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Cognition, body, and mind: A three-in-one coordinate-based fMRI meta-analysis on cognitive, physical, and meditative trainings

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Abstract

While mounting evidence shows promising effects of brain training on cognitive functioning in healthy and pathological conditions, the spread of variable training approaches highlights the need to compare their efficacy and identify their neural correlates, representing possible targets for neuromodulation treatments. We performed coordinate-based functional magnetic resonance imaging meta-analyses to compare the neural correlates and the cognitive outcomes of cognitive ($n = 22$), physical ($n = 22$), and meditative ($n = 20$) training in healthy non-expert individuals. Pre/post-training cognitive metrics improved after cognitive and physical training, but their heterogeneity, or even the lack of these measurements in some studies, highlights the need of more structured protocols. Cognitive, physical, and meditative interventions increased brain activity in distinct fronto-medial areas likely mediating training effects on cognitive, action, and attentional control, respectively. The modular, training-specific, engagement of a region that is known to mediate feedback-based learning provides cues for boosting brain training via combined interventions that might jointly outperform their individual effects.

KEYWORDS
cognitive training, fMRI, medial prefrontal cortex, meditative training, meta-analysis, physical training, treatment

1 | INTRODUCTION

The growth rate of world population and life expectancy generates concerns about the impact of ageing on well-being and healthcare costs. Age-related alterations of grey-and white-matter features (Damoiseaux, 2017; Ferreira & Busatto, 2013; Fjell & Walhovd, 2010; Fotenos et al., 2005; Gunning-Dixon et al., 2009) reflect in impaired cognitive performance (especially memory, attention and executive functions; Murman, 2015), decreased self-efficacy and autonomy (Hajek & König, 2019), and, therefore, worse quality of life in the elderly and their caregivers.

The effect of life experiences on the individual susceptibility to such decline, that is, "cognitive reserve" (Stern, 2002, 2009), is considered a potential moderator between disease onset and clinical outcome (Stern, 2012). Cognitively stimulating activities, fitness, and nutrition, as well as social, educational, and other environmental factors (Sampedro-Piquero & Begega, 2017), seem to enhance such reserve, acting as protective factor against degenerative diseases

Sara Lo Presti and Sara Origlia contributed equally to this study.

(Ducharme-Laliberté et al., 2022; Wrigglesworth et al., 2021). To boost their preventive effect, non-pharmacological "brain training" protocols have been developed, aimed at delaying and/or slowing cognitive decline. Such protocols entail any type of structured activity performed over time to maintain, train, and reinforce cognitive skills, either directly via cognitive training or indirectly through, for instance, physical exercise or meditative practise.

Cognitive training is directly targeted at functions such as working-memory, executive control and attention (Irazoki et al., 2020; Lobbia et al., 2019; Salmi et al., 2018). Encouraging data on its effects on cognitive performance, self-efficacy and everyday functioning have boosted its diffusion in healthy populations across the lifespan (Chaturvedi et al., 2022; Clark et al., 2017; Ng et al., 2020), as well as in psychiatric (Keshavan et al., 2014; Vinogradov et al., 2012) and neurological (Lasaponara et al., 2021; van Balkom et al., 2020) conditions, particularly when pharmacological support is limited or absent. A key criterion for assessing the outcome of any training is the generalization of acquired skills to non-trained functions, that is, so-called "transfer." Despite encouraging evidence of transfer to non-trained cognitive functions and long-lasting effects (Lintern & Boot, 2021), the actual extent of cognitive training effects is debated (e.g., Sala et al., 2019).

Combining cognitive *and* physical interventions has gained increasing popularity because of the larger effects of dual-task training compared with either modality alone (Gavelin et al., 2021), both in healthy subjects and patients (Karssemeijer et al., 2017; Netz, 2019; Reuter et al., 2012). While generally used for motor rehabilitation, indeed, physical interventions have also been shown to improve cognitive performance, by targeting either the intensity of training (aerobics and strength), or its complexity (balance, coordination and flexibility) (Netz, 2019). Their effects might be mediated by the resulting increase of brain plasticity, in turn enhancing executive functions and working-memory (Kramer et al., 1999; Nelles, 2004), and decreasing the risk of cognitive decline (Erickson et al., 2019). Cognitive and physical trainings seem to induce complementary effects at the neural level, that is, maintaining functional response versus structural/volumetric changes, respectively (Cheng, 2016). However, assessing the actual potential and duration of their effects is hampered by the heterogeneity of both physical activities (Netz, 2019) and methods of cognitive assessment (Erickson et al., 2019).

Cognitive enhancement might also be fuelled by meditative training, including techniques ranging from traditional breath-focused practices to mindfulness and its variants used in cognitive behavioural therapy (Sampaio et al., 2017). These practices are aimed to increase the awareness of oneself and present events (Brown et al., 2007), thus involving attention regulation skills (Malinowski, 2013). The loading on attentional control is shared not only with a subset of cognitive training protocols, but also with body–mind integrative approaches such as yoga and tai-chi. These activities combine physical exercise with meditative practices promoting relaxation, as well as training in sustained attention, shifting, and multitasking, and are therefore considered "mindful" activities (Malinowski, 2013). The partially overlapping target of cognitive and meditative training is confirmed by the evidence that the latter improve cognitive functions, particularly sustained attention and executive control (Jha et al., 2007; Tang et al., 2007), as well as working-memory (Cranson et al., 1991; Jha et al., 2010). However, meditative training stands out for its beneficial effects on general wellbeing (Majeed et al., 2018) and mental health, particularly on stress-relief (Chiesa & Serretti, 2009), anxiety, and depression (Hofmann et al., 2010), which explains their efficacy in psychiatric settings (Dakwar & Levin, 2009; Gallegos et al., 2017). Despite encouraging preliminary evidence (Malinowski & Shalamanova, 2017; Wells et al., 2019), instead, claims on its effects on cognitive reserve are limited both by the variety of meditative practices, and by the lack of rigorous control on possible confounding factors (Gard et al., 2014).

Whether cognitive, physical and meditative trainings target distinctive or overlapping neurocognitive processes is a key question with translational implications. While traditional cognitive training mainly reinforces the targeted cognitive skill (i.e., "near" transfer; Melby-Lervåg & Hulme, 2013), detecting cognitive benefits of physical and meditative trainings inherently provides evidence for "far" transfer (Barnett & Ceci, 2002). Although the aforementioned literature suggests overlapping targets at the cognitive level (particularly involving executive functioning, working-memory and attentional control), the effects of these types of intervention are likely to engage distinct brain networks underlying training-specific requirements. Previous studies reported, however, controversial findings.

Physical training has been often reported to increase activity in regions underlying sensorimotor processing, such as middle cingulate and supplementary motor cortex (SMA) (Baeck et al., 2012; Chen et al., 2019; Holzschneider et al., 2012; Nocera et al., 2017) alongside basal ganglia (Marin Bosch et al., 2020). The frequent engagement of fronto-parietal and dorsal attentional networks (Yu et al., 2020), however, suggests the additional contribution of executive processes underlying top-down attentional control on the processing of sensorimotor information (Chen et al., 2019). Cognitive training was found to modulate activity in key nodes of the executive networks, such as posterior fronto-medial, fronto-parietal, and fronto insular cortex (Heinzel et al., 2016; Iordan et al., 2020; Nęcka et al., 2021), alongside the striatum (Dahlin et al., 2008; Kühn et al., 2013). The direction of such changes is debated, however, as different studies reported either increased (Iordan et al., 2020; Nęcka et al., 2021) or decreased (Heinzel et al., 2016; Kühn et al., 2013) activation after training in distinct posterior fronto-medial and fronto-parietal regions. More consistent findings have been reported for meditative training, that was found to increase activity in the anterior cingulate (Tang et al., 2009) and fronto-polar (Allen et al., 2012) cortex, likely underlying self/emotion regulation and meta-awareness, respectively, and to decrease activity in the amygdala (see Tang et al., 2015).

While these findings suggest a common recruitment of "executive" brain regions by different training types, likely supporting control over domain-specific processes, the degree of overlap versus specificity of their neurocognitive effects remains debated. Addressing this question is crucial for tailoring treatment protocols to the abilities and needs of healthy individuals or patients. Due to the considerable

heterogeneity of this literature, pursuing this goal recommends a meta-analytic approach allowing comparing the effects of different training types, over and beyond the unique features and limitations of single studies.

We therefore compared the effects of cognitive, physical, and meditative training on brain response and cognitive performance. We pursued this goal through coordinate-based meta-analyses of fMRI studies investigating their effect in terms of task-related brain activity, while also extracting the effect-size of subjects' cognitive performance whenever available. To provide a baseline reference for future investigations on the effects of expertise or brain-disease, we selected studies on healthy participants, while excluding those on athletes, expert meditators, or neuropsychiatric patients. Based on the above-reviewed evidence we predicted physical, cognitive and meditative training to modulate activity in networks underlying control over motor, cognitive, and higher-order executive/attentional processes, particularly in the posterior fronto-medial and frontoparietal cortex (Duda & Sweet, 2020; Mansouri et al., 2017; Tang et al., 2015). While physical and meditative training were expected to increase activity in these regions, we did not have specific predictions about the direction of the effect of cognitive training on brain activity.

2 | METHODS

2.1 | Rationale of the meta-analytic approach

We aimed to identify the brain regions that, in previously published studies, displayed consistent changes of activity (either increase or decrease) after cognitive, physical, or meditative brain trainings in healthy individuals. We pursued this goal with activation likelihood estimation (ALE), a coordinate-based meta-analytic approach using the peak coordinates of previously reported locations to summarize and integrate published findings (Turkeltaub et al., 2002). This approach allows to overcome the typical limitations inherent in single neuroimaging experiments, for example, sensitivity to experimental and/or analytic procedures, lack of replication studies, as well as small sample size (Carp, 2012). These constraints are known to increase the likelihood of false negatives (Button et al., 2013), thus pushing researchers towards procedures which, conversely, might promote false positives (Eklund et al., 2016; Müller et al., 2018).

We first performed three separate ALE analyses addressing the neural effect of cognitive, physical, and meditative trainings. We then ran conjunction and contrast analyses to unveil both common and specific activations across (1) cognitive and physical training, (2) physical and meditative training, and (3) cognitive and meditative training.

2.2 | Literature search and study selection

All the inclusion criteria for each dataset were selected by SLP, and then checked and approved by the other authors. This procedure, entailing a double check by independent investigators, was aimed to reduce the chances of a selection bias (Müller et al., 2018). SLP and SO independently screened the papers resulting from the initial search (see below), and weekly meeting were scheduled to resolve doubts. To further improve the quality of the selection process, at the end of this first selection stage the two authors exchanged their databases for a cross-check. Finally, the two databases were also checked and approved by the other two authors (CG and NC).

2.2.1 | Neural effects of cognitive training

Following the guidelines for neuroimaging meta-analysis (Müller et al., 2018), we started our survey of the relevant literature by searching for the following keywords: "(cognitive) AND (training OR intervention OR enhancement) AND (fMRI OR functional MRI OR functional magnetic resonance imaging)" on Pubmed (https://www.ncbi.nlm.nih.gov/pubmed/; research date: 13 April 2021, updated on 22 December 2022; see Figure 1). We did not apply temporal filters (e.g., specific years of publication). After duplicate removal, a preliminary pool of 13,703 studies was first screened by title, and then by abstract. We retained only those studies fulfilling the following selection criteria:

1. studies written in English language;
2. studies on human subjects;
3. empirical fMRI studies, while excluding reviews, meta-analytic studies and those employing other techniques to ensure comparable spatial and temporal resolution;
4. fMRI studies reporting stereotactic coordinates of task-related activity associated with performing training-related experimental paradigms;
5. studies reporting whole-brain activation coordinates, rather than regions of interest (ROIs) or results of small volume correction (SVC). Studies based on ROIs or SVC must be excluded because a prerequisite for fMRI meta-analyses is that convergence across experiments is tested against a null-hypothesis of random spatial associations across the entire brain, under the assumption that each voxel has the same a priori chance of being activated (Eickhoff et al., 2011; Müller et al., 2018);
6. studies with adult or elderly subjects (age range: 18–99 years);
7. studies including drug-free and non-clinical participants, to prevent possible differences in brain activity associated with pharmacological manipulations or neuropsychiatric diseases;
8. a minimum of five participants included in the final analyses, as usually advised for neuroimaging meta-analyses (e.g., Zhang et al., 2019);

Studies not reporting some of the required information (e.g., sample size, age, or coordinates), and those addressing "training" meant as long-term expertise, were excluded. The following data are reported according to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Liberati et al., 2009; Page et al., 2021).

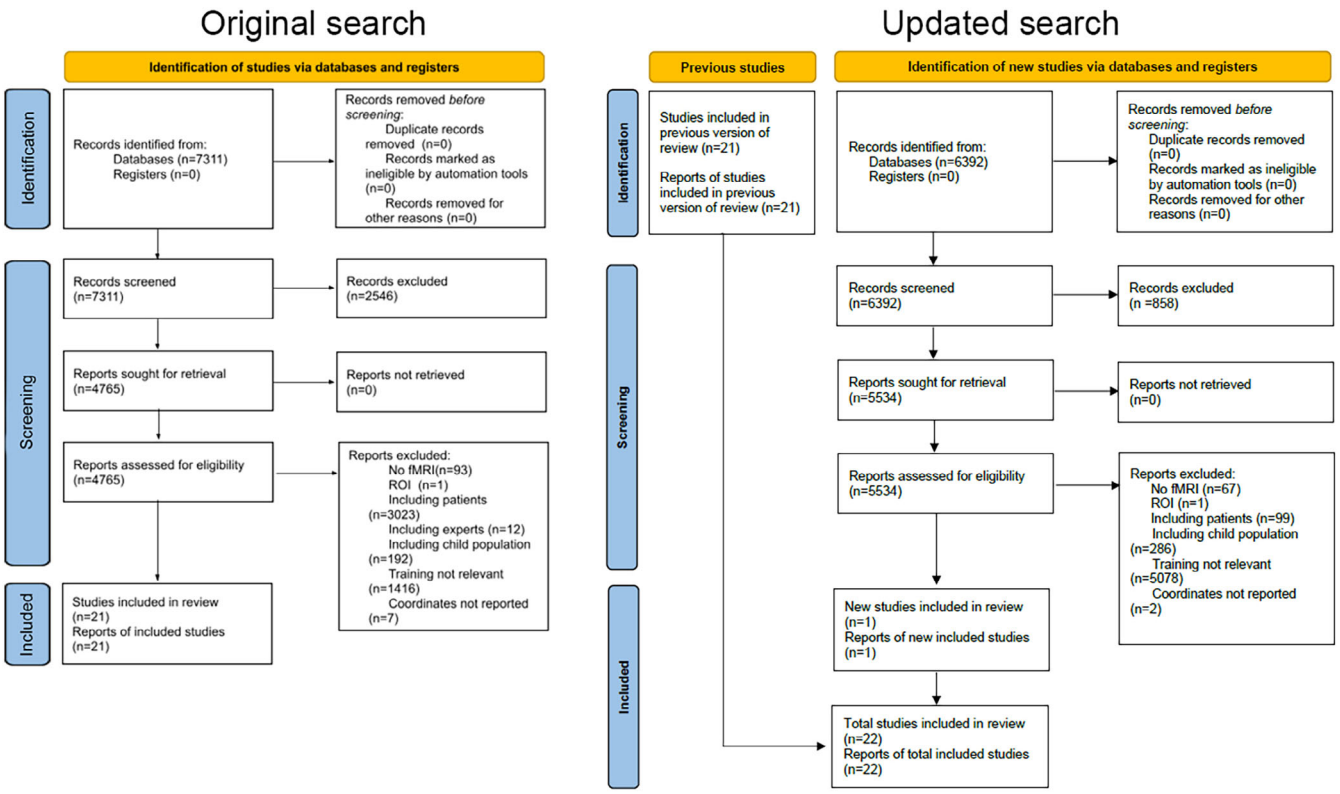

FIGURE 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart of both original (13 April 2021) and updated (22 December 2022) literature search and selection process for cognitive training.

Starting from an initial screening of 13,703 titles and abstracts, 10,299 papers deemed as potentially relevant were fully reviewed based on the aforementioned selection criteria (see Figure 1). We thus excluded: 2 study using ROIs or SVC; 478 studies focused on child population; 3122 studies focused on clinical populations; 12 studies including experts; 6493 studies focusing on other topics, in which the training was not relevant, or using inappropriate contrasts; 160 studies employing techniques other than fMRI; 9 studies not reporting coordinates. We then expanded our search for other potentially relevant studies by carefully examining both the studies quoting, and those quoted by, each of these papers, alongside previously published reviews, and meta-analysis papers on similar topics. This selection phase resulted in a final set of 22 studies fulfilling our selection criteria (see Supplementary Materials, Table 1).

2.2.2 | Neural effects of physical training

We started our survey of the relevant literature by searching for "(yoga OR tai chi OR physical exercise OR aerobic exercise) AND (training OR intervention OR enhancement) AND (fMRI OR functional MRI OR functional magnetic resonance imaging)," with the same selection procedure and inclusion/exclusion criteria described in Section 2.2.1 (research date: 13 April 2021, updated on 22 December 2022; see Figure 2). Because of the body–mind nature of these activities, we chose to include "yoga" and "tai chi" alongside the other keywords, with the intention of relocating them after a more accurate assessment of single papers; the same keywords were also used for searching articles on meditative training (see Section 2.2.3). After duplicate removal, a preliminary pool of 6539 studies was first screened by title, and then by abstract.

Starting from an initial screening of 6539 titles and abstracts, 939 papers deemed as potentially relevant were fully reviewed based on the aforementioned selection criteria (see Figure 2). We thus excluded: 4 studies using ROIs or SVC; 69 studies focused on child population; 360 studies focused on clinical populations; 53 studies including experts; 213 studies focusing on other topics, in which the training was not relevant or using inappropriate contrasts; 196 studies employing techniques other than fMRI; 22 studies not reporting coordinates. We then expanded our search for other potentially relevant studies by carefully examining both the studies quoting, and those quoted by, each of these papers, alongside previously published reviews and meta-analysis papers on similar topics. This selection phase resulted in a final set of 22 studies fulfilling our selection criteria (see Supplementary Materials, Table 2).

2.2.3 | Neural effects of meditative training

Finally, we used the following keywords to search for fMRI studies on meditative trainings: "(yoga OR meditation OR mindfulness OR

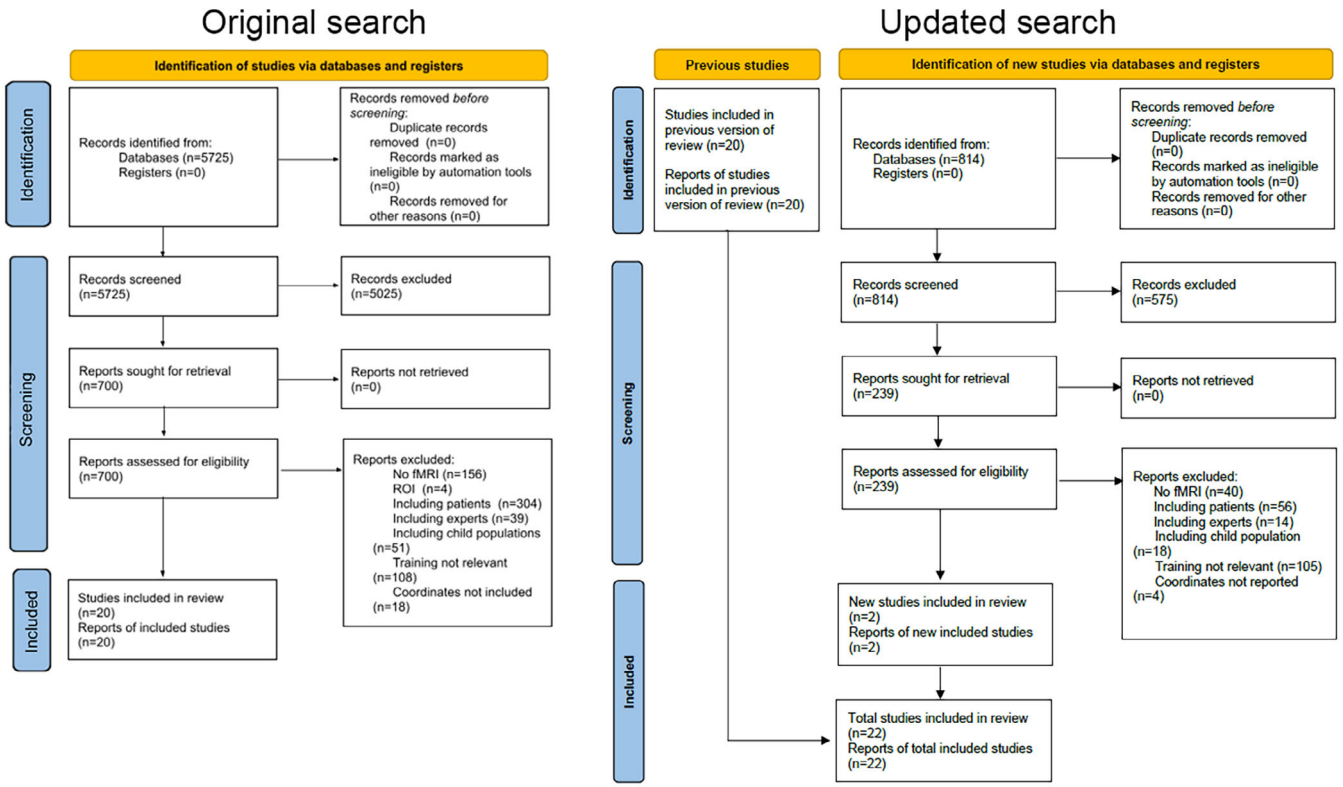

FIGURE 2 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart of both original (13 April 2021) and updated (22 December 2022) literature search and selection process for physical training.

MBSR OR MBCT) AND (training OR intervention OR enhancement) AND (fMRI OR functional MRI OR functional magnetic resonance imaging)" (research date: 13 April 2021, updated on 22 December 2022; see Figure 3). Again, we used the same selection procedure and inclusion/exclusion criteria described in Section 2.2.1. As specified in Section 2.2.2, we included studies using the keywords "yoga" and "tai chi" to place them—after a rigorous examination—in the analysis that best fitted the nature of the (physical or meditative) training at stake. After duplicate removal, a preliminary pool of 645 studies was first screened by title, and then by abstract.

Starting from an initial screening of 645 titles and abstracts, 479 papers deemed as potentially relevant were fully reviewed based on the aforementioned selection criteria (see Figure 3). We thus excluded: 5 studies using ROIs or SVC; 26 studies focused on child population; 116 studies focused on clinical populations; 66 studies including experts; 152 studies focusing on other topics, in which the training was not relevant or using inappropriate contrasts; 82 studies employing techniques other than fMRI; 12 studies not reporting coordinates. We then expanded our search for other potentially relevant studies by carefully examining both the studies quoting, and those quoted by, each of these papers, alongside previously published reviews and meta-analysis papers on similar topics. This selection phase resulted in a final set of 20 studies fulfilling our selection criteria (see Supplementary Materials, Table 3).

2.2.4 | Considerations on the tasks used in pre/post-training fMRI sessions

Coordinates from resting-state fMRI paradigms were not considered in this study, because a preliminary search had shown that the number of available studies for comparing the effects of the three training-types of interest was well below the recent prescriptions for ALE (i.e., a minimum of 17 experiments per condition; Eickhoff et al., 2016; Müller et al., 2018) (see Section 2.3).

After careful evaluation, we included studies based on yoga or tai-chi in the meta-analysis on meditative training, for two reasons. On the one hand, while entailing also physical activity, these practices are considered "mindful" (Malinowski, 2013) because of their loading both on sustained attention, shifting and multitasking, and on meditative practices promoting relaxation. On the other hand, they entail motor practises that are very different from those used in most of the studies on physical training, such as jogging, running, cycling, basketball, swimming, or tennis.

The neural correlates of cognitive training were mostly assessed by coupling fMRI with variations of working-memory tasks, as well as tasks assessing memory, spatial memory, decision-making, calculation or cognitive control (Supplementary Table 1). In the case of physical training, fMRI was performed during tasks assessing working-memory, memory, spatial memory, cognitive control, motor imagery or visual processing (Supplementary Table 2). Finally, the effects of meditative

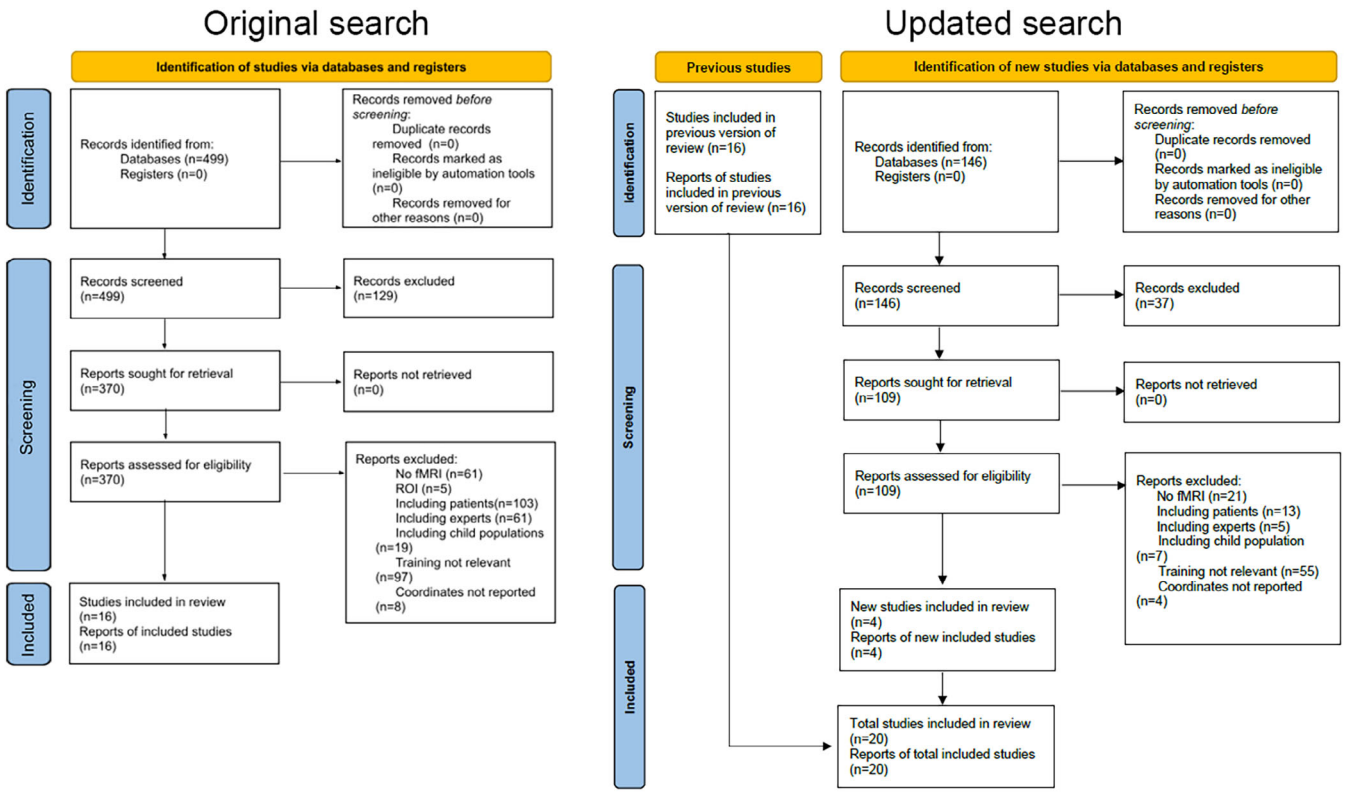

FIGURE 3 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart of both original (13 April 2021) and updated (22 December 2022) literature search and selection process for meditative training.

training on brain activity were investigated with tasks tapping cognitive control, decision-making, visual processing, as well as breathing, attention/meditation and body awareness (Supplementary Table 3). Overall, there was a large overlap between the tasks used to assess the neural effects of cognitive and physical training. While attentional, executive and decision-making tasks were used also in some studies investigating the effects of meditative training, this literature additionally included experimental paradigms grounded in distinctive features of meditation, such as breathing and body awareness.

2.3 | Activation likelihood estimation

We performed three ALE analyses, using the GingerALE 3.0.2 software (Eickhoff et al., 2009), to identify the regions consistently targeted by: (1) cognitive training, (2) physical training, and (3) meditative training. Importantly, the inclusion of multiple contrasts/experiments from the same set of subjects can generate dependence across experiment maps and thus decrease the validity of meta-analytic results. To prevent this issue, for each meta-analysis we adjusted for within-group effects by pooling the coordinates from all the relevant contrasts of a study into one experiment (Turkeltaub et al., 2002). The number of experiments included in each of the three meta-analyses is in line with the recent prescriptions for ALE (Eickhoff et al., 2016; Müller et al., 2018), suggesting a minimum of 17 experiments to ensure that results would not be driven by single experiments (see also Xiong et al., 2019). Moreover, as detailed in Section 2.5, we performed control analyses to ensure that results would not be driven by few hyper-influential studies.

We followed the analytic procedure previously described by Arioli, Gianelli, and Canessa (2021), Arioli, Ricciardi, and Cattaneo (2021), Arioli and Canessa (2019) and Arioli et al. (2023), based on Eickhoff et al. (2012), to identify the voxels consistently associated with each of the three training types. The ALE scores describing the voxel-wise convergence of results for each condition were thresholded at $p < .05$, corrected for cluster-level family wise error, with cluster level threshold at $p < .005$, to identify above-chance convergence in each analysis (Eickhoff et al., 2012). The resulting maps were then fed into direct comparisons and conjunction analyses, within GingerALE, to unveil the common and specific brain activations across: (1) cognitive and physical training, (2) physical and meditative training, and (3) cognitive and meditative training. For contrast analyses, we used a threshold set at $p < .05$, using 10,000 permutations, and minimum volume size of 15 mm^3.

Further exploratory analyses were performed to distinguish between the effects of single training types that had been reported either as increased or decreased activity in the included studies. To this purpose, distinct ALE analyses were repeated, for each training type, by including only the studies reporting either activations or, separately, deactivations. Although this procedure reduced the number of included studies below the suggested minimum of 17 experiments, the same corrected threshold of $p < .05$ described above was applied.

2.4 | Functional connectivity

Since even a superficial overlap between regions can be tied to distinct networks (Smith et al., 2015; Woo et al., 2014), we used the Neurosynth toolbox (Yarkoni et al., 2011) to enable an interpretation of ALE results via a network-level view of intrinsic (i.e., task-free) functional connectivity from training-specific regions. The peak-coordinates of the clusters resulting from training-specific ALE analyses were used as seeds, in Neurosynth, to generate functional coactivation maps based on resting-state fMRI data from 1000 healthy participants (Yeo et al., 2011). To assess the overlap among these intrinsic functional networks, we computed a conjunction image using the voxel-wise minimum value of their maps. All the resulting maps were anatomically labelled with the Anatomy toolbox (Eickhoff et al., 2005).

2.5 | Publication bias

The robustness and generalizability of findings from coordinate-based meta-analyses is known to be affected by a potential publication bias inherent in the analysed literature, that is, the higher likelihood of positive, compared with negative, findings to be reported. We took two distinct approaches to assure the robustness of our ALE meta-analytic findings against such publication bias. Namely, we calculated (a) the relationship between number of participants and numbers of significant findings reported (e.g., foci detected) (Alegria et al., 2016; David et al., 2013, 2018); and (b) for each cluster of each meta-analyses, the fail-safe N (FSN) (Acar et al., 2018).

The rationale for the former approach is that a negative correlation between sample size and number of foci is typical of analyses with publication bias, where studies with small samples are published only if their results match a priori hypotheses (David et al., 2013). Against this possible confound, for none of the performed ALE meta-analyses we observed a significant negative correlation between sample size and number of foci (cognitive training: $r = .07$, $p = .976$; physical training: $r = -.37$, $p = .09$; meditative training: $r = -.10$, $p = .707$).

We additionally performed an FSN analysis (Acar et al., 2018) to further ensure the robustness of our findings against unpublished studies with null results in the "file drawer" (i.e., driven by a bias towards publishing positive results). This approach entails investigating the effect of adding null-result experiments (i.e., null studies) to the original database of studies included in the meta-analysis. Null-result experiments were created in R 3.6.1 (https://www.r-project.org), using Acar et al. (2018) R code and guidelines to match the real experiments in terms of sample size and number of foci reported, but with foci being distributed randomly across the brain. The resulting null experiments were then used to perform new meta-analyses addressing the FSN. The latter represents the number of noise studies (i.e., fMRI studies with non-significant results) that can be added to an ALE meta-analysis before a cluster is no longer significant. In practical terms, this approach entails assessing whether the FSN is below the lower bound (indicating non-robustness against publication bias) or above the upper bound (indicating that results are driven by a small number of hyper-influential studies). When the FSN lies between these boundaries, results can be considered sufficiently robust against the publication bias and driven by at least the desired minimum number of contributing studies. Following Acar et al. (2018), we pre-specified lower and upper boundaries for the FSN of each cluster based on the following considerations. A recent modelling approach to data included in the BrainMap database (http://brainmap.org/) suggests a rate of publication bias up to 30% (i.e., up to 30 unpublished null studies per 100 published neuroimaging studies; Samartsidis et al., 2019). We thus pre-specified that the FSN for each cluster should exceed a lower boundary of 30% of the real data (e.g., with 20 experiments, the minimum FSN is defined as 6). As to the upper boundary, each cluster is expected to be driven by at least 10% of the included studies. Accordingly, the upper boundary of the FSN was calculated per cluster as: ((number of studies contributing to a cluster)/0.1)−(total number of studies included in the ALE meta-analysis). Only if the resulting FSN is between these two boundaries, the cluster can be assumed to be robust against both a potential "file drawer" effect and the effect of few hyper-influential experiments.

2.6 | Behavioural analysis

With the aim of comparing the behavioural effects of cognitive, physical, and meditative training, we performed three exploratory meta-analyses including a sub-sample of the studies included in the fMRI meta-analyses, that is, only those reporting pre/post-training cognitive measures. Studies not reporting cognitive measurements, or failing to include sufficient data for the purpose of effect size calculation, were excluded. Overall, we retained 20, 14, and 5 studies belonging to the cognitive, physical, and meditative training samples (i.e., 39 studies overall).

Effect sizes were calculated as Cohen's *d*, using the Meta-Essentials tool (Suurmond et al., 2017), as standardized mean differences between the pre- and post-training conditions divided by the pooled standard deviation. The within-subject correlation coefficient *r* was calculated using the *Practical Meta-Analysis Effect Size Calculator* online tool (Lipsey & Wilson, 2001). All subsequent statistical analyses were performed using the software R (version 4.0.5), with the packages *tidyverse* (Wickham et al., 2019), *meta* (Balduzzi et al., 2019), *metafor* (Viechtbauer, 2010), and *dmetar* (Harrer et al., 2019). For each of three training-specific meta-analyses, we first pooled effect sizes from individual studies using a random-effects model, and then assessed heterogeneity to evaluate the variation in study outcomes across experiments. Moderator analyses were performed only for the datasets concerning physical and cognitive training, that—unlike the dataset on meditative training—included an adequate number of studies ($k = 10$, Schwarzer et al., 2015). For both analyses, we considered the following moderators: "Gender" (>70% F, >70% M, mixed or not specified), "Age" (18–40, >40, mixed or not specified), "Experimental Setting" (at home, in lab/elsewhere, mixed or not specified),

"Experimental Design" (alone, in group, mixed or not specified), "Training Duration" (long [>1 week] or short [<1 week] duration), "Frequency of Sessions" (high [>1 × week] or low [<1 × week]), and "Duration of Session" (short [<30 min], long [>30 min] or not specified). Further analyses to assess publication bias, as well as sensitivity and *p*-curve analyses, are reported in full in the Supplementary Materials.

3 | RESULTS

3.1 | Neuroimaging results

3.1.1 | Activity and functional connectivity associated with single training-types

Cognitive, physical, and meditative trainings engaged consistent activations in nearby but distinct clusters within the medial prefrontal cortex (see Table 1 and Figure 4a). Cognitive training involved a cluster consistent with Vogt's (2016) anterior and posterior sectors of dorsal midcingulate cortex (adMCC and pdMCC), both located in the paracingulate gyrus according to the Harvard-Oxford structural atlas (Desikan et al., 2006; see also de la Vega et al., 2016). Based on the same anatomical conventions, a more caudal cluster encompassing the pdMCC and pre-SMA was found to be consistently engaged by physical training. Instead, meditative training recruited a more rostro-ventral cluster encompassing the dorsal sector of the anterior cingulate cortex (dACC).

Despite their anatomical proximity, these three clusters belong to distinct intrinsic functional networks, as shown by their Neurosynth "functional coactivation maps" (Yarkoni et al., 2011; Yeo et al., 2011) (see Table 2 and Figure 4b–d). The adMCC cluster associated with cognitive training showed strong coactivation with the dorso- and ventro-lateral prefrontal cortex, extending into the dorsal anterior insula, bilaterally but with a left-hemispheric dominance (Figure 4b). The pdMCC/pre-SMA cluster recruited by physical training strongly coactivates with a bilateral fronto-parietal network including anterior/middle dorsal insula, ventral/dorsal premotor cortex, dorsolateral prefrontal cortex, and secondary somatosensory cortex SII (Figure 4c). The dACC cluster associated with meditative training shows robust coactivation with the ventral anterior insula and posterior cingulate cortex, alongside the lateral frontopolar cortex, bilaterally (Figure 4d). A conjunction analysis among the maps of these intrinsic functional network highlighted their spatial overlap in the midcingulate cortex (*xyz* = −2, 15, 41; Figure 4e).

TABLE 1 Neural correlates of cognitive, physical, and meditative training

	x	*y*	*z*	*z*	*p*
a. Single conditions					
Cognitive training	−8	16	50	5.32	<.001
Physical training	−7	4	51	4.90	<.001
Meditative training	−9	31	28	4.18	<.001
b. Increase					
Cognitive training	−7	16	50	5.56	<.001
Physical training	−8	5	50	5.07	<.001
Meditative training	−11	30	29	4.23	<.001
c. Direct comparisons					
Cognitive > physical	−10	22	46	2.52	.006
Cognitive > meditative	−7	14	50	1.9	.029
Physical > cognitive	−4	3	49	2.06	.020
Physical > meditative	−7	5	51	2.15	.016
Meditative > cognitive	−10	31	28	2.03	.021
Meditative > physical	−10	30	28	2.01	.022

Note: The table reports the stereotactic coordinates of the peak maxima (*xyz*), the z-score and the associated *p*-value of the clusters that were separately associated with cognitive, physical and meditative training based on all the included studies (a) or only in those reporting increased training-related activation (b), as well as those resulting from pairwise direct-comparisons (c).

3.1.2 | Conjunction and contrast analyses

We found no significant evidence of consistent overlapping activations across any pairs of training. Instead, contrast analyses fully confirmed the findings on single training-types described above, with cognitive, physical, and meditative trainings eliciting distinctive activity in dorsal midcingulate cortex (adMCC and pdMCC), pre-SMA, and dACC, respectively (see Table 1 and Figure 5).

3.1.3 | Publications bias

The FSN was always included between the two boundaries for all clusters (cognitive: $7 < n < 29$; physical: $6 < n < 30$; meditative: $5 < n < 24$), indicating that results are sufficiently robust against the publication bias, and supported by at least the desired minimum number of contributing studies.

3.2 | Behavioural results

3.2.1 | Cognitive training

The combined effect size resulting from pooling 20 studies was $d = 0.83$ (rounded; 95% CI [0.5357; 1.1292], $p < .0001$), resulting in a significant positive effect of cognitive training with a large effect size (Figure 1 in Supplementary Materials). Further analyses revealed high heterogeneity ($Q = 163.42$, $p < .0001$; $I^2 = 88.4\%$), thus suggesting performing a subgroup or a moderator analysis. In the case of "Gender," a moderator analysis yielded a significant result for subgroup differences ($Q = 13.81$, $p = .001$), with low heterogeneity in the ">70% F" subgroup ($I^2 = 0.34$), although with a smaller effect size. Similarly,

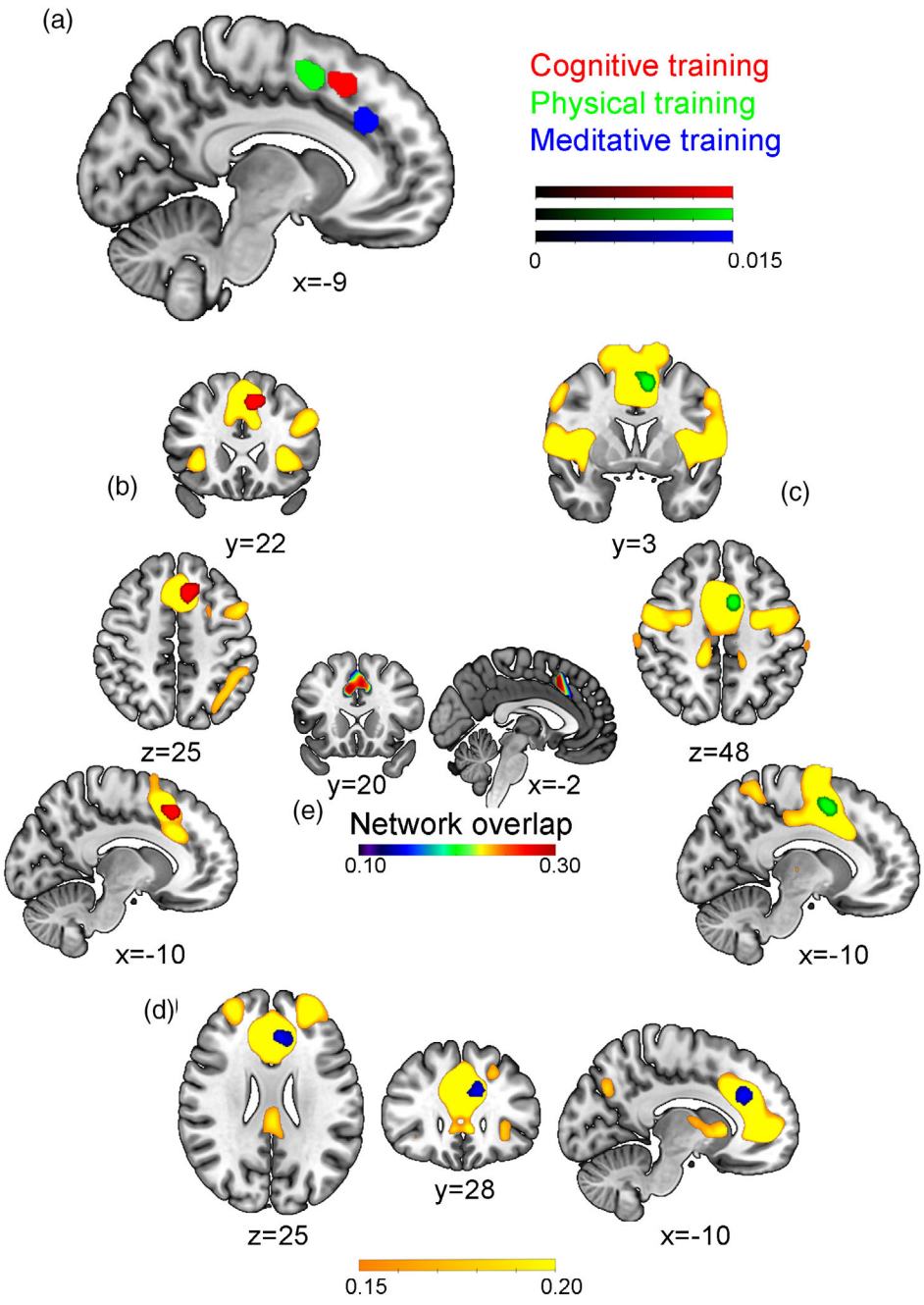

FIGURE 4 From top to bottom, the figure depicts the areas that were consistently associated with cognitive (red), physical (green), and meditative (blue) training (a), as well as their respective connectivity coactivation maps generated by Neurosynth (yellow; b–d) and the overlap of the coactivation maps in the midcingulate cortex (e). Colourbars represent the strength of activation likelihood estimation (ALE) scores, that is, the voxel-wise consistency of brain activity across the included studies.

significant subgroup differences were detected for the moderator "Experimental Design" ($Q = 11.77$, $p = .003$) with a larger effect size for trainings performed individually, although with high heterogeneity in all subgroups. All other analyses on subgroup differences showed high heterogeneity and no significant result (see Supplementary Materials).

3.2.2 | Physical training

The combined effect size resulting from pooling 14 studies was $d = 0.54$ (rounded, 95% CI [0.3258; 0.7467], $p = .0001$), resulting in a significant positive effect of physical training (Figure 4 in Supplementary Materials). A moderate degree of heterogeneity ($Q = 19.38$, $I^2 = 32.9\%$) recommended in-depth assessments with a moderator analysis that yielded significant results for "Age" and "Training Duration." As to the former, the analysis revealed significant subgroup differences ($Q = 7.66$, $p = .005$) with larger effect size and higher heterogeneity for the ">40" subgroup ($d = 0.69$, compared with 0.28 in the 18–40 subgroup). Concerning the latter, subgroup differences ($Q = 6.25$, $p = .001$) reflected a larger effect size and higher heterogeneity for long, compared to short, training durations.

TABLE 2 Functional connectivity coactivation maps

H	Anatomical region	*x*	*y*	*z*	*R*	*K*
Cognitive training						
L	Posterior-medial frontal cortex	−8	16	50	1	1499
L	ACC	−8	24	30	0.25	
L	Precentral gyrus	−44	8	32	0.25	585
L	Middle frontal gyrus	−50	24	32	0.23	
L	Precentral gyrus	−32	0	62	0.27	347
L	Superior frontal gyrus	−18	10	68	0.21	
L	Insula lobe	−30	24	2	0.31	311
R	Insula lobe	34	24	−2	0.24	61
L	Middle frontal gyrus	−34	56	16	0.2	3
Physical training						
L	Posterior-medial frontal cortex	−8	4	52	1	5727
L	Precentral gyrus	−30	−8	56	0.31	
R	Middle frontal gyrus	48	−6	54	0.27	
R	Precentral gyrus	30	−8	56	0.26	
R	Precentral gyrus	56	2	40	0.21	
R	Insula lobe	36	12	8	0.36	2469
R	Rolandic operculum	56	8	2	0.34	
R	Supramarginal gyrus	58	−28	30	0.29	
R	Insula lobe	38	−12	−2	0.21	
L	Insula lobe	−36	8	8	0.37	1636
L	Rolandic operculum	−48	2	4	0.35	
L	Supramarginal gyrus	−62	−22	20	0.29	831
R	MCC	14	−28	42	0.25	182
L	Middle frontal gyrus	−32	42	36	0.25	114
R	Middle frontal gyrus	32	44	30	0.23	55
L	Superior parietal lobule	−24	−50	68	0.22	44
L	Precentral gyrus	−56	2	40	0.23	44
L	MCC	−12	−22	40	0.22	39
Meditative training						
L	ACC	−10	32	28	1	5356
L	Superior frontal gyrus	−24	42	38	0.3	
L	Middle frontal gyrus	−30	58	18	0.28	
L	Insula lobe	−34	16	−8	0.32	344
R	Middle frontal gyrus	28	52	26	0.23	192
L	MCC	−4	−22	32	0.24	161
R	Insula lobe	36	16	−10	0.28	124
L	Putamen	−16	14	0	0.25	91
L	Putamen	16	14	0	0.21	24
L	Superior frontal gyrus	−20	16	66	0.22	23

Note: From left to right, the table reports the hemispheric laterality (*H*, L = left, R = right), size (*K*, number of 2 mm^3 voxels), anatomical region, stereotactic coordinates of the peak maxima (*xyz*), and connectivity strength (*r*, correlation index) of the voxels showing significant functional connectivity with the peak maxima of the clusters associated with cognitive (top), physical (middle), and meditative (bottom) training. Anatomical labelling was performed in the MNI space based on the overlap between each cluster and cytoarchitectonic probability maps on the Anatomy Toolbox for SPM (v.2.2c; Eickhoff et al., 2005) when available (AT), or with the AAL atlas (Tzourio-Mazoyer et al., 2002) otherwise (Anatomical region).
Abbreviations: AAL, automated anatomical labelling; ACC, anterior cingulate cortex; MCC, midcingulate cortex.

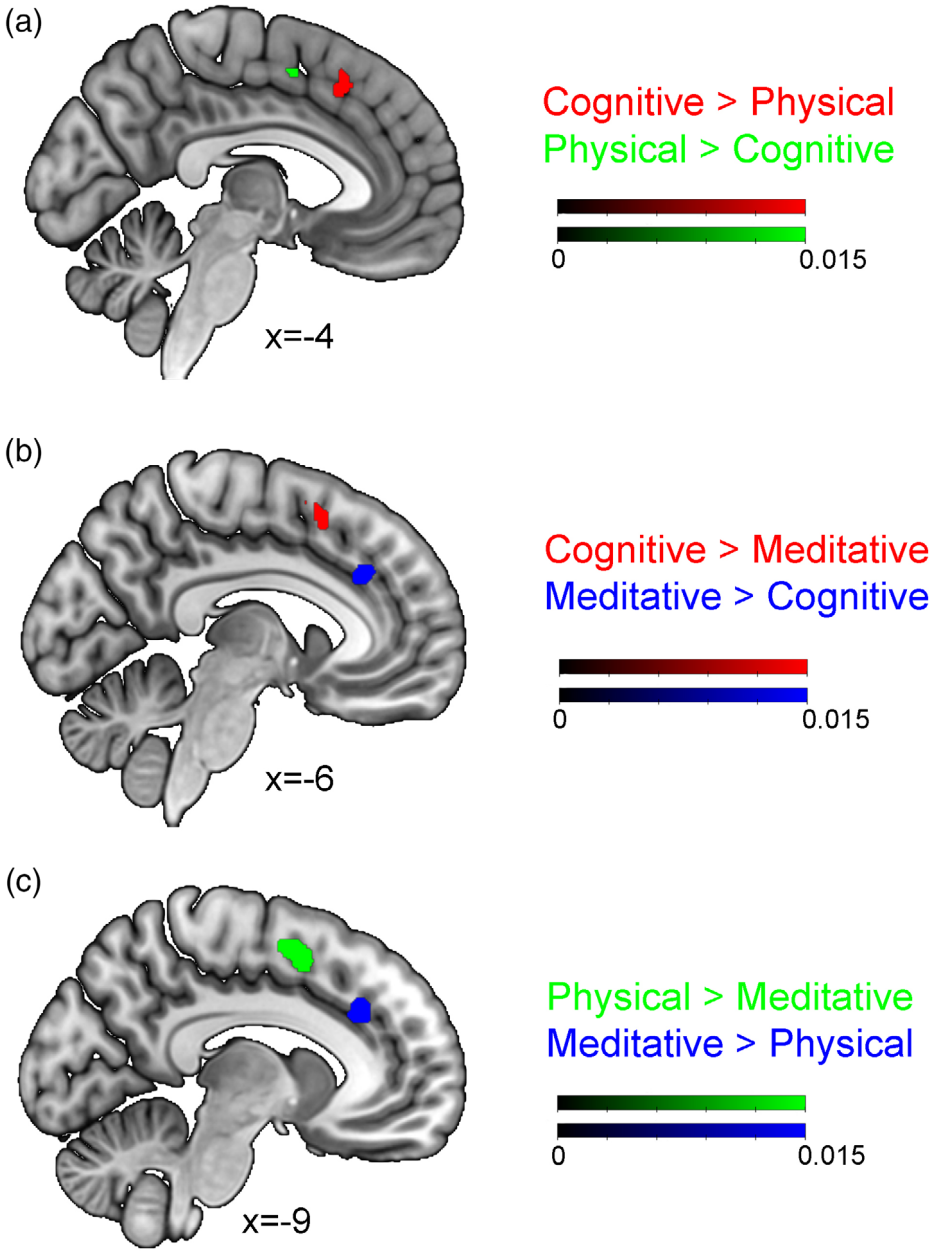

FIGURE 5 The figure depicts the areas that were specifically associated with cognitive, physical, or meditative training, as shown by pairwise direct comparisons.

3.2.3 | Meditative training

The combined effect size resulting from pooling five studies was $d = -0.18$ (rounded, 95% CI [−2.3291; 1.9584], $p = .8221$). This effect size was not statistically significant (Figure 7 in Supplementary Materials). The heterogeneity assessment revealed a large degree of heterogeneity ($Q = 29.16$, $p < .0001$, $I^2 = 86.3\%$), but the small number of included studies did not allow a moderator analysis (see Supplementary Materials).

4 | DISCUSSION

The spread of distinct approaches to cognitive enhancement highlights the need to compare their relative efficacy and unveil their overlapping or distinctive neural correlates. To fill this gap, we took a meta-analytic approach to compare the behavioural and neural effects of the three most popular types of intervention, that is, cognitive, physical and meditative trainings, as reported in previously published fMRI studies on healthy non-expert individuals.

Despite a considerable heterogeneity of the cognitive outcome metrics reported in the included studies, both cognitive and physical training were found to result in significant improvements, while no such effect was observed for meditative training. This negative finding might reflect the paucity of studies reporting pre/post-training cognitive data, which in turn highlights the need of structured and consistent protocols in this research field. The large methodological variability across the included studies clearly shows that the inquiry on the effects of brain training would benefit from standardized neuropsychological batteries (Weintraub et al., 2009, 2018) and

harmonized neuroimaging protocols (Nigri et al., 2022), which, together, might drive a leap forward in this literature. While cognitive performance represents the first line of evidence for comparing the effectiveness of different training types, indeed, identifying their neural correlates might inform alternative strategies to boost their underlying mechanisms, for example, by combining multiple protocol types or via neuromodulation.

The potential value of both these strategies was supported by the present meta-analytic evidence on the brain regions that have been consistently reported in association with meditative, cognitive, and physical trainings. The three training types elicited a consistent *increase* of brain activity in neighbouring portions of the posterior fronto-medial cortex extending from the dACC, through the dorsal midcingulate cortex, to the pre-SMA, respectively (Figure 4a). While a conjunction analysis highlighted no significant overlap across the clusters in which brain activity changed after the three training types, direct comparisons confirmed a specific involvement of dACC, dorsal midcingulate cortex and pre-SMA for meditative, cognitive, and physical training, respectively. This functional segregation was further supported by the *connectivity patterns* of such training-specific clusters.

These clusters connect with segregated networks (Figure 4b–d) that, however, overlap in the midcingulate cortex (Figure 4e). This region is considered an emerging target for neurostimulation (Downar et al., 2016; Mattavelli et al., 2022), because of its role in multiple facets of self-regulation and control, via performance monitoring, feedback detection and behavioural adjustments to improve performance based on both endogenous (e.g., goals) and exogenous (e.g., context) factors (Ridderinkhof et al., 2004). Importantly, this hypothesis is mostly based on fMRI data showing transient responses in the posterior fronto-medial cortex to multiple facets of pre-response conflict and post-response feedback-based learning (Venkatraman et al., 2009). However, the fact that its grey matter volume predicts the success of neuro-feedback (Enriquez-Geppert et al., 2013) is suggestive of ongoing neuro-plastic processes underlying the role of this region in increasing and maintaining control over cognitive performance. Based on this view of the posterior fronto-medial cortex as the common target region of distinct training types, it is thus crucial to investigate the possible functional role of the *distinctive clusters and connectivity patterns* associated with specific types of training.

In particular, the adMCC is known for its crucial role in aspects of executive functioning targeted by cognitive training (Hoffstaedter et al., 2014; Margulies & Uddin, 2019; de la Vega et al., 2016), such as monitoring one's own and others' decision and outcomes (Apps et al., 2013; Rolls, 2019; Rushworth et al., 2004), error and novelty detection (Procyk et al., 2014), or task switching (Rushworth et al., 2002; Worringer et al., 2019). Connectivity associations maps from Neurosynth highlight this cluster as responsible for monitoring (Benn et al., 2014; Botvinick et al., 2004; Nachev et al., 2005), and coactivated both with the dorsal sector of anterior insula and the lateral prefrontal cortex. Both findings point to the prominent role of the anterior cingulo-insular, or "salience," network in maintaining cognitive performance. This network, indeed, regulates the switch between rest and effortful cognitive activity depending on the salience (i.e., motivational relevance) of external stimuli with respect to behavioural goals, thus mediating the switch between automatic and controlled processing associated with the default-mode and fronto-lateral executive networks, respectively (Canessa et al., 2021; Galandra et al., 2018, 2019; Uddin, 2015; Uddin et al., 2017). It is thus well-suited to underpin monitoring functions, a crucial common ground for every task-demand, through which the detection of performance drops, conflicts and interferences prompts inhibitory control and/or behavioural adjustments (Garavan et al., 2002; Iannaccone et al., 2015; Irlbacher et al., 2014; Obeso et al., 2013).

Despite the substantial overlap between the tasks used to detect changes of brain activity after cognitive and physical training, the latter recruited a more caudal cluster, located between pdMCC and pre-SMA. Also this cluster belongs to the wide posterior fronto-medial region associated with multiple facets of cognitive control (Cieslik et al., 2015), such as conflict resolution and task-switching (Chouinard & Paus, 2010), inhibitory control (Nachev et al., 2007; R. Zhang et al., 2017), sequential learning (Shimizu et al., 2020), and working-memory (Buchsbaum & D'Esposito, 2019; Marvel et al., 2019). Despite its proximity with that engaged by cognitive training, this cluster, however, shows a different connectivity pattern, involving premotor and somato-motor regions in charge of motor cognition and action control (Kim et al., 2010; Nachev et al., 2008), that Neurosynth associated with "motor performance."

Finally, meditative training was found to modulate brain activity in the dorsal sector of dACC. This region has been typically considered to support executive control through processes shared with the adMCC and pre-SMA, such as conflict monitoring (van Veen et al., 2001), decision-making, and reward evaluation (Bush et al., 2002; Cohen et al., 2005), and behavioural adjustments (Heilbronner & Hayden, 2016; Sheth et al., 2012). The dACC, however, seems to play a prominent role in aspects of executive functioning that might be specifically targeted by meditative practises, such as emotional processing (Devinsky et al., 1995; To et al., 2017), focused attention (Weissman, 2004), emotional awareness (McRae et al., 2008), and emotional regulation via appraisal (Piretti et al., 2021). In expert meditators, indeed, dACC displays increased connectivity (Brewer et al., 2011) and cortical thickness (Afonso et al., 2020; Grant et al., 2010), which, based on the role of this region in pain processing (Russo & Sheth, 2015), might support the greater pain tolerance compared with naïve subjects (Khoo et al., 2019; Zeidan & Vago, 2016). While these data are suggestive of neuroplastic changes prompted by long-term meditation practice, the present results confirm previous evidence that even brief training sessions are capable of modulating prefrontal activity, although in different regions such as the inferior frontal gyrus (Dodich et al., 2019). Therefore, doubts remain about the prefrontal circuitry mediating the effects of meditative practices. The frequent association between dACC and meditation (particularly mindfulness; Zsadanyi et al., 2021) might reflect the role of this region in regulating the impact of emotions on cognitive processing (Stevens et al., 2011), but other prefrontal regions are likely engaged as well. Neurosynth showed that intrinsic

connectivity from the dACC cluster involves the lateral frontopolar cortex, that recent models associate with a specific facet of monitoring such as evaluating the significance of multiple goals in parallel, as well as switching between them (Mansouri et al., 2017). In particular, a growing neurophysiological and neuroimaging literature suggests that the frontopolar cortex is involved in functions that allow redistributing cognitive resources away from the current task, towards alternative targets for attention (Mansouri et al., 2015), such as cognitive flexibility, parallel monitoring, evaluation, and selection between different goals (Boschin et al., 2015). This interpretation of its role in executive control has been usually considered to explain the engagement of the frontopolar cortex in high-order aspects of decision-making such as pursuing goals in changing environments (e.g., so-called "exploration-exploitation dilemma"; see Brusoni et al., 2020; Laureiro-Martínez et al., 2014, 2015). The present findings additionally suggest that the lateral frontopolar cortex might mediate the effects of meditation, in connection with the dACC, by supporting the ability to maintain and enhance focused attention while avoiding both exterior and internal (e.g., affective) distractions.

Overall, the present findings show that cognitive, physical and meditative trainings induce increased brain activity in close but distinct medial prefrontal areas, in turn connected with specific networks likely mediating their requirements in terms of, respectively, performance monitoring and behavioural adjustments by adMCC and fronto-lateral cortex, implementing control via action selection by pdMCC and sensorimotor areas, as well as focused attention and cognitive flexibility by dACC and lateral frontopolar cortex. These data provide several insights into current debates on the factors shaping the efficacy of brain training, at the behavioural and neural levels.

First, all the present findings involve training-related *activations*, with no evidence for significant decreases of activity after training. This is a key issue in the case of cognitive training, that some studies associated with decreasing, rather than increasing, activation (Clark et al., 2017; Heinzel et al., 2016; Miró-Padilla et al., 2020). The direction of training-related neural changes was suggested to reflect participants' expertise, that is, decreased activation of highly connected and efficient neural mechanisms with long-term practise (Buschkuehl et al., 2014; Kühn et al., 2013; Nęcka et al., 2021; Tang et al., 2015), and increased training-related activation, tracking the readiness of neural mechanisms encoding recent learning traces, in naïve populations (e.g., Dahlin et al., 2008). However, another interpretation of these patterns revolves around task-difficulty. In line with the relationship between higher task-demands and larger increase in functional supply (Lövdén et al., 2010), adaptively adjusting task difficulty to performance was found to result in larger transfer effects and decreased fronto-lateral activity (Flegal et al., 2019). The present evidence of exclusively increased activity, also in association with cognitive training, might thus reflect the prominent use of sub-optimal protocols characterized by pre-defined and/or limited difficulty levels. While guiding the interpretation of the processes underlying training effects, the present data therefore highlight the importance of standardized protocols (Green et al., 2014; Noack et al., 2014; Shipstead et al., 2012) based on adaptive task difficulty (Flegal et al., 2019).

Moreover, the recruitment of specific brain areas underlying multiple facets of executive control highlights the distinctive requirements of different training types, that might reinforce each other, to enhance cognitive functioning and/or counteract cognitive decline, in *combined interventions* tailored to individual needs. It must be considered, indeed, that single training types are not exempt from flaws and implementation issues. For instance, cognitive trainings (particularly those that are not implemented in engaging apps, or even gamified) might be perceived as repetitive and boring, therefore increasing the risk of dropout (Arbiv & Meiran, 2015; Savulich et al., 2017). On the other hand, physical trainings are not suitable for everyone, because pursuing their benefits entails minimum requirements in terms of physical effort that might not be fulfilled by patients and elderly people. Finally, meditation techniques carry a number of preconceptions and scepticism that, as discussed above, are sometimes grounded in the lack of methodological control and structured protocols (Davidson & Kaszniak, 2015).

On this basis, it is increasingly acknowledged that combining multiple training types might outperform their individual effects (Gavelin et al., 2021; Karssemeijer et al., 2017). For instance, meditative body–mind trainings, such as yoga, seem to bring more benefits than physical interventions alone, because of its loading on multiple domains (Govindaraj et al., 2016). Meditation and physical activity are known to support mental health (McGee, 2008; Sharma et al., 2006), both alone and combined (Alderman et al., 2016; Prochilo et al., 2021), acting particularly on stress, anxiety and depression (Desrosiers et al., 2013; Hofmann et al., 2010; López-Torres Hidalgo & DEP-EXERCISE Group, 2019; Philippot et al., 2022). The potential benefits of their combination are therefore not limited to psychiatric (Bendixen & Engedal, 2016; Gum & Cheavens, 2008) and neurological (Forlenza et al., 2016; Maxwell et al., 2019) conditions, and might rather help counteracting the onset of anxiety and mood disorders in physiological ageing (Han, 2021; Subramanyam et al., 2018). The latter might also benefit from combined cognitive and physical training as a promising resource against cognitive decline, while also taking advantage of the high customizability of protocols according to the cognitive skills to be enhanced. Combining a cognitive and a motor task is indeed known to require resources exceeding the mere sum of those demanded by the two tasks in isolation, resulting in the so-called dual-task effects (Plummer & Eskes, 2015). Once translated into a challenging combined protocol, such effects might serve both as screening tool and customizable training procedure (Lemke et al., 2019). Overall, taking advantage of the flexibility and customisation of cognitive training, the boost offered by the integration of physical exercises, and the attentional and emotional control provided by meditative training, appears a promising recipe for improving cognitive reserve and prevent decline.

While providing novel insights into the potential of brain training in healthy and pathological conditions, this study has *limitations*, mainly arising from those of the included studies. First, the considerable heterogeneity of their aims and methods forced a rough categorization in macro-domains regardless of the presence of mixed protocols (e.g., meditative trainings entailing physical effort) and their

duration. Partially related to this issue, the considerable differences in task difficulty across studies, both within and between training types, hampers interpreting the neural correlates of their effects, that have been shown to depend on task demands (e.g., Flegal et al., 2019). Moreover, the lack of a sufficient number of resting-state fMRI studies prevented the extraction of meta-analytic evidence of changes in "intrinsic" brain activity unbiased by the tasks used to detect training effects (see Tables 1–3 in Supplementary Materials for details on the tasks). Importantly, however, all the modelled activation coordinates were reported as related to the effects of training, therefore transcending the potential confound represented by the tasks used to elicit them. It should also be noted that meditative protocols might be more susceptible to low compliance and adherence to treatment compared with cognitive and physical training. The large variability of the neurocognitive measures reported by single studies represents another weakness of this literature, limiting the comparative assessment and interpretation of training effects on cognitive functioning. For instance, even if meditative training had a significant effect on cognitive functioning, it would not be possible to detect it because of the lack of a sufficient number of studies reporting neurocognitive outcome variables. Most of these limitations point to *standardized protocols*, concerning both neurocognitive (Weintraub et al., 2009, 2018) and neuroimaging (Nigri et al., 2022) data, as a necessary step forward for the field enabling more robust findings, particularly concerning crucial issues such as the degree of near- and far-transfer (Simons et al., 2016).

Despite these limitations, the present findings provide novel insights into the development of intervention protocols based on non-invasive and customizable resources with considerable translational implications. Further research in this field might take advantage of the present evidence on the outcomes of different training types, for example, by testing their combination, or by tailoring protocols to individual abilities and needs, both in healthy and pathological populations. For instance, cognitive training might be combined with physical or meditative training depending on participants' motor abilities, and/or on their need to pursue cardiorespiratory fitness versus anxiety relief. Moreover, our results may also pave the way for advanced protocols combining brain training and state-of-the-art neurostimulation techniques, such as high-definition tES of the posterior fronto-medial cortex (Downar et al., 2016), that has been recently shown to modulate multiple facets of cognitive control (Mattavelli et al., 2022). In this case, training-specific neurocognitive effects might be enhanced via brain-stimulation applied on target regions identified based on training type (e.g., SMA or dACC for physical or meditative training, respectively), or even on individual targeting though task-related fMRI.

5 | CONCLUSIONS

A meta-analysis of previously published fMRI data showed that the effects of cognitive, physical and meditative training have been consistently associated with increased brain activity in the anterior dorsal mid-cingulate cortex, pre-SMA, and dACC, likely supporting executive control in terms of, respectively, performance monitoring, action control, and attentional control. The training-related engagement of distinct clusters within a sector of the fronto-medial cortex that is known to mediate feedback-based learning highlights the potential of combined interventions that might jointly boost its level of activation. All the observed clusters were indeed found to increase their activity with training, which provides novel cues into the different processes underlying short- and long-term practice. Alongside significant evidence on the neural effect of all the assessed training types, and on the beneficial effects of cognitive and physical protocols on cognitive functioning, the present study highlighted critical shortcomings in this research field, mainly revolving around the lack of standardized neurocognitive and neuroimaging protocols, and of pre-post training behavioural assessments. Notwithstanding these limitations, the present findings provide novel insights into the effects of brain training, at the behavioural and neural levels, that might help driving this field towards structured rehabilitation protocols.

AUTHOR CONTRIBUTIONS

Sara Lo Presti, Claudia Gianelli, and Nicola Canessa: Study concept and design. Sara Lo Presti and Sara Origlia: Data collection. Sara Origlia and Nicola Canessa: Statistical analyses. Sara Lo Presti, Sara Origlia, Claudia Gianelli, and Nicola Canessa: Interpretation of findings. Sara Lo Presti and Nicola Canessa: Manuscript drafting. Nicola Canessa, Sara Origlia, and Claudia Gianelli: Manuscript review and editing. All authors approved final version for publication.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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