $p < 0.001$, and studies that examined ERN

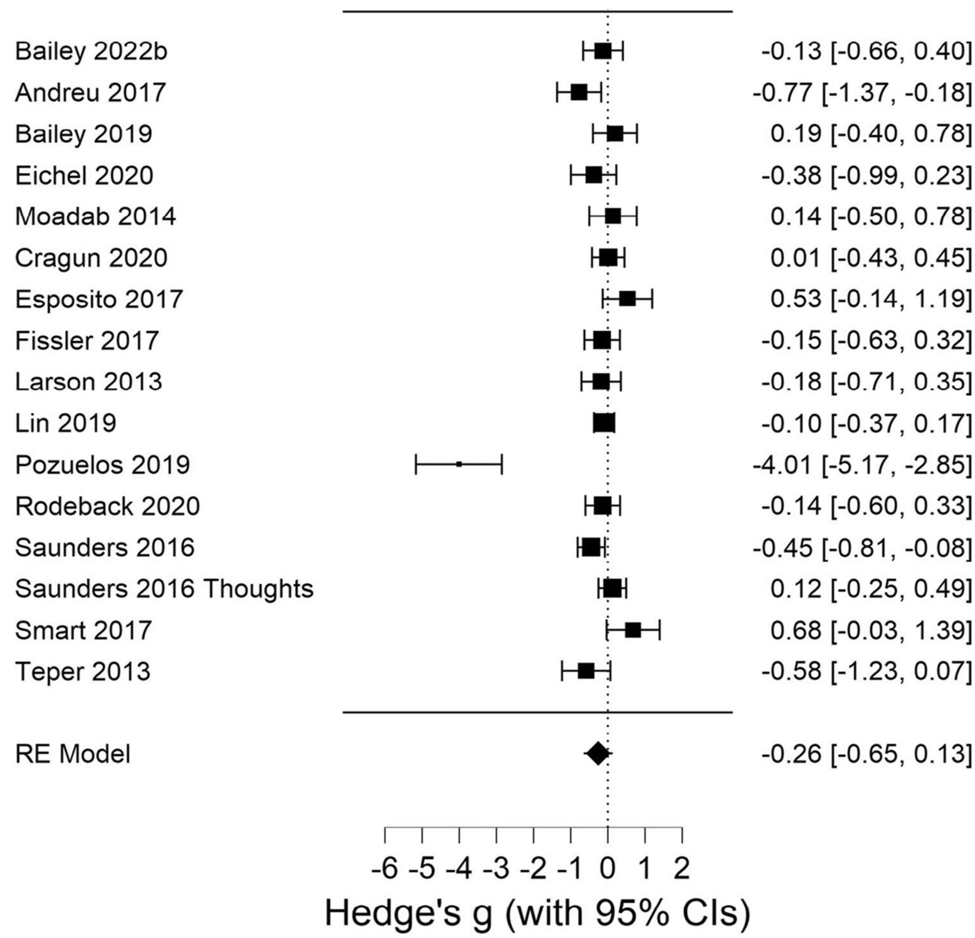

Fig. 2 Forest plot for all studies that examined the ERN amplitude, with a preference for extracting data from electrode FCz. No significant overall difference between the mindfulness and control groups was found Q(4) = 5.771, ***p*** = 0.217

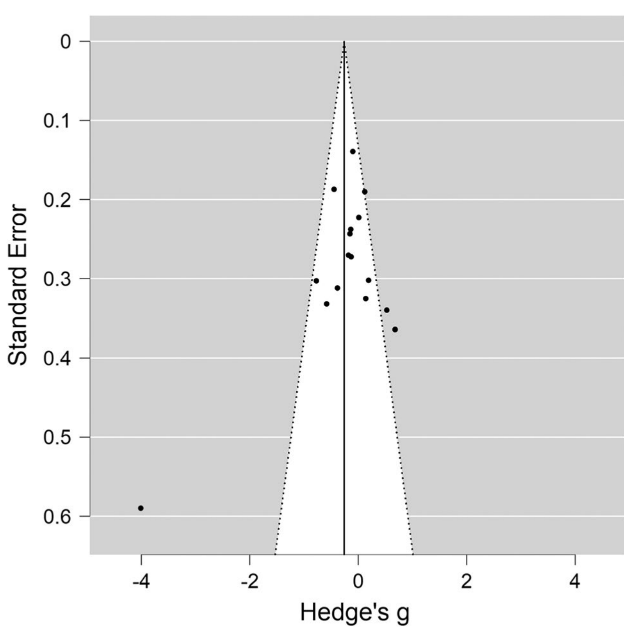

Fig. 3 Funnel plot for all studies that examined the ERN amplitude

amplitude showed asymmetry with a significant Egger's regression test value $z = -4.355$, $p < 0.001$ (the funnel plot can be viewed in Fig. 3), including three influential studies identified by casewise diagnostics (Cragun et al., 2020, Fissler et al., 2017, and Pozuelos et al., 2019). These results indicate that there was significant variation between studies in the outcome of the studies examining ERN amplitude, and also suggest the presence of publication bias. Additionally, the effect of the factor of studies that included healthy individuals was significant $z = -2.321$, estimate $= -1.775$, $SE = 0.765$, $p = 0.020$, 95% $CI = [-3.274, -0.276]$, indicating that within the studies that included healthy individuals only, the mindful group showed more negative ERN values. No other factors provided significant effects (all $p > 0.05$, see Table 3).

Inspection of the information obtained from Cragun et al. (2020) and Fissler et al. (2017) provided no methodological reason to exclude the studies, so analyses were performed including those studies, despite their identification as outliers. However, inspection of the ERP waveforms for the ERN reported by Pozuelos et al. (2019) suggested the difference between the groups may have been related to the baseline correction of the data or pre-existing differences between the

Table 3 The effect of each factor on ern amplitudes. Statistics are reported from the Wald test

					95% confidence interval	
Coefficients	Estimate	Standard error	z	p	Lower	Upper
Intercept	1.627	0.841	1.934	0.053	−0.021	3.276
Length of meditation practice (weeks)	−1.024	0.600	−1.706	0.088	−2.201	0.153
Length of meditation practice (years)	−0.082	0.505	−0.162	0.871	−1.073	0.909
Clinical or healthy (clinical)	−0.756	0.988	−0.766	0.444	−2.692	1.180
Clinical or healthy (healthy)	−1.775	0.765	−2.321	0.020*	−3.274	−0.276

groups (with their waitlist group showing positive voltages across the entire epoch after responses, both prior to the intervention and after the intervention, including in the ERN period, while the mindfulness group showed the expected negative voltages during the ERN period, both prior to the intervention and after the intervention, see Fig. 8 in Pozuelos et al., 2019). As such, the data from Pozuelos et al. (2019) was excluded from further analyses.

The analysis following exclusion of Pozuelos et al. (2019) provided an omnibus test of model coefficients that was not significant $Q(4)=7.777$, $p=0.100$ indicating that overall, there was no significant difference in the ERN between meditators and controls. The test of residual heterogeneity was no longer significant $Q(10)=13.498$, $I^2=24.406$, 95% $CI=[0\ 79.097]$, $p=0.197$, and Egger's regression test for funnel plot asymmetry was also no longer significant $z=-0.583$, $p<0.560$, suggesting there was no longer variation between studies or a publication bias after the results from Pozuelos et al. (2019) were excluded. The effect of the factor of studies that included healthy individuals remained significant $z=-2.172$, estimate $=-0.735$, $SE=0.338$, $p=0.030$, 95% $CI=[-1.398, -0.072]$, indicating that within the studies that included healthy individuals only, the mindful group showed more negative ERN values. Again, no other factors provided significant effects (all $p>0.05$, see Table 4). It is worth noting that only three studies examined non-healthy participants, with two focusing on "at risk" populations (Esposito, 2015: children in institutional care; Smart & Segalowitz, 2017: older adults with subjective cognitive decline), and only one focused on a clinical (depressed) population (Fissler et al., 2017). Therefore, only minimal data is available for the conclusion that non-healthy populations show no effect of mindfulness on the ERN.

Since the effect of the factor examining studies that included healthy individuals was significant, sub-analysis of all datasets including only healthy individuals (except Pozuelos et al., 2019 who showed outlying data) was performed. The analysis showed that the omnibus tests of model coefficients were significant $Q(1)=4.725$, $z=-2.174$, $g=-0.163$, $SE=0.075$, $p=0.030$, 95% $CI=[-0.310, -0.016]$, with mindfulness associated with more negative ERN amplitudes in studies that only included healthy individuals, and no influential studies (Fig. 4). The test of residual heterogeneity was not significant $Q(11)=13.722$, $I^2=15.721$, (95% $CI=[0\ 76.334]$, $p=0.249$, and Egger's regression test for funnel plot asymmetry was not significant $z=-0.722$, $p=0.470$ (the funnel plot can be viewed in Fig. 5), suggesting no significant variation in results across the different studies nor publication bias.

The Bayesian analysis of the studies including only healthy individuals suggested inconsequential evidence for the alternative hypothesis for fixed effects (BF10 = 1.146), inconsequential evidence for the null hypothesis for random effects (BF01 = 1.410) and inconsequential evidence for the null hypothesis for an effect averaged over fixed and random effects (BF10 = 1.071). The analysis also showed inconsequential evidence for the influence of fixed effects over random effects (BF10 = 1.714). Rosenthal's file drawer analysis provided $N=16$, which is below the 65 studies required for robustness against publication bias ($5n+10=65$), suggesting that these results are vulnerable to publication bias. Overall, the results suggest that mindfulness may be related

Table 4 The effect of each factor on ERN amplitudes after the initial exclusion of Pozuelos et al. (2019). Statistics are reported from the Wald test

					95% confidence interval	
Coefficients	Estimate	Standard error	z	p	Lower	Upper
Intercept	0.591	0.355	1.666	0.096	−0.104	1.287
Length of meditation practice (weeks)	0.008	0.234	0.034	0.973	−0.450	0.466
Length of meditation practice (years)	−0.082	0.184	−0.443	0.658	−0.443	0.280
Clinical or healthy (clinical)	−0.753	0.387	−1.946	0.052	−1.510	0.005
Clinical or healthy (healthy)	−0.735	0.338	−2.172	0.030	−1.398	−0.072

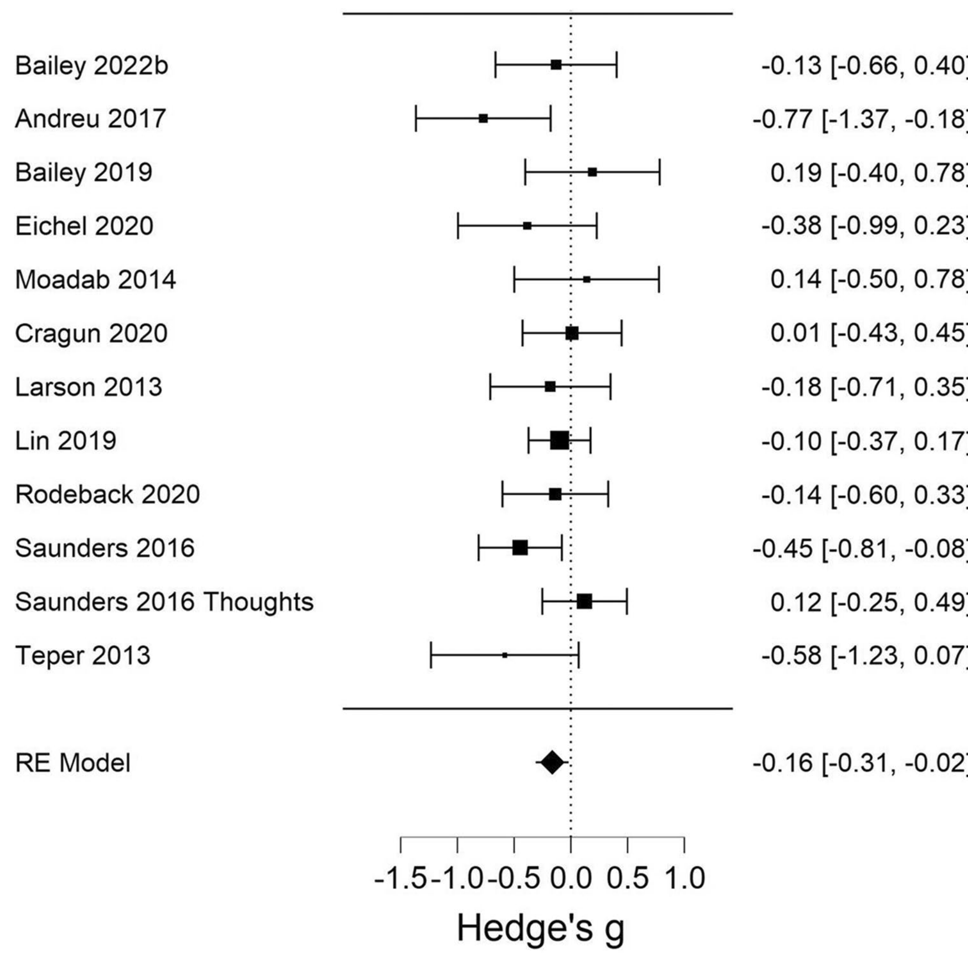

Fig. 4 Forest plot for studies that examined the ERN amplitude with only healthy individuals included after the exclusion of Pozuelos et al. (2019). Mindfulness was associated with more negative ERN amplitudes than the control groups, Q(1) = 4.725, ***p*** = 0.030

to a more negative ERN values in healthy individuals, however, with only very weak evidence and this result may be vulnerable to publication bias (although no evidence of publication bias was apparent in the Egger's test).

Pe Amplitudes

The omnibus test of model coefficients with the factors of practice time and population type when including data from central or posterior electrodes was not significant $Q(2) = 0.579$, $p = 0.749$, indicating there is no significant effect of meditation on Pe amplitude (Fig. 6). The test of residual heterogeneity was moderate and significant $Q(6) = 22.782$, $I^2 = 71.932$ (95% $CI = [32.880\ 93.832]$, $p = 0.002$, suggesting significant variation in results across the different studies. In assessment of whether the between-study heterogeneity was driven by the amount of mindfulness practice, the analysis including the practice time and population type variables as factors indicated no effect of factor was significant (all $p > 0.20$, see Table 5). Egger's regression test for funnel plot asymmetry was not significant $z = -0.684$, $p = 0.517$, suggesting no publication bias (Fig. 7). Therefore, no studies were excluded as outliers. The Bayesian analysis suggested evidence against the alternative hypothesis for fixed effects (BF01 = 5.275), random effects (BF01 = 6.478), and an effect averaged over fixed and random effects (BF01 = 6.336). These results provide evidence that there was no effect of the mindfulness conditions on central/posterior Pe amplitude, and while the effect differed across studies, this was not due to the effect of different mindfulness practice times nor whether the study was an interventional design or cross-sectional design.

Pe amplitudes are often reversed in polarity between frontal and parietal electrodes, so to test for the possibility that effects may be present in specific electrodes overlying either parietal or frontal regions, we performed separate analyses restricted to only the studies that reported data specifically from Pz (Bailey et al., 2019, 2022b; Cragun et al., 2020; Lin et al., 2019; Rodeback et al., 2020; Saunders et al., 2016; and Smart & Segalowitz, 2017) and from FCz (or the average of Fz and Cz) (reported later). The analysis for studies that reported data from Pz showed that the omnibus test of model coefficients was significant $Q(2) = 8.023$, $p = 0.018$ (Fig. 8). The test of residual heterogeneity was not significant

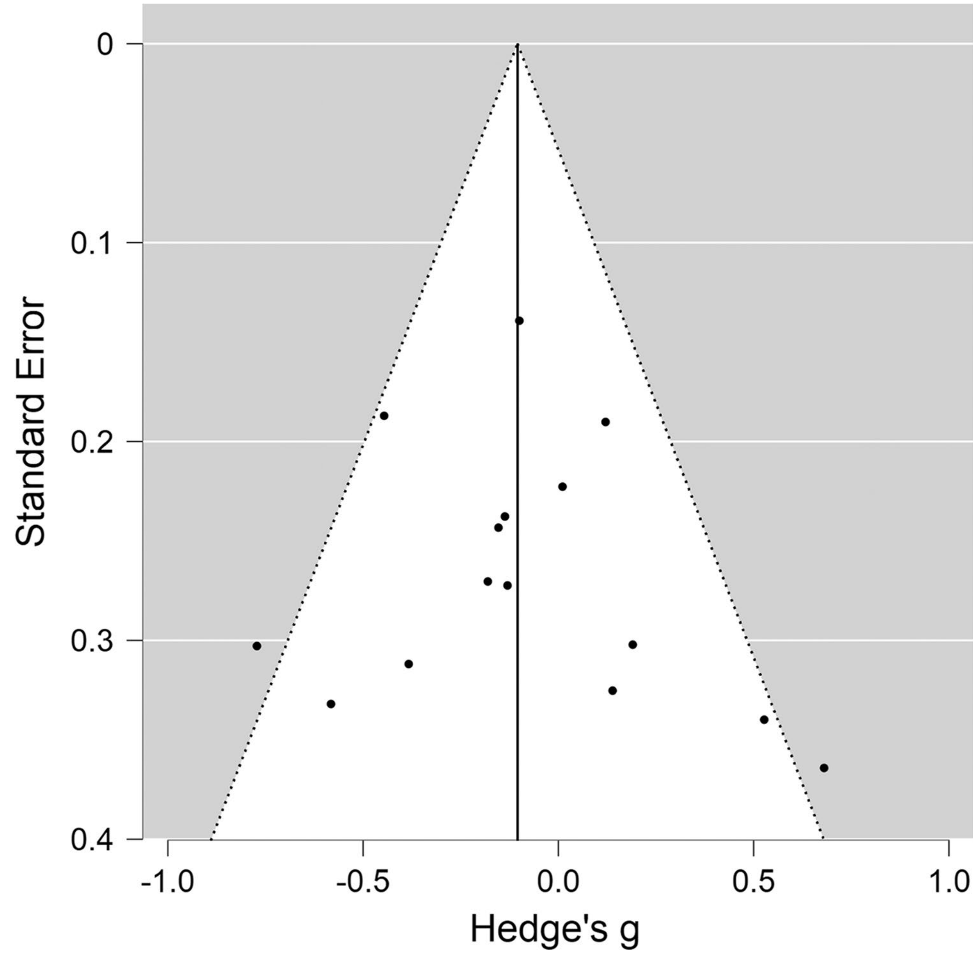

Fig. 5 Funnel plot for studies including healthy individuals that examined the ERN amplitude, excluding Pozuelos et al. (2019)

$Q(4) = 5.278$, $I^2 = 4.896$ (95% $CI = [0, 92.974]$, $p = 0.260$. Egger's regression test for funnel plot asymmetry was not significant $z = -0.888$, $p = 0.374$, suggesting no publication bias (Fig. 9). Therefore, no studies were excluded as outliers. The effect of the factor of studies that included years as the length of meditation practice was significant $z = -2.242$, Estimate $= -0.540$, $SE = 0.241$, $p = 0.025$, 95% $CI = [-1.013, -0.068]$ (Table 6). The effect of the factor of studies that included weeks as the length of meditation practice was also significant $z = -2.254$, Estimate $= -0.516$, $SE = 0.229$, $p = 0.024$, 95% $CI = [-965, -0.067]$. These results provide a preliminary suggestion that mindfulness is associated with lower (or more negative) amplitudes of the Pe at Pz, but only in studies that include at least weeks of meditation practice. However, of the studies included in this analysis, only the two studies from our lab reported Pe amplitudes at Pz for a sample of participants who had been meditating for years. Both studies reported negative voltages at Pz during the Pe window, with meditators showing more negative values than controls (a result that was only significant in Bailey et al., 2022b). Additionally, only two studies reported Pe amplitudes from a sample of participants who had been meditating for weeks. Both of these studies reported positive (although small) values for the Pe at Pz and while meditators showed less positive values in Smart & Segalowitz (2017), the reported result was non-significant. Additionally, neither of these results are consistent with the results of the analysis that included electrodes across the broader central parietal region. As such these results should be viewed with caution.

Lastly, we performed an analysis restricted to only the studies that reported data from FCz (Bailey et al., 2019, Bailey et al., 2022b, Teper & Inzlicht, 2013) or averaged across Fz and Cz, Andreu et al., 2017). These studies also happened to be the studies that only examined long-term meditators in cross-sectional designs; therefore, no between-study factors (such as mindfulness practice time) were included in the analysis. The analysis showed that the omnibus test of model coefficients without factors was not significant $Q(1) = 4.436\text{e-}4$, $z = -0.021$, $g = -0.006$, $SE = 0.272$, $p = 0.983$, 95% $CI = [-0.540, 0.528]$ (Fig. 10). The test of residual heterogeneity, however, was moderate and significant $Q(3) = 9.906$, $I^2 = 69.108$ (95% $CI = [5.335\ 97.717]$, $p < 0.019$.

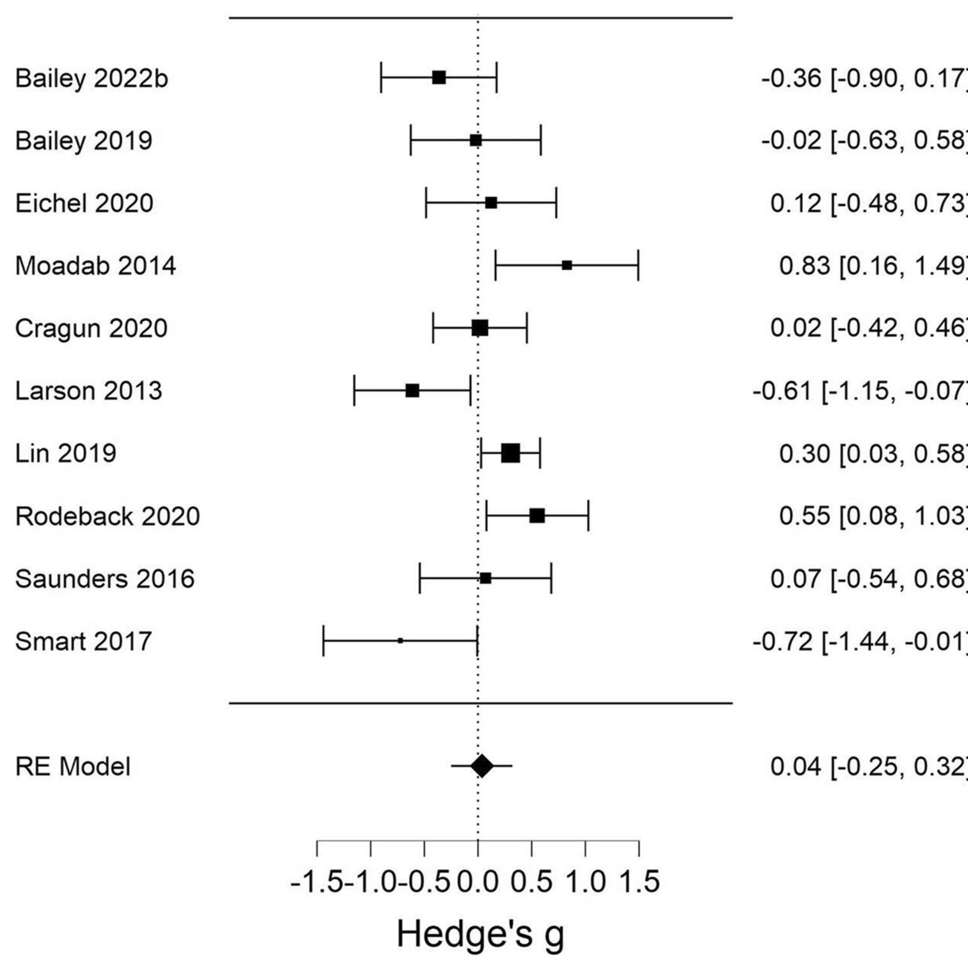

Fig. 6 Forest plot for all studies that examined the Pe amplitude, at central or posterior electrodes, without including the effect of factors. No significant difference between the groups was detected, $Q(2) = 0.579$, $p = 0.749$

Table 5 The effect of each factor on Pe Amplitudes, at central or posterior electrodes. Statistics are reported from the Wald test

Coefficients	Estimate	Standard error	z	p	95% confidence interval Lower	Upper
Intercept	0.102	0.243	0.421	0.674	−0.374	0.579
Length of meditation practice (weeks)	−0.261	0.384	−0.680	0.496	−1.015	0.492
Length of meditation practice (years)	0.016	0.387	0.043	0.966	−0.742	0.775

Egger's regression test for funnel plot asymmetry was not significant $z = 0.964$, $p = 0.335$, suggesting no publication bias (Fig. 11). Therefore, no studies were excluded as outliers. The Bayesian analysis suggested evidence against the alternative hypothesis for fixed effects (BF01 = 6.082), random effects (BF01 = 4.435), and an effect averaged over fixed and random effects (BF01 = 4.921). These results suggest that there was no effect of the mindfulness conditions on Pe amplitude at FCz, but that there was variability in the effect reported between the studies.

While both studies that reported reduced Pe amplitudes in the mindfulness group used averaged mastoids or linked ears as the referencing montage, and both studies reporting increased Pe amplitudes in the mindfulness group used average referencing montages, re-analysis of data from a combined dataset of Bailey et al. (2022b) and Bailey et al. (2019) referencing to an average of T7 and T8 (very close to the mastoid) provided effect sizes in the same direction as when both studies used the average re-referencing montage. This suggested that the reference montage was not the explanation for the results.

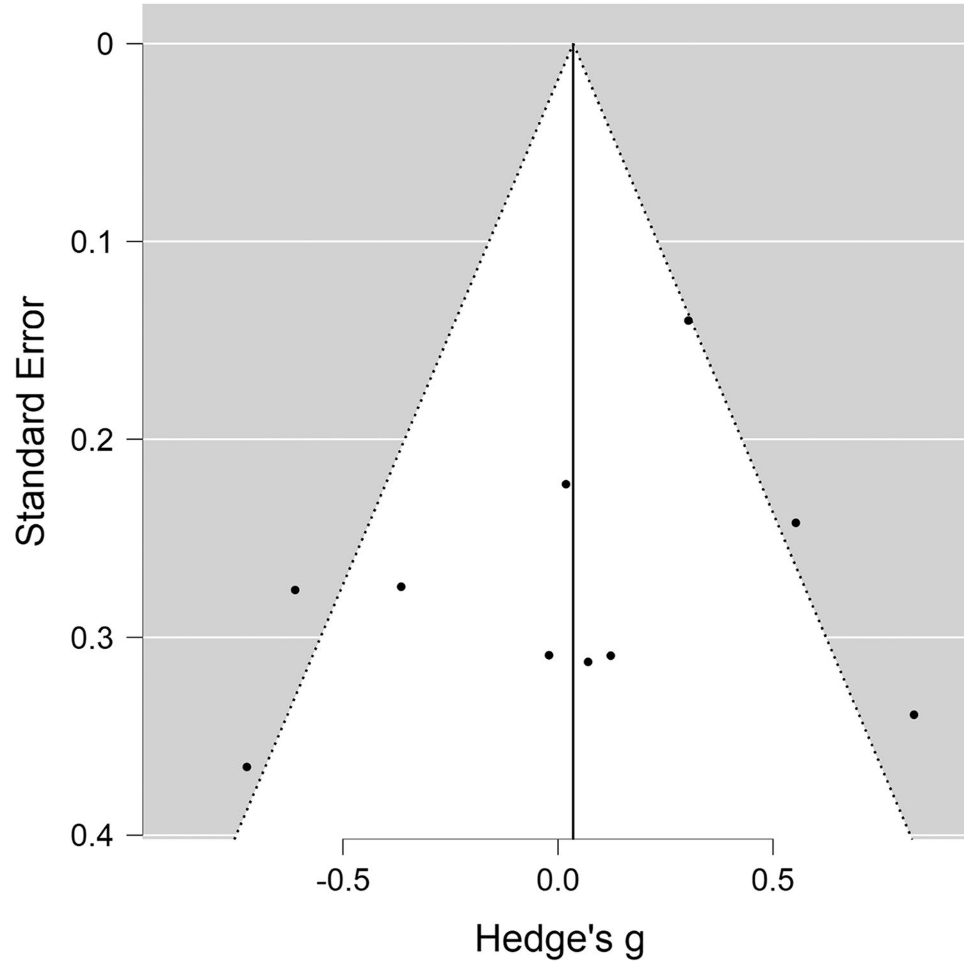

Fig. 7 Funnel plot for all studies that examined the Pe amplitude at central or posterior electrodes

Quality Assessment Results

The full details of the quality assessment can be found in the supplementary materials. In short, all 15 studies recorded a high risk of bias in the CCRBT, all studies scored between 3 and 7/11 on the PEDro scale (reflecting poor quality when assessed on these scales), but all studies except one scored > 0.8 on the SQAC (reflecting reasonable performance on this scale). Most studies did not adequately report or control for potential biases in group allocation, nor did they adequately address blinding. However, overall, the studies scored higher on criteria related to recruitment, study design, and the reporting of results (which are more of a focus in the SQAC).

Discussion

The aim of the present analysis was to review and analyse the existing literature to determine the effects of mindfulness on ERN and Pe amplitudes. It was first expected that mindfulness groups would produce significantly larger ERN and Pe amplitudes when compared with non-meditators. The primary analysis revealed that mindfulness meditation was not associated with larger ERN amplitudes, with the exception of when the analysis was restricted to healthy individuals only. However, the effect showing larger ERN amplitudes in healthy individuals who had practiced mindfulness was weak and Bayesian statistics showed only inconsequential evidence in support of this alternative hypothesis. Our analyses additionally suggested that mindfulness may be associated with significantly smaller or more negative Pe amplitudes, but only when measured at one electrode (Pz) and only when including populations who had practiced mindfulness for weeks to years (not brief mindfulness interventions comprised of only minutes in length, which perhaps reflect "mindfulness inductions" rather than mindfulness practice). However, this result was produced by the inclusion of only two studies that examined mindfulness practice lasting weeks and two studies for years of practice, and one of which only one study actually reported positive results. As such, this significant result should be viewed as a preliminary suggestion at most and should be investigated through further study.

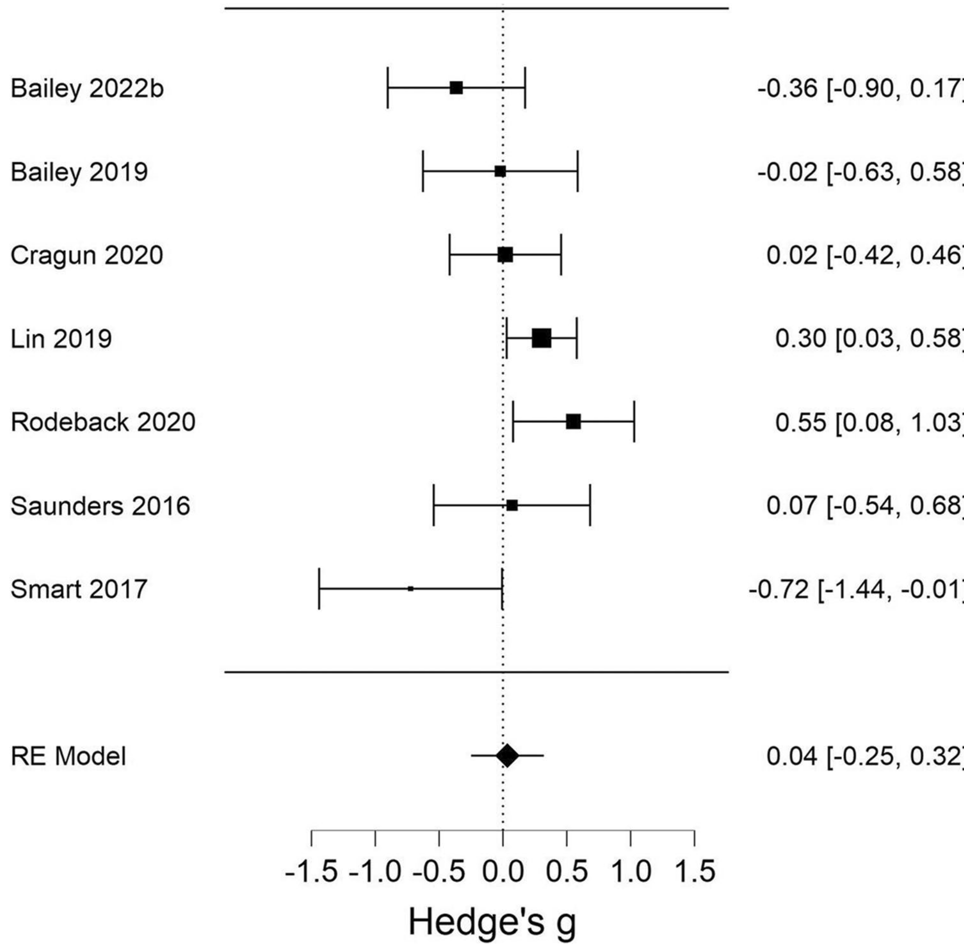

Fig. 8 Forest plot for all studies that examined the Pe amplitude, only including data from electrode Pz

The second part of our analysis explored the effects of duration of mindfulness practice on ERN and Pe amplitudes. We expected that the influence of mindfulness meditation on the ERN and Pe would be stronger in participants with greater mindfulness experience or longer interventions, when compared to participants with less mindfulness experience or shorter interventions. There was no effect of duration of mindfulness practice on the ERN, with some studies involving mere minutes of mindfulness practice (or mindfulness inductions) and only weeks of practice showing larger effect sizes than some studies involving participants with years of mindfulness practice and many hours per week. However, as mentioned previously, our analysis suggested that weeks to years of mindfulness experience may be associated with reduced or more negative Pe amplitudes. This suggests that the effects of mindfulness on the Pe are not apparent from studies that involve mindfulness interventions that are briefer than multiple weeks in length. However, due to the weakness of the findings from our primary analysis and the overall poor quality of the studies included, the results of this second hypothesis should also be viewed with caution.

The third exploratory hypothesis predicted that there might be a different pattern of the effect of mindfulness meditation on ERN and Pe amplitudes between clinical populations and healthy populations. Given that the results for the ERN indicated that the effect of mindfulness on the ERN was only apparent in healthy populations, it may be that mindfulness does not affect the ERN in clinical populations. However, given the weakness of the findings in the primary analysis, it is perhaps more likely that mindfulness does not affect the ERN amplitude in either population. Additionally, the minimal number of non-healthy population studies available means we are unable to conclude with any certainty that the ERN is not affected by mindfulness in non-healthy populations.

Implications

There are a number of possible explanations for why the effects of mindfulness on ERN amplitudes are only present in non-clinical populations. It is worth noting that, in contrast to our initial suggestion that mindfulness could be useful for clinical application in conditions that show an

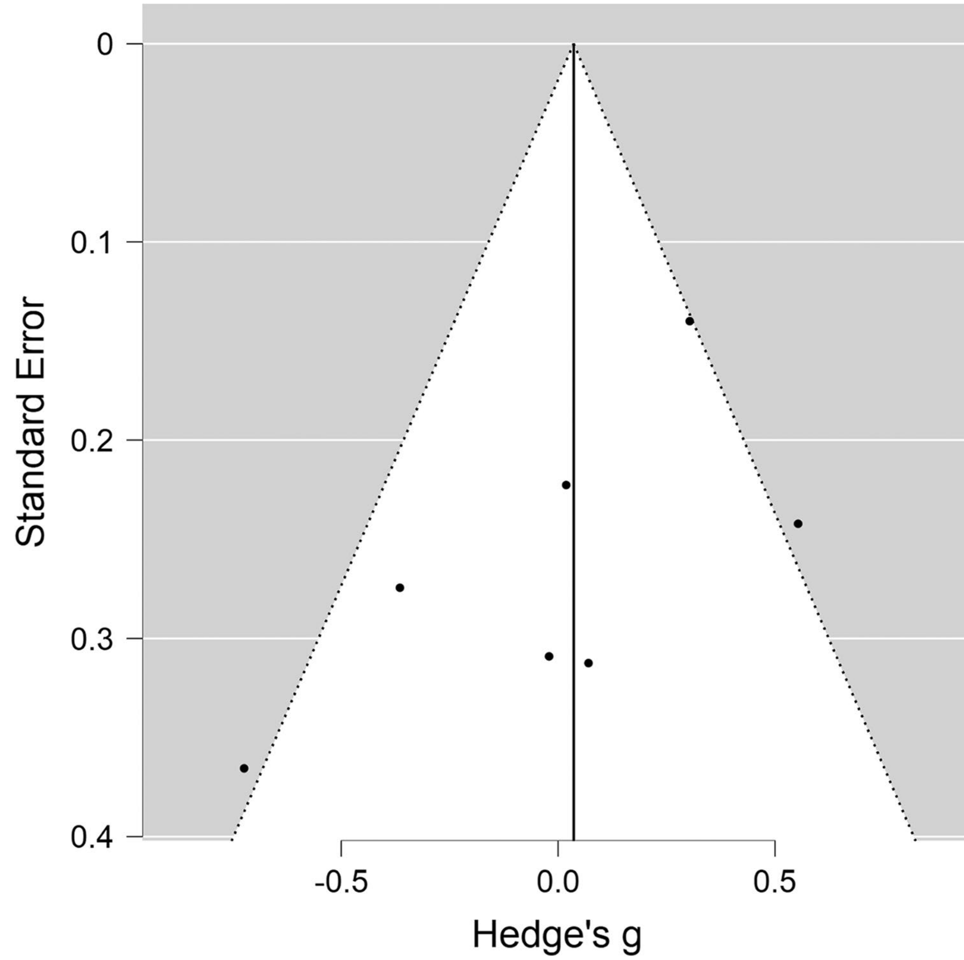

Fig. 9 Funnel plot for all studies that examined the Pe amplitude, only including studies that reported data from Pz

Table 6 The influence of length of practice factors on Pe amplitudes from studies that reported data from Pz. Statistics are reported from the Wald test

					95% confidence interval	
Coefficients	Estimate	Standard error	*z*	*p*	Lower	Upper
Intercept	0.328	0.120	2.741	0.006	0.093	0.563
Length of meditation practice (weeks)	−0.516	0.229	−2.254	0.024	−0.965	−0.067
Length of meditation practice (years)	−0.540	0.241	−2.242	0.025	−1.013	−0.068

ERN that differs from controls in the opposite direction to the effect of mindfulness on the ERN, the results of the meta-analysis indicated that the effect of mindfulness on the ERN (in healthy individuals) was an increase in amplitude. This effect is in the same direction as the proposed effect of depression and anxiety on the ERN (Michael et al., 2021; Moran et al., 2017). As such, it may be that no effect was detected in the clinical populations, as the effect of mindfulness on the ERN in those populations may be the same as the effect of the clinical or at-risk condition, leaving the ERN less room for change by mindfulness practice. This raises a confusing conclusion; anxiety is associated with larger ERN amplitudes (Meyer & Hajcak, 2019; Michael et al., 2021), exposure to unpleasant emotional stimuli is associated with larger ERN amplitudes (Wiswede et al., 2009), and individuals with obsessive compulsive disorder show larger ERN amplitudes (Riesel, 2019). Why then would the effect of mindfulness, which is typically considered to counter these factors, be associated with increased ERN amplitudes? One possible interpretation of our results is

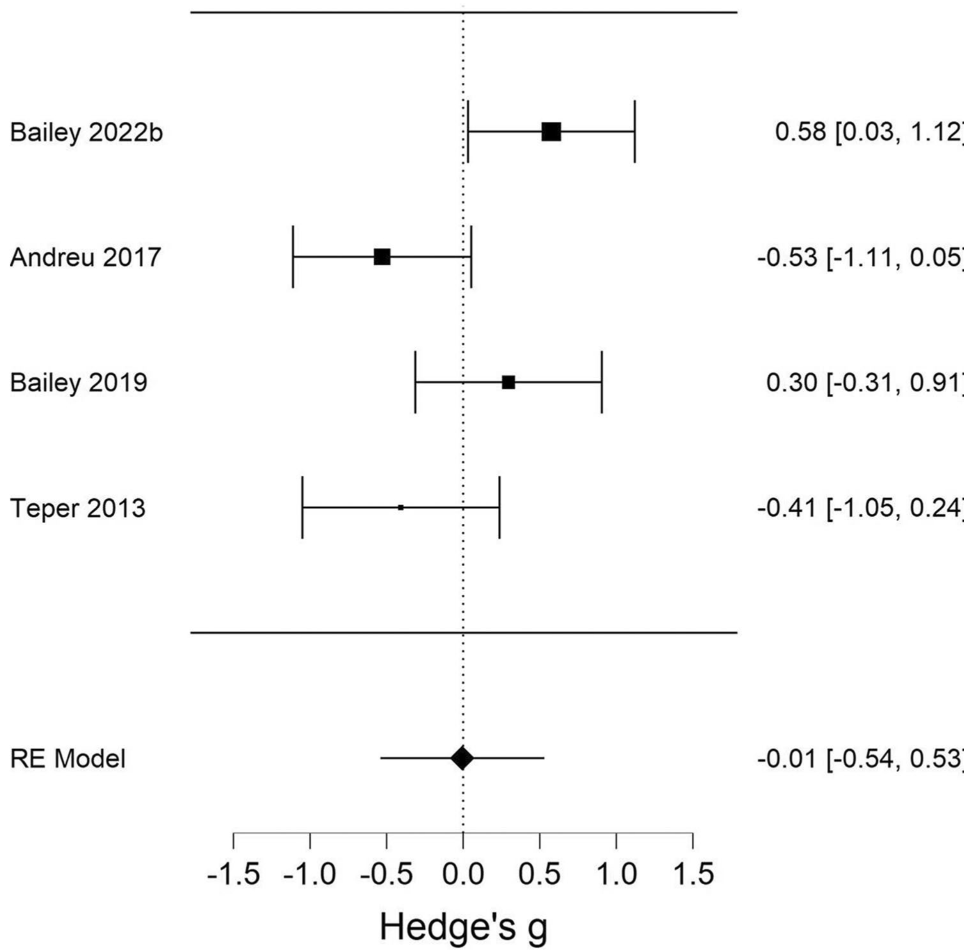

Fig. 10 Forest plot for all studies that examined the Pe amplitude, only including data from electrode FCz (or the average of data from Fz and Cz)

that there may be an enhancement of the ERN that does not necessarily imply increased affective reactions in the mindful group, but may reflect increased detection of conflict (through enhanced attention in the mindful group). Different models of the generation of the ERN suggest it is influenced by affective reactions to errors (Inzlicht & Al-Khindi, 2012) or conflict monitoring processes (Yeung et al., 2004). It may be that both models of the ERN are correct, and that mindfulness enhances the ERN amplitude through enhanced conflict monitoring processes, while clinical conditions show enhanced ERN amplitudes as a result of increased affective reactions. This aligns with a perspective of mindfulness affecting the ERN via changes to conflict monitoring and attention-based neural activity. Enhanced ERNs also seem to be related to both phase re-setting of theta oscillations and modulation of the power of theta oscillations (Trujillo & Allen, 2007), which aligns with research suggesting theta oscillations in the ACC relate to attentional function, that mindfulness increases theta phase locking to events (Lutz et al., 2009; Slagter et al., 2009) and theta power related to autonomic nervous system function (Tang et al., 2009).

However, given the small amount of data with which to draw these conclusions, these points are simply rational speculation. Similarly, regarding a lack of effect of mindfulness in clinical populations, the more parsimonious explanation is that the ERN might only be affected by mindfulness in healthy individuals. It may be that the mechanisms underpinning the ERN are more resistant to change than other neural mechanisms that have been shown to be altered by mindfulness practice. When mindfulness is used to treat clinical populations, other attentive mechanisms may be primarily affected, while the ERN may remain resistant to change. Indeed, the ERN has been suggested to be an endophenotype for many mental health disorders, highlighting its probable resistance to change by interventions (Olvet & Hajcak, 2008). In contrast, it may be that mechanisms underpinning the ERN are more available to be affected by mindfulness in non-clinical populations. However, this explanation is also unlikely to be complete, as clinical populations may experience greater effects from mindfulness interventions than healthy individuals, with meta-analytic evidence for this at least in children (Zoogman et al., 2015).

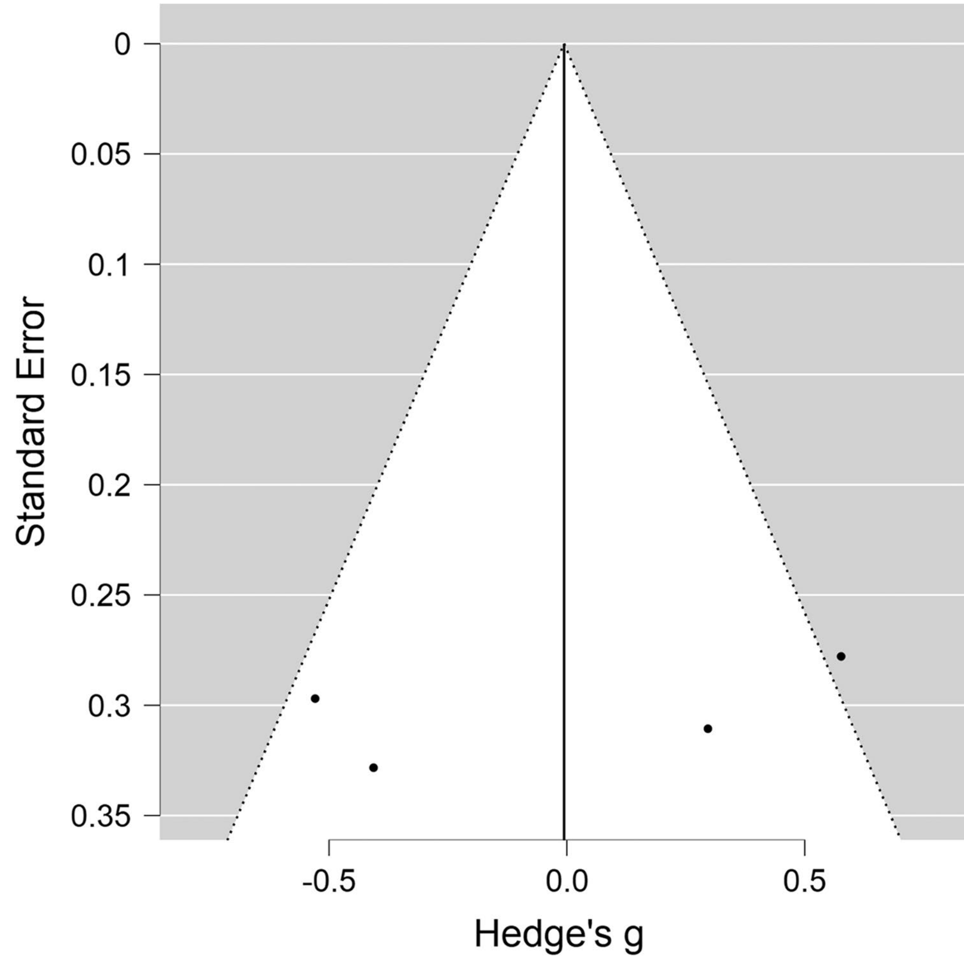

Fig. 11 Funnel plot for all studies that examined the Pe amplitude, only including studies that reported data from FCz (or the average of Fz and Cz)

For this explanation to be true, we would be suggesting another pathway in which ERN changes only occur once other mechanisms are healthy.

A third, and perhaps more likely, explanation is that, in reality, there is no effect. While the effect remained significant without any publication bias detected, it was small and Bayesian statistics suggested minimal evidential strength for changing our beliefs from the null hypothesis. Event-related potential research is also notoriously vulnerable to experimenter effects. As such, even in the absence of publication bias, a large number of studies may have used methods that were biased towards positive results. This is due to the number of parameters that can be varied in the data processing steps between the collection of data and the publication of statistical effects. The cleaning of muscle and blink artifacts from the raw EEG data, the choice of reference montage (Klawohn et al., 2020), the choice of baseline correction periods, the number of epochs for inclusion in the analysis, and the choice of electrodes and windows for analysis may all be varied by the experimenter and, thus, influence results. In particular, the choice of electrodes and windows for analysis can be selected after inspection of group means, which has been demonstrated by simulations to inflate false positive rates (Kilner, 2013). While this bias can be prevented by the inclusion of all electrodes and timepoints in the analysis, or by pre-registration of analysis methods, only two studies in the current meta-analysis took steps to eliminate the potential for this bias. Both studies reported null results for the ERN comparisons. Additionally, if the ERN effect were present, it could be expected to show a dose–response relationship, where the longest periods of mindfulness practice would show the strongest effect. However, there was no such finding in this analysis. As such, we believe it is possible that the effect of mindfulness on the ERN reflects a spurious finding and that the contribution of more rigorous studies may reduce this to a null result.

The significant finding for the Pe at Pz in studies testing the effect of mindfulness in individuals who had been practicing for years should be subject to high levels of caution. While this result is sensible from a dose–response perspective, it is not clear why the result is only apparent at Pz. The Pe is generated by a range of regions, and generally shows a positive voltage maximum at FCz, with voltages tending towards negative at Pz. Brain activity is generally detected at the scalp in a dipolar configuration. Stronger Pe currents produced by the underlying generator brain regions are characterized by more positive Pe voltages detected at FCz and, conversely, more negative voltages detected at posterior regions. As such, if a larger amplitude Pe were generated by meditators, results would indicate more positive values at FCz and more negative values at Pz compared to controls. An effect isolated to Pz might suggest an altered distribution of neural activity (with different brain regions activated in the mindfulness group compared to the control group, an effect we have previously observed: Bailey et al., 2020, Wang et al., 2020) rather than an altered overall amplitude. However, this altered distribution characterization of the effect of mindfulness on the Pe has not been reported in the literature, while an increased overall Pe amplitude has been suggested (Bailey et al., (2022b). Given the paucity of evidence in this analysis and an inability to characterize the overall neural response strength or the distribution of activity within the current meta-analysis, there lies a large gap in our understanding of the effects of long-term mindfulness on Pe amplitude. We suggest further research is required before potential interpretations of the functional significance of the effects of mindfulness on the Pe will be clear.

Limitations and Future Research

The overall low quality of the studies included in the meta-analysis has been likely to influence the validity of our findings. Only two studies reported the internal consistency or data quality assessment of the ERN or Pe measures (Bailey et al., 2022b; Rodeback et al., 2020). The lack of reporting of internal consistency/data quality is typical for the field of error-processing research, but has recently been highlighted as even more important than participant sample size (Kolossa & Kopp, 2018). It is also likely that the majority of the studies included in our analysis were underpowered to detect the small effect size suggested by our meta-analysis, which is also typical in this area of research. Additionally, there was considerable variability in the methods used to analyse the ERN and Pe. Variability in EEG pre-processing steps has been demonstrated to lead to variability in results (Bailey et al., 2022a; Barban et al., 2021; Robbins et al., 2020), an issue that has also been demonstrated in research examining error processing (Bailey et al., 2022c; Clayson et al., 2021a). In particular, the majority of the studies used a subtraction baseline correction method to account of voltage drift, with very little consistency in the baseline period used. The subtraction baseline correction method has recently been demonstrated to transpose the inverse of the voltage pattern and topography from the baseline period to the active period, such that differences detected in the active periods may actually reflect differences in the baseline periods (Alday, 2019). This is especially concerning in error processing research, where the baseline period typically follows visual stimuli, responses to which may differ between groups. To address this, we recommend using a regression or linear mixed modelling baseline correction method (Alday, 2019; Bailey et al., 2022c). Additionally, the number of error responses required for inclusion in the study varied across the studies. Statistical approaches to test the reliability of error processing related EEG activity have recently demonstrated that more error-related trials are required for statistical reliability than expected and typically used (Clayson et al., 2021b). We recommend the use of methods like the ERP Reliability Analysis toolbox to provide objective assessment of how many trials are required from each participant for the analysis to be reliable (Clayson et al., 2021b). As such, it may be that the results provided by previous research are less reliable than intended. Furthermore, many of the studies used different time windows for their definitions of the ERN and Pe. If mindfulness specifically affected an early or late component of these ERPs, some studies may not have included the period affected by mindfulness practice, and as a result may have detected a null result when a positive result was hiding just outside the window. To address this, we recommend the use of data-driven analysis methods that analyse the entire epoch while still controlling for multiple comparisons (for example, Koenig et al., 2011).

The results of our meta-analysis are not encouraging for researchers interested in performing additional studies of associations or effects of mindfulness on EEG activity related to neural processing. If our results reflect the actual effect sizes, then future studies using between-group *t*-test designs would require 484 participants per group to detect a significant effect on the ERN in healthy individuals with 80% power, and 215 participants in a pre-post design (using effect size estimate = 0.16 from our results, calculated in G-power). It is worth considering that the majority of the control groups included in the meta-analysis were non-active and, as such, this effect size is likely to be even smaller when compared to an active control. With effect sizes this small and no clear and direct current application of the results, the question naturally arises; is it worth the resource cost to provide good evidence for an effect of mindfulness on the ERN or Pe? In particular, the dose effect of mindfulness practice (i.e. the amount of daily practice required to observe positive effects on mental health and whether the effect increases with more practice) has only been minimally studied thus far, and researching the dose effect might better inform our knowledge of the positive health outcomes from mindfulness meditation than further research on the effects of mindfulness on error-processing.

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Declarations

Ethics Approval Due to the meta-analytic approach taken by this study, no individual participant data was collected, the manuscript does not contain clinical studies or patient data, and no ethical approval or participant consent was necessary.

Conflict of Interest PBF has received equipment for research from MagVenture A/S, Medtronic Ltd, Cervel Neurotech and Brainsway Ltd and funding for research from Neuronetics and Cervel Neurotech. PBF is on the scientific advisory board for Bionomics Ltd. NWB, MO, SS, OS, KG, BC, MPNP, JM, and MW have no conflicts of interest to declare.

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