Impact of Cognitive Training on Metacognitive Abilities: A Multilevel Meta-Analysis of Interventional Efficacy and Contributing Factors

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***Abstract*:** Metacognition, a higher-order cognitive function, involves the evaluation and regulation of one's cognitive processes. Strong metacognitive skills enable individuals to recognize and adapt to variations in task performance, enhancing overall behavioral output. This study focuses on cognitive intervention as a potent tool for augmenting metacognition. We acknowledge that the impact of various cognitive interventions on metacognition is not uniform. Our systematic exploration of intervention effects and contributing factors aids in decoding their operational mechanisms, offering theoretical backing for future metacognitive training. Employing meta-analysis techniques, we assessed metacognitive efficiency, bias, sensitivity, and scores via established assessment tools. We examined the moderating influences of training type, participant age, intervention duration, and feedback. Our analysis included 46 articles, encompassing 83 effect sizes and 5618 participants. Utilizing R 4.2.3 for data analysis, we found significant intervention effects on overall metacognition and on individual outcome variables. The overall effect size of cognitive training on metacognition was moderate to high (g=0.585). Specifically, intervention effects on scale scores and metacognitive efficiency reached medium to large effect sizes (scale scores: g=0.627, metacognitive efficiency: g=0.619), while intervention effects on metacognitive bias and metacognitive sensitivity were small to medium (metacognitive bias: g=0.490, metacognitive sensitivity: g=0.327). Moderation analysis indicated that training type and feedback significantly influenced cognitive training effects on metacognition, while intervention duration and participant age did not. Our findings support the notion that cognitive training can enhance metacognitive abilities, particularly in efficiency, bias, and scores, addressing discrepancies in prior research. This contributes to methodological advancements, broadens intervention scopes, and provides practical guidelines for improving metacognitive skills.

***Keywords*:** cognitive training, metacognition, intervention, moderating effects, meta-analysis

1 INTRODUCTION

The term “metacognition” was coined by the American psychologist John Flavell in the 1970s (Flavell, 1979), marking the genesis of a critical field in psychological research. Over the past four decades, researchers have conducted extensive studies on metacognition, shedding light on the mechanisms by which individuals monitor and regulate their own cognitive processes. Strong metacognitive abilities enable individuals to quickly detect fluctuations in their behavioral performance and adjust their confidence levels appropriately, thus optimizing their behavioral outcomes. Conversely, a deficiency in metacognitive abilities can lead to individuals making biased judgments about their own behavior, affecting the effective regulation of their self-awareness activities.

In recent years, the focus has broadened to the development and plasticity of metacognitive abilities from an interdisciplinary perspective (Fleur et al., 2021). Cognitive intervention has emerged as a promising avenue for enhancing metacognitive functions. Understanding the influence of diverse cognitive training approaches on metacognition, and the variables modulating their success, is of paramount importance. This study conducts a meta-analysis to systematically assess the impacts of varying cognitive training types on metacognition, exploring the factors that may moderate the efficacy of these interventions.

1.1 Definition and Measurement of Metacognition

Metacognition encompasses both the knowledge of and regulation over one’s cognitive processes, as initially described by Flavell (Flavell, 1979). It plays a vital role in learning and task performance, enabling individuals to oversee and direct their cognitive strategies (Pintrich, 2010). The so-called cognition refers to the knowledge structure that people use for assessment or decision-making, while metacognition is the higher-order process that controls the existing knowledge structure (Cho & Linderman, 2019). Essentially, metacognition, as a regulatory activity, is realized through two fundamental processes: monitoring and control. The former involves individuals acquiring information about the progress and effectiveness of cognitive activities, while the latter involves individuals planning and adjusting the process of activities. Therefore, in various educational contexts, high-achieving students often exhibit superior metacognitive abilities compared to their counterparts (Desoete et al., 2001; Veenman et al., 2005).

Metacognition, as a characteristic that varies among individuals, it is better to establish consistent and comparable measures across different cognitive domains. In this study, we approach this from two perspectives: behavioral tasks and subjective assessments. In behavioral tasks, our focus is on three behavioral indicators—Metacognitive Sensitivity, Metacognitive Bias, and Metacognitive Efficiency. In subjective assessments, individuals’ metacognitive scores are obtained through self-report questionnaires. Specifically, Metacognitive Sensitivity, also known as Metacognitive Accuracy, Type-2 Task Sensitivity, Discrimination, etc., represents an individual’s ability to differentiate between correct and incorrect self-judgments. Particularly in discrimination tasks, individuals with high Metacognitive Sensitivity demonstrate that their confidence ratings can effectively predict response accuracy; that is, higher confidence is associated with correct responses and vice versa (Galvin et al., 2003; Maniscalco & Lau, 2012). Metacognitive Bias refers to the difference in individuals’ subjective confidence while maintaining consistent performance in the basic task. It can also be understood as Type-2 task bias, indicating over- or under-confidence

(Fleming & Lau, 2014). On the other hand, Metacognitive Efficiency refers to the level of metacognitive sensitivity exhibited by participants at a given task performance level (Bang et al., 2017). As for self-report questionnaire scores, most studies commonly utilize metacognitive scales such as the Metacognitive Awareness Inventory (MAI) (Schraw & Dennison, 1994) or employ metacognitive interviews to assess individuals' metacognitive abilities following cognitive training. These approaches are instrumental in deriving comprehensive metacognitive profiles.

1.2 Cognitive Intervention and Metacognition

Recent evidence highlights the malleability of metacognitive abilities. At the behavioral level, cross-sectional studies have found that groups with long-term meditation experience exhibit better performance in self-reflection, monitoring emotional states, and attention (Fox et al., 2012). Yet, the latest large-scale intervention study, spanning 9 months, suggests that mindfulness-based psychological training does not impact metacognitive performance in perceptual tasks (Böckler & Singer, 2022). On the neural level, differences in the functionality and structure of relevant brain regions correlate with individual differences in metacognitive levels (Fleming et al., 2010). For instance, the prefrontal cortex and posterior parietal cortex play crucial roles in metacognitive processes, particularly in perceptual and memory task-related metacognitive processes (Fleming et al., 2014; Morales et al., 2018; Ye et al., 2019; Ye et al., 2018); signals within the prefrontal cortex further divide metacognition into monitoring subsystems and control subsystems (Qiu et al., 2018); and region-specific involvement of the frontoparietal control network participates in metacognitive monitoring and regulation (Goupil & Kouider, 2019). These findings collectively suggest that, whether in the domain of behavioral intervention or neural foundations, metacognition exhibits promising plasticity potential.

Building on this premise, we propose an intervention model for metacognition through cognitive training. Nelson and Narens (1990) proposed a dual-layered structural model of cognition and metacognition. In this model, they established a cyclic hierarchical relationship between cognition and metacognition by distinguishing two levels: the object-level and the meta-level (Nelson, 1990). According to Nelson and Narens' definition, the object-level includes cognitive functions relevant to tasks, such as object recognition, representation, and encoding. The meta-level is responsible for processing information from the object-level and regulating the functions of the object-level from top to bottom. Therefore, the meta-level represents an individual's metacognitive functions, which inherently encompass cognitive knowledge and cognitive management (Cunningham et al., 2016). These two levels are connected through monitoring and control signals. During the learning process, information constantly flows between these two levels. Monitoring involves the meta-level being informed of the processes occurring at the object-level, while control refers to the meta-level adjusting and aligning the processes at the object-level to achieve specific goals and mechanisms (Nonose et al., 2012). This dynamic interaction facilitates a continuous exchange of information during the learning process. Our proposition is that by strengthening the cognitive processes at the object-level through targeted intervention, we can indirectly enhance the meta-level. This, in turn, bolsters overall metacognitive capabilities.

Over the past two decades, research on metacognition through cognitive intervention has consistently demonstrated positive outcomes. However, the effectiveness of different types of cognitive intervention on metacognition varies. In a longitudinal study spanning two years, metacognitive skills training for mathematical task-solving abilities was conducted through classroom instruction with 66 children in the third and fourth grades. The results indicated improvements in both metacognitive abilities and mathematical skills before and after training, with children in the metacognitive group outperforming the control group (Desoete, 2009). A study in 2014 employed teaching strategies based on reading comprehension and listening comprehension to intervene in children's metacognition, and both approaches yielded significant results (Carretti et al., 2014). Mindfulness research has suggested that training enhances accurate reflection on self-awareness and experiential states, resulting in a significant improvement in metacognitive abilities (Baird et al., 2014). An eight-day adaptive training significantly improved participants' metacognitive efficiency and demonstrated transferability to untrained stimulus types and task types (Carpenter et al., 2019). However, some studies have reported ineffective outcomes in metacognitive improvement (Böckler & Singer, 2022; Cogliano et al., 2021; Zepeda et al., 2015). In a study where participants underwent three days of adaptive visual perceptual training, there was no observed improvement in metacognitive accuracy (Chen et al., 2019). One study exploring metacognitive efficiency before and after two meditation training programs found that the mental monitoring group maintained stable metacognitive efficiency, while the body scanning group exhibited a significant reduction in metacognitive efficiency post-training (Schmidt et al., 2019).

Despite mixed results, the prevailing evidence supports cognitive intervention as a viable method for fostering metacognitive abilities. This study will therefore investigate the effects of various cognitive intervention approaches on metacognition, considering the methodologies employed in these interventions.

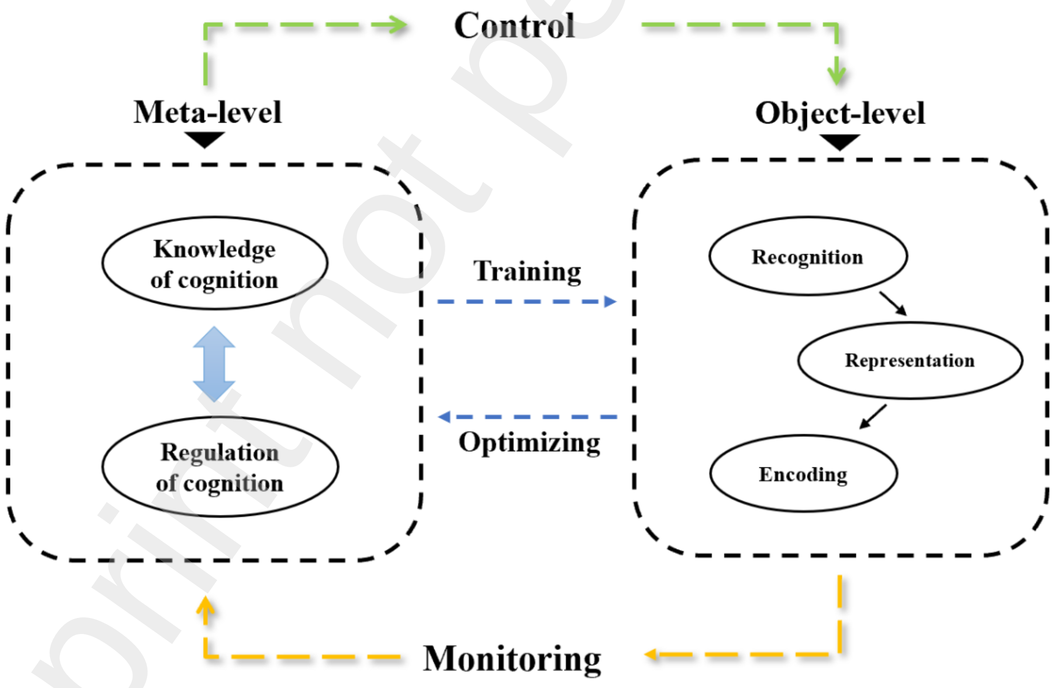

Figure 1: Metacognitive Enhancement Model. Information between the object-level and the meta level achieves cyclic flow through monitoring and control. By training cognitive functions at the object-level, individual metacognitive abilities at the meta-level can be optimized, thereby enhancing the overall cyclic process of information flow. Adapted from Nelson and Narens' metacognitive cognitive psychology model.

1.3 Potential Moderators

Based on the principles of Evidence-Based Medicine, we focus on the research question of intervention from four aspects: Population, Intervention, Comparison, and Outcome (PICO) (Akobeng, 2005). Integrating existing research, we hypothesize that participant age, training duration, and feedback type may substantially influence the efficacy of these interventions on metacognitive outcomes.

1.3.1 Participant Age

Previous studies have demonstrated that even during early childhood, children exhibit certain levels of metacognitive abilities. Around the age of one, children demonstrate the capacity to monitor and regulate their cognitive abilities (Goupil et al., 2016), and by the age of five, they become aware of information they do not know (Filevich et al., 2020). As children progress into the school-age stage, metacognitive abilities flourish, concomitant with the continual expansion of individual knowledge structures and the emergence of cross-domain learning. This development gradually manifests characteristics indicative of domain generality (Vo et al., 2014). Therefore, it prompts the question: is the efficacy of cognitive training interventions on metacognition subject to the moderating influence of age? In a meta-analysis investigating the enhancement of metacognitive monitoring accuracy through strategy teaching, distinct participant ages—children, adolescents, and adults—were considered as moderating variables, revealing statistically significant moderating effects (Gutierrez de Blume, 2022). Another meta-analysis exploring the impact of physical activity interventions on the cognitive and metacognitive functions of children highlighted a significant positive correlation between intervention effects and age (Álvarez-Bueno et al., 2017). This leads us to surmise that the effects of cognitive intervention on metacognition may indeed be contingent upon age.

1.3.2 Training Duration

The length of cognitive intervention programs varies, and its relation to training outcomes merits investigation. Does the duration of training have an impact on its effectiveness? Previous research suggests that in the training of children's psychological theories, the effectiveness of training increases with the prolongation of training time (Hofmann et al., 2016). In a meta-analysis exploring mindfulness training, a significant positive correlation was found between the effectiveness of mindfulness training and the training duration (Zenner et al., 2014). Rochat et al. (2018) pointed out that the efficacy of metacognitive therapy in improving mental health is significantly modulated by the treatment duration. However, in a recent study investigating the immediate and sustained effects of metacognitive training, no significant moderating effect of training duration on its effectiveness was observed (Penney et al., 2022). These mixed results warrant further exploration of training duration as a moderator of cognitive intervention's impact on metacognition.

1.3.3 Feedback Type

The role of feedback in enhancing metacognitive abilities is increasingly documented. In a study involving three independent experiments to explore the evaluation of global self-performance evaluations (SPEs) based on local decision confidence, the results indicated that in the absence of feedback, despite maintaining stable objective performance, self-performance evaluations were systematically underestimated compared to the feedback group. This suggests that timely and effective feedback can enhance participants' confidence assessments, aiding in the construction of

SPEs (Rouault et al., 2019). Cortese et al. (2016)utilized neurofeedback methods, demonstrating the bidirectional manipulation of perception and confidence without altering task performance. This provided robust evidence supporting the view that confidence emerges as a metacognitive process at later stages. In a recent 2022 study, researchers employed sequential feedback to investigate the impact of feedback on perceptual decision-making and metacognition through a controlled experiment comparing a feedback group with a no-feedback group. The study found that feedback significantly reduced perceptual and metacognitive bias, influencing participants' response strategies (Haddara & Rahnev, 2022). In contrast, some studies have not observed significant effects of feedback (Goldhacker et al., 2014; Petrov et al., 2006; Shibata et al., 2009). Therefore, based on the diverse results from these studies, we consider feedback type (yes/no) as a moderating variable and explore its potential regulatory effects on metacognition.

2 METHODS

2.1 Search and Study Selection

We conducted searches for all relevant literature in five databases, namely PubMed, Web of Science, APA PsycArticles, APA PsycInfo, and Psychology and Behavioral Sciences Collection, from the inception of our database up to November 2022. Additionally, a second update was performed in December 2023. The objective of the search was to identify cognitive interventions or training methods that have an impact on individual metacognition. The search keywords primarily included "metacognition", "cognitive", "cognition", "intervention", and "training". The inclusion criteria were as follows: (1) Studies included controlled trials, encompassing both randomized controlled trials and non-randomized controlled trials, to examine changes in metacognition in the intervened population before and after cognitive training. (2) The studies must have employed one or more cognitive training methods. (3) Outcome variables had to include measurements related to metacognitive indicators, including at least metacognitive efficiency, metacognitive sensitivity, metacognitive bias, or assessments through measurement tools such as questionnaires or interviews. (4) If the same study reported multiple independent samples, they were coded separately. The exclusion criteria were as follows: (1) Meta-analyses, reviews, book reviews, reports, or conference abstracts, etc.; (2) Non-English literature; (3) Interventions targeting various disease patients or non-human populations. The literature search keywords and inclusion/exclusion criteria were jointly determined by the first author and the corresponding author. Screening was conducted by the first author, with the second author cross-checking the selections. Any disagreements regarding literature inclusion were resolved through consensus with the corresponding author. Refer to Figure 2 for the literature search and screening process.

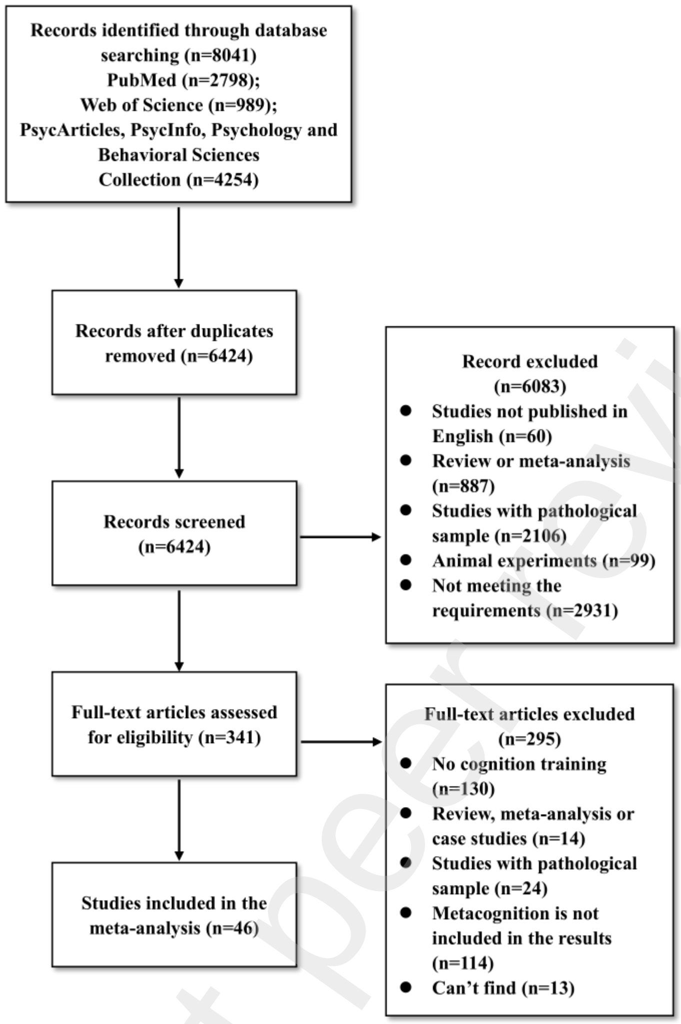

Figure 2. Flowchart of Literature Inclusion and Exclusion Process

2.2 Meta-Analysis Procedure

Meta-analysis was conducted using the metafor package in R version 4.2.2.

2.2.1 Data Collection

Extraction and encoding of the characteristics of each literature and the data included in the analysis. Two researchers initially conducted independent extraction and encoding, resulting in two coding schemes. In cases of inconsistencies between the two coding schemes, after consulting the original literature, a final coding scheme was agreed upon through discussion with the corresponding author. Literature feature coding included: author (year), sample size, gender ratio, participant age, training type, training duration, feedback type, outcome variables, measurement indicators, and more. For specific coding results, please refer to Table 1.

This study focuses on the impact of intervention types on the effectiveness of metacognitive and explores the potential moderating effects of participant age, training duration, and feedback type. According to the experimental methods used in the study, cognitive training is further divided into three types: mindfulness training, strategy intervention, and teaching guidance. Mindfulness training is a deliberate mental training method that focuses attention on the present moment and maintains an accepting attitude toward all present perceptions(Creswell, 2017). Strategy intervention refers to participants completing experimental tasks in the laboratory under the experimenter's guidance using metacognitive training methods such as feedback, recall, and prompts. Teaching guidance primarily occurs in classroom settings, where teachers use specific metacognitive methods to accomplish teaching tasks for the benefit of students. Participant ages were divided into three age ranges: elementary school stage (6-12 years old), middle and high school stage (12-18 years old), and university and above (older than 18 years old). Training durations were categorized into three time periods: one month or more, one week to one month, and less than one week. Feedback types were classified into two categories: with feedback and without feedback.

Based on different calculation methods for metacognition (Fleming & Lau, 2014), this study primarily extracted four categories of outcome variables: (1) Calculation metrics related to metacognitive efficiency, such as Meta-d'/d', Mratio; (2) Calculation metrics related to metacognitive sensitivity, such as Meta-d', AUROC2; (3) Calculation metrics related to metacognitive bias, such as Confidence gap, Criterion c; (4) Scores from scales and questionnaires, such as scores derived from common metacognitive scales (e.g., MAI) and metacognitive interviews, among other methods.

The rules for data extraction are as follows:(1) If a single study includes multiple measurements related to outcome variables, extract and code them separately. (2) When metacognitive scales include both total scores and subscale scores, prioritize extracting the total scores. If only subscale scores are available, extract the subscale scores relevant to metacognitive concepts. Considering that a study with multiple conditions or experiments can potentially introduce bias by giving unequal weight to different effect sizes, for studies with two or more control groups and different outcome measurement methods, we initially assess whether the different conditions reported in the literature align with the focus of our study. If aligned, they were treated as independent studies for effect size calculation.

2.2.2 Model Selection and Effect Size Calculation

In traditional meta-analysis models, it is assumed that effect sizes are independent within each study, typically resulting in the extraction of a single effect size per study. However, the literature in our current study includes multiple independent effect sizes. These arise due to: (1) the use of various tools assessing the same construct; (2) the reporting of multiple outcome variables; and (3) the presentation of similar effect sizes under different temporal conditions (Van den Bussche et al., 2009). Cheung (2014) pointed out effect sizes within the same study should not be presumed independent. Such an assumption can exaggerate the correlation between variables, challenging the foundational premise of independence in traditional meta-analysis (Lipsey & Wilson, 2001). Therefore, the current study employs a Three-level meta-analytic model to address this issue.

The conventional meta-analysis model distinguishes between sampling error (level 1) and between-study error as sources of variance. In contrast, the three-level meta-analytic integrative model further dissects the between-study error into within-study error (level 2) and between-study error (level 3). To be more specific, the distinct advantage of the three-level meta-analytic integrative model compared to its traditional counterpart lies in its consideration of correlations among various effect sizes within the same study during the data analysis process. Furthermore, while the traditional meta-analysis often resorts to averaging or discarding methods to extract effect sizes from the same study, potentially leading to information loss, the three-level meta-analytic integrative model can extract all effect sizes from a study, thereby maximizing information integrity and enhancing statistical efficiency.

The study employs the standardized mean difference Hedge's g, also known as Cohen's d correction, as the effect size for the experimental and control groups, aiming to correct biases introduced by small sample sizes (Hedges, 1984). Effect size evaluation criteria are as follows: 0.2 indicates a small effect size, 0.5 represents a moderate effect size, and 0.8 indicates a large effect size (Kallapiran et al., 2015). To assess the heterogeneity of the studies, likelihood ratio tests are utilized to examine both between-study and within-study heterogeneity (Raudenbush & Bryk, 2002). If evidence suggests the presence of heterogeneity in effect sizes, further adjustment analyses are conducted.

2.2.3 Assessment of Publication Bias and Sensitivity Analysis

Publication bias refers to a bias phenomenon where the literature already published cannot systematically and comprehensively represent the entire body of completed research in a field (Rothstein et al., 2005). It is emphasized here that there is currently no perfect technique for assessing and correcting publication bias (Pham et al., 2001; Stanley, 2017), and existing methods have various limitations and weaknesses (Carter et al., 2019). Considering the suitability of adopting a multilevel meta-analysis approach in this study, a preliminary assessment of publication bias risk will be conducted using a funnel plot and the corrected Egger's regression. This involves evaluating the relationship between effect sizes (gs) and their corresponding standard errors (se) (Egger et al., 1997). In this analysis, the observed values of effect sizes serve as the dependent variable, and the standard errors of effect sizes are added to the regression model of the three-level meta-analysis. A significant slope indicates the presence of publication bias. If publication bias is identified, robust variance estimation will be applied for correction using JASP.

Sensitivity analysis will be performed to test the robustness of the results. The standard selection of literature, data extraction methods, and handling of missing values can all impact the outcomes of a meta-analysis. Therefore, it is essential to conduct sensitivity analysis. In this study, the method used will involve studentized deleted residuals (SDR) to identify and remove outliers, and this will be implemented within the R environment.

2.2.4 Moderators

The heterogeneity test revealed that there might be an influence of moderator variables on the outcome variable of scale scores. Subgroup analysis was employed as one of the most commonly used methods to delve deeper into the sources of heterogeneity and examine how study characteristics might moderate the effect sizes. Specifically, we focused on the moderating influence of training type, training duration, participant demographics, and feedback on the outcomes of metacognitive interventions. Furthermore, an exploration was conducted to assess potential interactions between cognitive training types and other moderating factors, shedding light on the combined impact of these variables within the same type of training.

Table 1. Extracted Information from the Literature

Number	Study	N	Sex	Age	Training type	Training duration	Feedback	Outcome	Metacognitive index
1	Schmidt et al., 2019	13	0.22	17-43	Mindfulness	>1 month	No	Metacognitive Efficiency	Meta-d′/d′
2	Vickery & Dorjee, 2015	71	0.51	7-9	Mindfulness	>1 month	Yes	Score	BRIEF
3	Baird et al., 2014 a	50	0.34	19-21	Mindfulness	1week-1 month	No	Metacognitive Efficiency	Meta-d′/d′
4	Baird et al., 2014 b	50	0.34	19-21	Mindfulness	1week-1 month	No	Metacognitive Efficiency	Meta-d′/d′
5	Böckler & Singer, 2022 a	332	0.41	20-55	Mindfulness	>1 month	No	Metacognitive Sensitivity	AUROC2
6	Böckler & Singer, 2022 b	332	0.41	20-55	Mindfulness	>1 month	No	Metacognitive Sensitivity	AUROC2
7	Wagener, 2013 a	83	NA	NA	Mindfulness	>1 month	No	Score	MAI KC
8	Wagener, 2013 b	83	NA	NA	Mindfulness	>1 month	No	Score	MAI RC
9	Carpenter et al., 2019 a	58	0.43	20-64	Adaptive	1week-1 month	Yes	Metacognitive Efficiency	Log(meta-d'/d')
10	Carpenter et al., 2019 b	58	0.43	20-64	Adaptive	1week-1 month	Yes	Metacognitive Bias	Confidence gap
11	Bang et al., 2019 a	202	NA	NA	Adaptive	1week-1 month	No	Metacognitive Efficiency	Meta-d′/d′
12	Bang et al., 2019 b	202	NA	NA	Adaptive	<1 week	No	Metacognitive Efficiency	Mratio
13	Bang et al., 2019 c	202	NA	NA	Adaptive	1week-1 month	Yes	Metacognitive Efficiency	Mratio
14	Chen et al., 2019 a	40	0.35	19-30	Adaptive	<1 week	No	Metacognitive Sensitivity	AUROC2
15	Chen et al., 2019 b	40	0.3	19-30	Adaptive	<1 week	No	Metacognitive Sensitivity	AUROC2
16	Rouy et al., 2022 a	50	0.44	19-59	Adaptive	1week-1 month	Yes	Metacognitive Efficiency	Log(meta-d'/d')
17	Rouy et al., 2022 b	50	0.44	19-59	Adaptive	1week-1 month	Yes	Metacognitive Bias	Confidence gap
18	Haddara & Rahnev, 2022 a	443	NA	NA	Adaptive	<1 week	Yes	Metacognitive Sensitivity	Meta-d′
19	Haddara & Rahnev, 2022 b	443	NA	NA	Adaptive	<1 week	Yes	Metacognitive Bias	Criterion c
20	Haddara & Rahnev, 2022 c	60	NA	NA	Adaptive	<1 week	Yes	Metacognitive Sensitivity	Meta-d′
21	Cetin et al., 2014	51	0.55	19-29	Teaching	>1 month	Yes	Score	MAI
22	Engeler & Gilbert 2020 a	106	0.4	20-71	Strategy	<1 week	Yes	Metacognitive Bias	NA
23	Engeler & Gilbert 2020 b	106	0.4	20-71	Strategy	<1 week	Yes	Metacognitive Bias	NA
24	Cogliano et al., 2021	103	0.25	18-52	Teaching	>1 month	Yes	Score	MAI
25	Saadawi et al., 2010 a	23	NA	NA	Strategy	<1 week	Yes	Metacognitive Bias	Confidence gap
26	Saadawi et al., 2010 b	23	NA	NA	Strategy	<1 week	Yes	Metacognitive Sensitivity	Meta-d′
27	Desoete et al., 2003	107	0.52	8-8.5	Strategy	1week-1 month	No	Score	EPA2000
28	Desoete, 2009 a	66	NA	NA	Strategy	1week-1 month	No	Score	EPA2000
29	Desoete, 2009 b	66	NA	NA	Strategy	1week-1 month	No	Score	EPA2000
30	Schuster et al., 2020 a	78	0.5	11-16	Teaching	>1 month	No	Score	MST-E
31	Schuster et al., 2020 b	78	0.5	11-16	Teaching	>1 month	No	Score	MST-T
32	Kramarski et al., 1997	68	0.56	12-14	Strategy	>1 month	No	Score	Metacognitive interview
33	Hargrove et al., 2015	118	0.5	NA	Teaching	>1 month	No	Score	MAI
34	saks, 2018 a	56	0.16	16-23	Strategy	>1 month	Yes	Score	MSLQ
35	saks, 2018 b	56	0.16	16-23	Strategy	>1 month	Yes	Score	LLS
36	Andersen et al., 2019	103	0.52	6-9	Teaching	>1 month	No	Score	BRIEF
37	Graham & Wong, 1993 a	90	0.58	9-13	Strategy	1week-1 month	No	Score	Metacognitive Questionnaires
38	Graham & Wong, 1993 b	90	0.58	9-13	Strategy	1week-1 month	No	Score	Metacognitive Questionnaires
39	Zepeda et al., 2015 a	46	0.72	NA	Teaching	>1 month	No	Score	MAI
40	Zepeda et al., 2015 b	46	0.72	NA	Teaching	>1 month	No	Metacognitive Sensitivity	Meta-d′
41	Carretti et al., 2014 a	130	0.56	9-11	Teaching	>1 month	No	Score	Metacognitive Questionnaires
42	Carretti et al., 2014 b	130	0.56	9-11	Teaching	>1 month	No	Score	Metacognitive Questionnaires
43	Langdon et al., 2019 a	34	0.8	>18	Teaching	>1 month	No	Score	MAI-KC
44	Langdon et al., 2019 b	34	0.8	>18	Teaching	>1 month	No	Score	MAI-RC
45	Johnson et al., 2010 a	267	0.42	16-23	Teaching	1week-1 month	No	Score	MCSI
46	Johnson et al., 2010 b	267	0.42	16-23	Teaching	1week-1 month	No	Score	MCSI
47	Teng, 2022 a	100	0.35	18-20	Teaching	>1 month	Yes	Score	MAI
48	Teng, 2022 b	100	0.35	18-20	Teaching	>1 month	Yes	Score	MAI
49	Persky & Dinsmore, 2019	158	0.35	M=22	Teaching	>1 month	No	Metacognitive Bias	Confidence gap
50	Pennequin et al., 2010	32	0.06	68-90	Strategy	>1 month	Yes	Score	Metacognitive Questionnaires
51	Cornoldi et al., 2015	135	0.41	8-10	Teaching	>1 month	Yes	Score	Metacognitive Questionnaires
52	Doyle, 2022	95	NA	19-43	Teaching	>1 month	No	Score	MAI
53	Abed, 2021	358	0.52	20-82	Strategy	<1 week	Yes	Score	assessment discrepancy
54	Murray, 2008 a	77	0.39	NA	Strategy	>1 month	Yes	Score	SRLSIS
55	Murray, 2008 b	77	0.39	NA	Strategy	>1 month	Yes	Score	SRLSIS
56	Marulis, 2015 a	83	0.59	4-6	Strategy	1week-1 month	No	Score	McKI
57	Marulis, 2015 b	83	0.59	4-6	Strategy	1week-1 month	No	Score	McK

Continued

Number	Study	N	Sex	Age	Training type	Training duration	Feedback	Outcome	Metacognitive index
58	Martel, 2011 a	124	0.3	19-37	Teaching	>1 month	No	Score	SRLI
59	Martel, 2011 b	124	0.3	19-37	Teaching	>1 month	No	Score	SRLI
60	Martel, 2011 c	124	0.3	19-37	Teaching	>1 month	No	Score	SRLI
61	Liu, 1999 a	249	NA	19-21	Teaching	>1 month	No	Score	MAI
62	Liu, 1999 b	249	NA	19-21	Teaching	>1 month	No	Score	MAI
63	Liu, 1999 c	249	NA	19-21	Teaching	>1 month	No	Score	MAI
64	Liu, 1999 d	249	NA	19-21	Teaching	>1 month	No	Score	MAI
65	Liu, 1999 e	249	NA	19-21	Teaching	>1 month	No	Score	MAI
66	Liu, 1999 f	249	NA	19-21	Teaching	>1 month	No	Score	MAI
67	Liu, 1999 g	249	NA	19-21	Teaching	>1 month	No	Score	MAI
68	Mullick-Martinez, 2021 a	43	NA	NA	Strategy	>1 month	Yes	Score	Jr. MAI-KC
69	Mullick-Martinez, 2021 b	43	NA	NA	Strategy	>1 month	Yes	Score	Jr. MAI-RC
70	Li et al., 2022	96	0.14	20-22	Strategy	>1 month	Yes	Score	MAI
71	Cano et al., 2014 a	72	0.49	13-15	Teaching	1week-1 month	Yes	Score	Jr. MAI-KC
72	Cano et al., 2014 b	72	0.49	13-15	Teaching	1week-1 month	No	Score	Jr. MAI-KC
73	Chen et al., 2022 a	47	0.57	5-7	Strategy	>1 month	Yes	Score	MKI Questionnaire
74	Chen et al., 2022 b	47	0.57	5-7	Strategy	>1 month	Yes	Score	Metacognitive Monitoring Task
75	Chen et al., 2022 c	47	0.57	5-7	Strategy	>1 month	Yes	Score	Metacognitive Skill Task
76	Rezai et al., 2023	90	0	15-25	Strategy	>1 month	Yes	Score	MALQ
77	Breland et al., 2023	443	0.4	NA	Strategy	>1 month	Yes	Score	MAI
78	Endalamaw et al., 2023 a	84	0.76	18-24	Teaching	>1 month	Yes	Score	MARS-EM
79	Endalamaw et al., 2023 b	84	0.76	18-24	Teaching	>1 month	Yes	Score	MARS-EM
80	Endalamaw et al., 2023 c	84	0.76	18-24	Teaching	>1 month	Yes	Score	MARS-EM
81	Biwer et al., 2023	258	0.3	21-25	Strategy	>1 month	Yes	Score	Effectiveness ratings
82	Martelletti et al., 2023	117	NA	NA	Teaching	1week-1 month	Yes	Score	Test score
83	Cale et al., 2023	109	0.17	21-25	Teaching	>1 month	No	Score	MAI

Note. The lowercase letter after the name represent different independent effect sizes from the same study; Sex refers to the proportion of males.

3 RESULTS

3.1 Characteristics of studies

After the initial search, a total of 8,041 articles were retrieved, with 2,798 from PubMed, 989 from Web of Science, and 4,254 from APA PsycArticles, APA PsycInfo, and Psychology and Behavioral Sciences Collection combined. Following deduplication and a stepwise screening process, 46 articles meeting the criteria were ultimately included, comprising 83 independent effect sizes with a total sample size of 5,618 (Figure 2).

Five studies employed mindfulness training, involving 549 participants (9.8%). Strategy interventions were used in 22 studies, with a participant pool of 2896 (51.5%), while 19 studies utilized instructional guidance, engaging 2173 individuals (38.7%). Regarding participant demographics, the majority were university students and children/adolescents. Specifically, nine studies focused on elementary school children aged 6-12 years (785 participants, *13.9%*), six studies involved middle/high school students aged 12-18 years (471 participants, *8.4%*), and 31 studies concentrated on individuals in university and above (age > 18), totaling 4362 participants (*77.6*%).. The studies also varied in their use of feedback. Half of the studies, totaling 24, integrated feedback mechanisms, covering 3175 participants (56.5%). The remaining 24 studies, with 2717 participants (48.4%), did not employ feedback strategies. Finally, the duration of the training programs was a key variable. The majority of studies, 30 in total, had programs extending over one month, encompassing 3426 participants (*61.6*%). Eleven studies had interventions lasting between one week and one month (1162 participants, *20.7%*), and six studies featured programs shorter than one week (1232 participants, *21.9%*). (Refer to Figure 3).

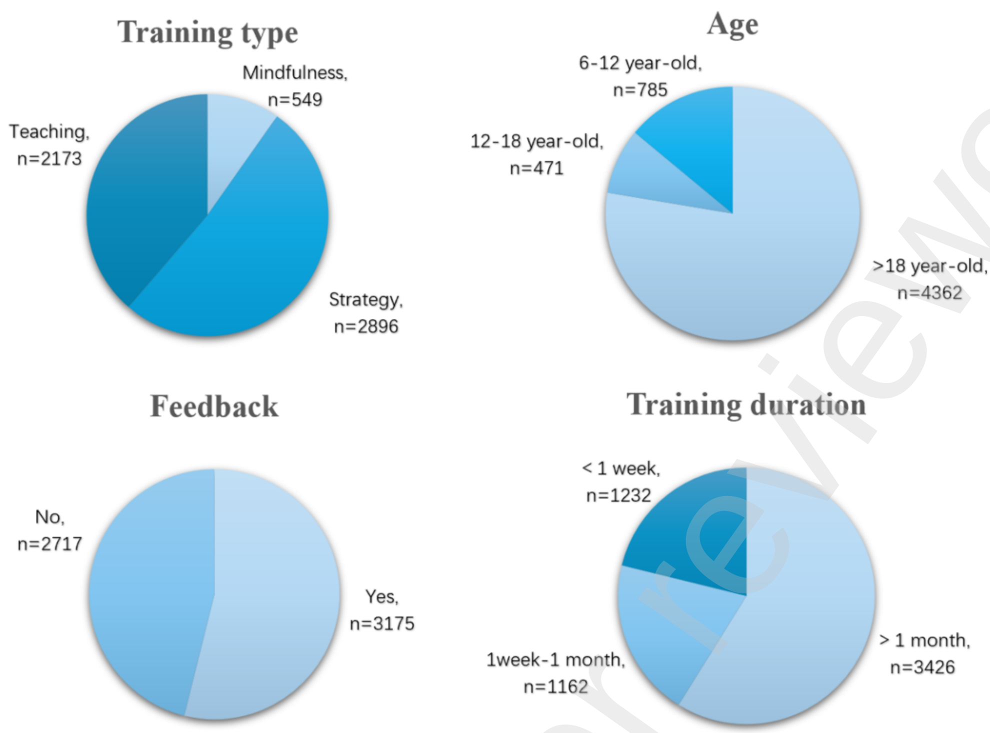

Figure 3. Distribution of sample sizes across various moderator variables.

3.2 Effect Size Estimation and Heterogeneity Test

Considering the varied measurement and calculation methods for metacognition in different studies, an overall effect analysis and effect size analysis for each outcome variable were conducted separately for the included literature (Table 2).

In this study, a random-effects model was employed to examine the main effect of cognitive training on metacognition and the effects on each outcome variable. The Knapp and Hartung (2003) adjustment was applied to ensure a reasonable number of statistically significant study results. The results revealed a total effect size of 0.585 for cognitive training intervention on metacognition, with a standard deviation of 0.083, indicating a moderate to large effect. The overall effect was statistically significant ($t(82) = 7.053$, $p < .001$). Regarding the intervention effects on each outcome variable, all reached statistically significant levels except for metacognitive sensitivity. Specifically, the interventions for scale scores, metacognitive efficiency, and metacognitive bias achieved effect sizes close to moderate or moderate to large levels (Score: $g = 0.627$, Metacognitive Efficiency: $g = 0.619$, Metacognitive Bias: $g = 0.490$), while the intervention effect size for metacognitive sensitivity was relatively smaller ($g = 0.327$). This indicates that cognitive training significantly enhances participants' metacognitive levels, especially concerning scale score measurements and indicators of metacognitive efficiency and metacognitive bias.

Additionally, a one-sided log-likelihood ratio test was used to determine the significance of within-study variance (level 2) and between-study variance (level 3). In this test, the original three-level model's fit was compared with the fit of the remaining two-level models under the condition of manually fixing the variance of level 2 or level 3 to zero, determining whether it is necessary to consider within-study or between-study variance in the meta-analysis model. The results indicated a significant difference in between-study error (level 3) at the overall level ($p < 0.01$). Among the outcome variables, significant between-study error (level 3) was only found in the scale score variable ($p < 0.01$). These results suggest significant between-study heterogeneity, indicating the presence of moderator variables influencing the relationship between different studies and the effectiveness of metacognitive interventions. Therefore, this study will continue to analyze the impact of moderator variables on the relationship between them in studies using scale scores as outcome variables to explain the variation in level 3 variance.

Table 2. Cognitive intervention on metacognition: effect sizes and heterogeneity tests

Outcome Variables	*#studies*	*#ES*	*Mean g(SE)*	*95%CI*	*t-Statistic*	*p-Value*	*Variance level 2*	*Variance level 3*
Overall	46	83	0.585(0.083)	[0.420,0.750]	7.053	<.001***	0.000	0.174**
Score	35	60	0.627(0.112)	[0.403,0.851]	5.595	<.001***	0.018	0.275**
ME	5	8	0.619(0.190)	[0.170,1.068]	3.258	0.014*	0.000	0.002
MS	5	8	0.327(0.162)	[-0.056,0.710]	2.020	0.083	0.000	0.000
MB	6	7	0.490(0.166)	［0.083,0.897］	2.945	0.026*	0.000	0.000

Note. #studies = number of independent studies; # ES = number of effect sizes; Mean g = mean effect size; CI = confidence interval; Score: scale scores (e.g., questionnaires, interviews); ME: metacognitive efficiency; MS: metacognitive sensitivity; MB: metacognitive bias.

Variance level 2: Variance between the effect sizes from the same study.

Variance level 3: Variance between studies.

∗ $p < 0.05$; ∗∗ $p < 0.01$; ∗∗∗ $p < 0.001$.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Schmidt et al., 2019	0.697	0.392	0.154	-0.071	1.465	1.779	0.075
Vickery & Dorjee, 2015	0.232	0.246	0.061	-0.250	0.715	0.944	0.345
Baird et al., 2014 a	0.139	0.279	0.078	-0.408	0.686	0.498	0.618
Baird et al., 2014 b	0.418	0.282	0.079	-0.134	0.970	1.484	0.138
B?ckler & Singer, 2022 a	0.295	0.163	0.027	-0.025	0.614	1.805	0.071
B?ckler & Singer, 2022 b	0.142	0.161	0.026	-0.173	0.457	0.885	0.376
Wagener, 2013 a	0.156	0.229	0.053	-0.294	0.605	0.678	0.498
Wagener, 2013 b	0.089	0.228	0.052	-0.358	0.537	0.391	0.696
Carpenter et al., 2019 a	0.650	0.266	0.071	0.129	1.172	2.444	0.015
Carpenter et al., 2019 b	0.900	0.272	0.074	0.366	1.433	3.305	0.001
Bang et al., 2019 a	1.087	0.424	0.180	0.255	1.918	2.562	0.010
Bang et al., 2019 b	0.597	0.147	0.022	0.309	0.884	4.063	0.000
Bang et al., 2019 c	1.896	0.480	0.230	0.955	2.836	3.951	0.000
Chen et al., 2019 a	0.682	0.319	0.102	0.056	1.307	2.136	0.033
Chen et al., 2019 b	0.182	0.311	0.096	-0.427	0.791	0.587	0.557
Rouy et al., 2022 a	0.192	0.291	0.084	-0.377	0.762	0.662	0.508
Rouy et al., 2022 b	1.016	0.307	0.094	0.414	1.619	3.308	0.001
Haddara & Rahnev, 2022 a	0.129	0.101	0.010	-0.068	0.326	1.282	0.200
Haddara & Rahnev, 2022 b	0.213	0.101	0.010	0.015	0.410	2.110	0.035
Haddara & Rahnev, 2022 c	0.381	0.257	0.066	-0.123	0.885	1.483	0.138
Cetin et al., 2014	-0.021	0.276	0.076	-0.561	0.520	-0.076	0.940
Engeler & Gilbert, 2020 a	0.775	0.191	0.037	0.400	1.150	4.049	0.000
Engeler & Gilbert, 2020 b	0.566	0.188	0.035	0.197	0.935	3.009	0.003
Cogliano et al., 2021	0.401	0.198	0.039	0.013	0.789	2.028	0.043
Saadawi et al., 2010 a	0.197	0.403	0.163	-0.594	0.987	0.488	0.626
Saadawi et al., 2010 b	0.937	0.425	0.181	0.103	1.770	2.202	0.028
Desoete et al., 2003	0.979	0.205	0.042	0.577	1.381	4.772	0.000
Desoete, 2009 a	1.609	0.281	0.079	1.059	2.159	5.732	0.000
Desoete, 2009 b	0.474	0.247	0.061	-0.010	0.957	1.920	0.055
Schuster et al., 2020 a	0.127	0.224	0.050	-0.313	0.567	0.568	0.570
Schuster et al., 2020 b	-0.054	0.224	0.050	-0.493	0.386	-0.239	0.811
Kramarski et al., 1997	1.082	0.257	0.066	0.578	1.586	4.208	0.000
Hargrove et al., 2015	0.213	0.211	0.044	-0.200	0.626	1.012	0.312
saks, 2018 a	0.983	0.279	0.078	0.436	1.531	3.519	0.000
saks, 2018 b	0.496	0.268	0.072	-0.029	1.021	1.853	0.064
Andersen et al., 2019	0.172	0.204	0.042	-0.228	0.572	0.843	0.399
Graham & Wong, 1993 a	0.679	0.262	0.069	0.165	1.193	2.588	0.010
Graham & Wong, 1993 b	0.679	0.262	0.069	0.165	1.193	2.588	0.010
Zepeda et al., 2015 a	0.256	0.291	0.085	-0.315	0.826	0.878	0.380
Zepeda et al., 2015 b	0.638	0.304	0.092	0.042	1.234	2.099	0.036
Carretti et al., 2014 a	0.792	0.206	0.042	0.390	1.195	3.855	0.000
Carretti et al., 2014 b	0.644	0.234	0.055	0.185	1.102	2.751	0.006
Langdon et al., 2019 a	0.136	0.240	0.058	-0.334	0.607	0.567	0.571
Langdon et al., 2019 b	0.295	0.241	0.058	-0.178	0.767	1.223	0.221
Johnson et al., 2010 a	0.286	0.087	0.008	0.116	0.456	3.291	0.001
Johnson et al., 2010 b	0.163	0.087	0.007	-0.007	0.333	1.881	0.060
Teng, 2022 a	0.034	0.198	0.039	-0.355	0.423	0.172	0.864
Teng, 2022 b	3.120	0.298	0.089	2.536	3.703	10.474	0.000
Persky & Dinsmore, 2019	0.229	0.159	0.025	-0.082	0.540	1.441	0.150
Pennequin et al., 2010	3.536	0.561	0.315	2.436	4.635	6.304	0.000
Cornoldi et al., 2015	-0.042	0.173	0.030	-0.381	0.298	-0.241	0.810
Doyle, 2022	0.120	0.148	0.022	-0.170	0.409	0.808	0.419
Abed, 2021	0.034	0.106	0.011	-0.172	0.241	0.325	0.745
Murray, 2008 a	3.643	0.368	0.135	2.922	4.365	9.903	0.000
Murray, 2008 b	2.701	0.316	0.100	2.082	3.319	8.560	0.000
Marulis, 2015 a	0.079	0.249	0.062	-0.409	0.566	0.317	0.751
Marulis, 2015 b	0.970	0.264	0.070	0.453	1.488	3.677	0.000
Martel, 2011 a	0.322	0.243	0.059	-0.154	0.798	1.328	0.184
Martel, 2011 b	0.807	0.251	0.063	0.315	1.298	3.218	0.001
Martel, 2011 c	0.669	0.248	0.061	0.184	1.155	2.701	0.007
Liu, 1999 a	0.263	0.289	0.084	-0.304	0.830	0.908	0.364
Liu, 1999 b	0.324	0.308	0.095	-0.281	0.928	1.049	0.294
Liu, 1999 c	0.171	0.298	0.089	-0.412	0.755	0.576	0.565
Liu, 1999 d	0.455	0.307	0.094	-0.147	1.057	1.482	0.138
Liu, 1999 e	-0.297	0.308	0.095	-0.901	0.307	-0.965	0.335
Liu, 1999 f	0.011	0.328	0.108	-0.632	0.654	0.034	0.973
Liu, 1999 g	0.149	0.328	0.108	-0.495	0.792	0.453	0.651
Mullick-Martinez, 2021 a	1.450	0.241	0.058	0.978	1.921	6.024	0.000
Mullick-Martinez, 2021 b	0.850	0.223	0.050	0.412	1.288	3.807	0.000
Li et al., 2022	1.345	0.225	0.050	0.905	1.786	5.991	0.000
Cano et al., 2014 a	0.279	0.268	0.072	-0.245	0.803	1.043	0.297
Cano et al., 2014 b	-0.644	0.314	0.099	-1.259	-0.028	-2.051	0.040
Chen et al., 2022 a	0.869	0.301	0.091	0.279	1.459	2.886	0.004
Chen et al., 2022 b	0.723	0.297	0.088	0.141	1.305	2.434	0.015
Chen et al., 2022 c	0.801	0.299	0.089	0.215	1.387	2.678	0.007
Rezai et al., 2023	1.645	0.296	0.087	1.065	2.224	5.560	0.000
Breland et al., 2023	0.222	0.067	0.005	0.090	0.354	3.293	0.001
Endalamaw et al., 2023 a	0.964	0.279	0.078	0.418	1.511	3.457	0.001
Endalamaw et al., 2023 b	0.725	0.268	0.072	0.201	1.250	2.710	0.007
Endalamaw et al., 2023 c	0.982	0.284	0.081	0.425	1.540	3.454	0.001
Biwer et al., 2023	0.412	0.125	0.016	0.167	0.657	3.294	0.001
Martelletti et al., 2023	0.746	0.191	0.037	0.372	1.121	3.903	0.000
Cale et al., 2023	0.445	0.163	0.026	0.126	0.764	2.736	0.006
	0.586	0.057	0.003	0.474	0.698	10.273	0.000

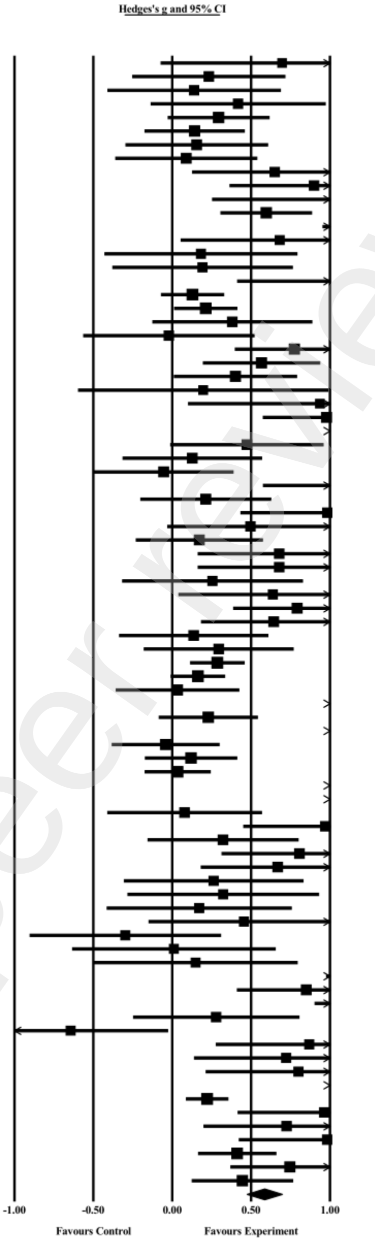

Figure 4. Forest plot of cognitive intervention effects on metacognition. The same study appears multiple times, indicating that the study includes multiple independent effect sizes. Black diamonds represent the overall effect size and confidence interval estimates.

3.3 Publication Bias and Sensitivity Analysis

A funnel plot was initially employed to assess publication bias, coupled with further examination using the Egger linear regression method. The funnel plot serves as a subjective evaluation of publication bias, where a symmetrical distribution of data around the center and above generally indicates a lower likelihood of publication bias. Drawing a funnel plot based on the overall studies revealed a generally symmetrical pattern around the center and upper sides, suggesting the potential presence of publication bias (Figure 5). Additionally, the corrected Egger linear regression test was applied, revealing $t(81) = 4.630$, $p < .001$, further indicating a potential risk of publication bias. Therefore, the Robu Meta method in JASP was employed to correct the effect size, resulting in g = 0.571 [0.445, 0.701].

Sensitivity analysis was conducted by screening outliers in R, utilizing the studentized deleted residual (SDR) as the criterion. SDR represents the deviation of the magnitude of an individual effect size observation from the predicted average effect size. An absolute SDR value greater than 1.96 implies that the effect size is an outlier (Viechtbauer & Cheung, 2010). As shown in Figure 6, among the 83 effect sizes in this study, only 4 were identified as outliers. Overall, the results of this study demonstrate a certain level of robustness.

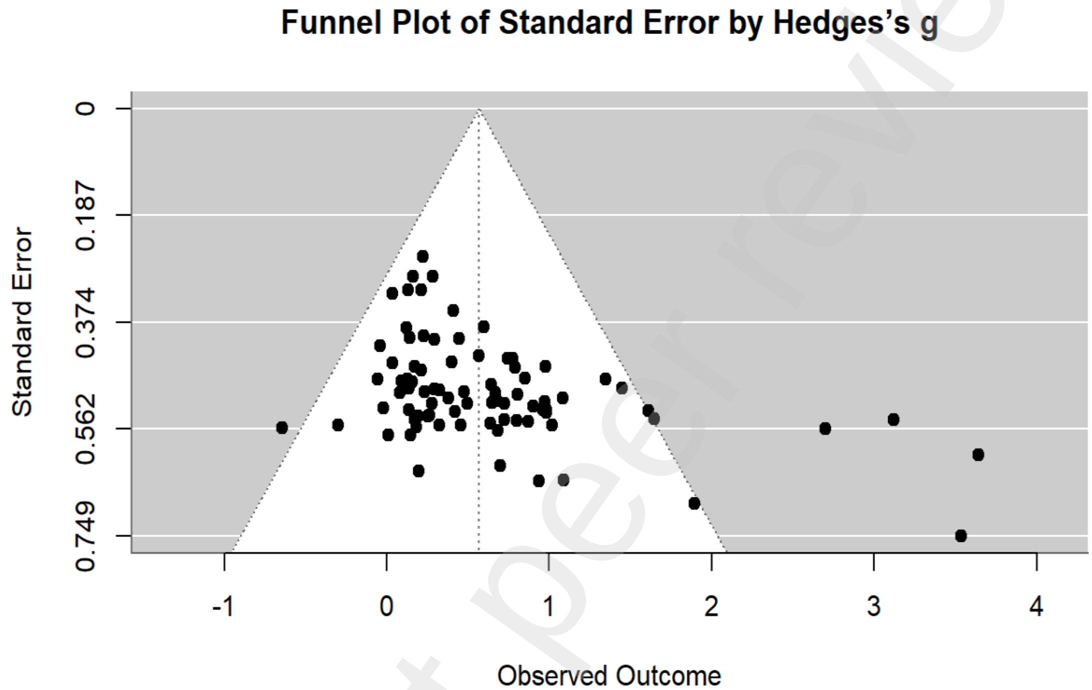

Figure 5. Funnel plot for publication bias in cognitive intervention effects

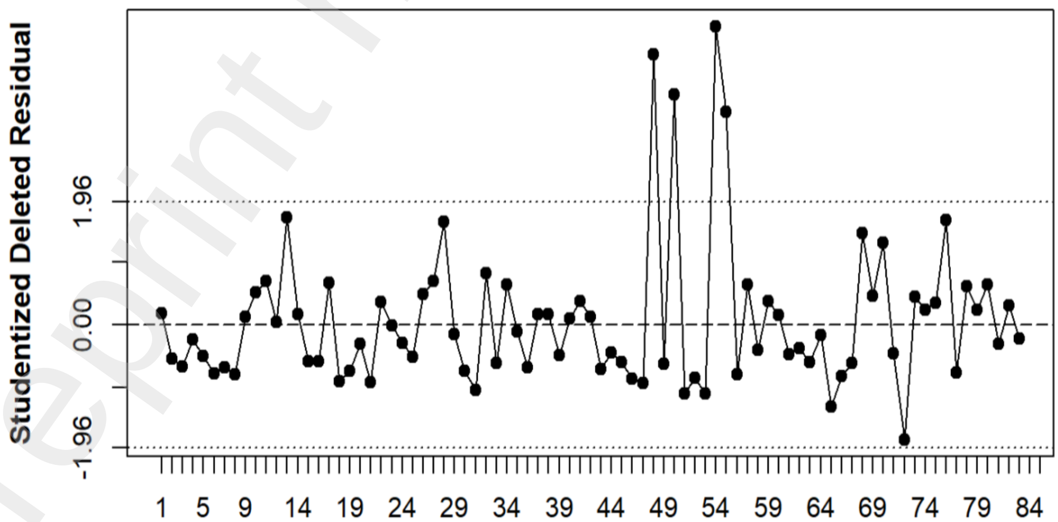

Figure 6. Removal of Outliers Using SDR in Sensitivity Analysis

3.4 Moderator analyses

The results of the heterogeneity test indicated that, in the analysis of within-study variance (level 2) and between-study variance (level 3) for outcome variables, significant between-study error (level 3) was only found in the scale score outcome variable ($p < 0.01$), suggesting potential moderator effects. Considering the moderator variables influencing the effectiveness of metacognitive interventions, the following subgroups were proposed: (1) Training type: Mindfulness training vs. Strategy intervention vs. Instructional guidance; (2) Feedback type: Yes vs. No; (3) Intervention duration: One month and above vs. One week to one month vs. Less than one week; (4) Participant group: Elementary school (6-12) vs. Middle/high school (12-18) vs. University and above (>18).

The subgroup analysis results for scale scores indicated a significant effect of training type on the metacognitive intervention outcomes ($p = 0.008$). Specifically, the training effect of strategy intervention was superior to instructional guidance and mindfulness training. In contrast, mindfulness training showed a less favorable intervention effect compared to strategy intervention and instructional guidance (g: 1.004 > 0.360 > 0.168). The training effect also significantly differed based on feedback type ($p = 0.025$), with metacognitive intervention having significantly better outcomes when feedback was present compared to interventions without feedback (g: 0.870 > 0.390). However, the moderating effects of intervention duration and participant age were not significant (Intervention duration: $p = 0.538$; Participant age: $p = 0.716$).

Table 3. Subgroup analysis results for the scale score(***Variance level 3***)

Moderator variables	***#studies***	***#ES***	***Mean g(SE)***	*95%CI*	***F-Statistic***	***p-Value***	***Variance level 3***
Training type					$F(2,57)=5.213$	0.008^{**}	0.213
Mindfulness	5	8	0.168(0.437)	[-0.708,1.044]			
Strategy	22	39	1.004(0.158)	[0.688,1.320]			
Teaching	19	36	0.360(0.140)	[0.080,0.640]			
Duration					$F(2,57)=0.538$	0.587	0.303
＞1Month	30	52	0.673(0.131)	[0.411,0.935]			
1Week-1Month	11	20	0.550(0.250)	[0.050,1.050]			
＜1Week	6	11	0.034(0.639)	[-1.246,1.315]			
Feedback					$F(1,58)=5.292$	0.025^{*}	0.248
No	24	45	0.390(0.147)	[0.067,0,684]			
Yes	24	38	0.870(0.152)	[0.566,1.174]			
Age					$F(2,57)=0.335$	0.716	0.311
＞18	31	59	0.683(0.151)	[0.380,0.985]			
12-18	6	10	0.418(0.286)	[-0.154,0.991]			
6-12	9	14	0.634(0.227)	[0.180,1.089]			

4 DISCUSSION

4.1 Effects of Cognitive Intervention on Metacognition

Recent research continually supports the premise that cognitive intervention has a tangible impact on metacognitive abilities. Despite the wealth of empirical data, a gap remains in the form of a holistic meta-analysis concerning the effects of cognitive intervention on metacognition. Addressing this, our study utilizes meta-analytic techniques to synthesize findings from various studies, scrutinizing not only the impact of cognitive training on metacognition but also the moderation effects of variables such as training types, participant age, training duration, and the use of feedback. This research presents a nuanced, evidence-based understanding of cognitive training's influence on metacognition, thus contributing to both theoretical knowledge and practical applications aimed at bolstering metacognitive skills.

The meta-analysis of 46 selected empirical studies substantiates that cognitive intervention has a positive effect on metacognitive abilities. Specifically, interventions demonstrated moderate to large effect sizes for scale scores and metacognitive efficiency, while interventions for metacognitive sensitivity and metacognitive bias showed small to moderate effect sizes. Based on the metacognitive enhancement model, when individuals confront a new cognitive task, the object-level contains knowledge relevant to the new task and potential problem-solving strategies. In contrast, the meta-level cognition encompasses the task model and cognitive operations required to perform the task. For instance, when lacking the correct rules to solve a new problem, information flows between the two cognitive levels in the form of monitoring and control. The meta-level monitors cognition and thinking at the object-level, including individuals' judgments of confidence, speed of generating solutions, or the time needed to complete partial solution steps when solving problems. The degree or accuracy of monitoring determines the extent to which information about the problem can be recalled in the future. At the meta-level, individuals compare their level of learning with the expected level, deciding not only what information to study but also when and how to study it. They can, through altering psychological and physical behaviors at the object-level, control or regulate their learning (Molin et al., 2022). Thus, the effectiveness of cognitive interventions lies in elevating individuals' cognitive proficiency at the object-level. Faced with decision-making, cognitive intervention achieves this by gathering more pertinent information, diminishing cognitive bias, and thereby preventing the emergence of errors stemming from overconfidence at the meta-level (Moritz et al., 2014). Concurrently, it fortifies monitoring and control capabilities within the information flow, fostering more positive self-acceptance and evaluation, ultimately enhancing metacognitive levels. Metacognitive training, in particular, also serves to impart metacognitive knowledge by heightening awareness of cognitive bias. This aims to rectify errors in a gentle, non-confrontational manner, leading to memorable metacognitive experiences (Moritz et al., 2019).

4.2 Moderation analysis Following the PICO principle, we comprehensively explored moderating variables and their effect magnitudes on metacognitive intervention outcomes from four perspectives: training type, training duration, participant age, and feedback type. Through a one-sided log-likelihood ratio test to assess the significance of within-study variance (level 2) and between-study variance (level 3), we only found significant differences in between-study variance (level 3) at the overall level and for the outcome variable of scale scores. Therefore, we conducted an adjustment effect analysis solely for scale scores.

The results indicate that both training type and feedback type reached a significant level, suggesting that the analyzed influencing factors can explain the differences in intervention effects to a considerable extent. Notably, strategy-based interventions showed greater effectiveness over instructional guidance and mindfulness training. This may be attributed to the fact that strategy guidance often occurs in tightly controlled laboratory environments, allowing for better control over the environment and various artificial factors, thus minimizing external interference. Regarding feedback type analysis, interventions with feedback demonstrated superior outcomes compared to those without feedback, aligning with the longstanding notion in experimental psychology that "feedback enhances behavioral performance" (Judd, 1905). The early "law of effect" (Thorndike, 1927) postulated that feedback strengthens automatic associations between stimuli and responses; individuals receiving external feedback automatically reinforce internal connections, thereby improving behavioral performance. Therefore, timely and appropriate feedback during training, whether positive or negative, enables subjects to better monitor and adjust their task performance.

In contrast, the results of the analysis for intervention duration and participant age are inconsistent with previous studies (Rochat et al., 2018; Zenner et al., 2014). In the adjustment effect analysis, these factors presented non-significant results, contradicting our initial hypotheses. Upon reflection, the discrepancy may be attributed to the fact that, based on prior research, the number of studies for each subgroup or interaction term should be no fewer than four (Bar-Haim et al., 2007; Fu et al., 2011). While this study had a total of 83 effect sizes, the average number of effect sizes for each outcome variable was insufficient due to the presence of multiple outcome variables. This resulted in low statistical power, particularly for metacognitive sensitivity, metacognitive efficiency, and metacognitive bias.

Furthermore, based on the heterogeneity results, adjustment analysis was only performed for the outcome variable of scale scores. Within this outcome variable, most intervention durations were concentrated at one month or more, and participant ages were mostly focused on 18 years and above. There were relatively fewer effect sizes at other levels, resulting in inadequate statistical power and potentially failing to detect genuine differences in adjustment effects. Additionally, the majority of current metacognitive training studies are applied in the field of educational science (Dinsmore et al., 2008; Park, 2003). In this field, researchers often train students through classroom teaching or strategic interventions, and the most popular method for measuring metacognition is self-report questionnaires, interviews, and thinking aloud methods (Zimmerman & Pons, 1986). Consequently, there are relatively fewer effect sizes for other outcome variables.

4.3 Limitations and future directions Having a well-developed capacity for introspection is crucial for both personal development and societal progress. On one hand, it assists us in self-regulating our behavior, particularly when we recognize suboptimal choices, enabling timely adjustments in thoughts and guiding actions (Folke et al., 2016; Purcell & Kiani, 2016). On the other hand, metacognition represents a potential target for interventions in mental health conditions, including schizophrenia and depression (Moritz & Woodward, 2007). Thus, the development of tools and training methods to enhance metacognitive abilities could therefore yield benefits extending from individual cognitive enhancement to broader clinical applications.

However, this study has several limitations. Firstly, A lack of granularity in the classification of outcome variables presents a challenge. Specifically, diverse psychological scales with varying benchmarks were consolidated in this study, which could mask nuanced differences in the assessment outcomes. All scales here were grouped together without a detailed exploration of potential differences among them. In future studies, a more detailed dissection of these measures is warranted to discern their distinct impacts.

In addition, future research could consider examining transfer and long-term effects. The debate over whether these abilities are domain-general or domain-specific is ongoing, with evidence on both sides (Galvin et al., 2003; Maniscalco & Lau, 2012). Some researchers argue that strong metacognitive abilities have domain-general characteristics (Ais et al., 2016; McCurdy et al., 2013; Samaha & Postle, 2017), while others point out the domain specificity of metacognition (Baird et al., 2013; Kelemen et al., 2000). Our study's focus was limited to the immediate impacts of cognitive training on metacognition, omitting an investigation into the sustained and cross-domain effects of such improvements. A more exhaustive approach to this line of inquiry could provide a more comprehensive understanding of the long-term benefits of metacognitive interventions.

Finally, exploring additional moderating variables could yield interesting insights. For instance, the cultural origins hypothesis posits that different cultural learning experiences shape diverse metacognitive abilities (Heyes et al., 2020). This is evident in the observed variances in decision-making confidence between individuals from Western individualistic societies and those from East Asian collectivist cultures (Mann. et al., 1998). Beyond this, considerations should be given to the impact on different participant types, such as the significant effects of metacognitive therapy on anxiety and depression patients (Normann et al., 2014). Given that our meta-analysis largely focused on English-language studies with healthy subjects, the effects of cultural background and health status on metacognition were not accounted for. Future research could profit from a closer examination of these variables, providing a more nuanced understanding of metacognitive training's efficacy across different populations.

COMPETING INTERESTS

The authors declare no competing interests.

DATA AVAILABILITY

All data files are openly available from the OSF database: https://osf.io/t38wu/

CODE AVAILABILITY

All code files are openly available from the OSF database: https://osf.io/t38wu/

REFERENCES

Ais, J., Zylberberg, A., Barttfeld, P., & Sigman, M. (2016). Individual consistency in the accuracy and distribution of confidence judgments. *Cognition, 146*, 377-386. https://doi.org/10.1016/j.cognition.2015.10.006

Akobeng, A. K. (2005). Principles of evidence based medicine. *Arch Dis Child, 90*(8), 837-840. https://doi.org/10.1136/adc.2005.071761

Álvarez-Bueno, C., Pesce, C., Cavero-Redondo, I., Sánchez-López, M., Martínez-Hortelano, J. A., & Martínez-Vizcaíno, V. (2017). The Effect of Physical Activity Interventions on Children's Cognition and Metacognition: A Systematic Review and Meta-Analysis. *J Am Acad Child Adolesc Psychiatry, 56*(9), 729-738. https://doi.org/10.1016/j.jaac.2017.06.012

Baird, B., Mrazek, M. D., Phillips, D. T., & Schooler, J. W. (2014). Domain-specific enhancement of metacognitive ability following meditation training. *J Exp Psychol Gen, 143*(5), 1972-1979. https://doi.org/10.1037/a0036882

Baird, B., Smallwood, J., Gorgolewski, K. J., & Margulies, D. S. (2013). Medial and lateral networks in anterior prefrontal cortex support metacognitive ability for memory and perception. *J Neurosci, 33*(42), 16657-16665. https://doi.org/10.1523/JNEUROSCI.0786-13.2013

Bang, J. W., Shekhar, M., & Rahnev, D. (2017). Sensory noise increases metacognitive efficiency. *J Exp Psychol Gen, 148*(3), 437-452. https://doi.org/10.1101/189399

Bar-Haim, Y., Lamy, D., Pergamin, L., Bakermans-Kranenburg, M. J., & van, I. M. H. (2007). Threat-related attentional bias in anxious and nonanxious individuals: a meta-analytic study. *Psychol Bull, 133*(1), 1-24. https://doi.org/10.1037/0033-2909.133.1.1

Böckler, A., & Singer, T. (2022). Longitudinal evidence for differential plasticity of cognitive functions: Mindfulness-based mental training enhances working memory, but not perceptual discrimination, response inhibition, and metacognition. *J Exp Psychol Gen, 151*(7), 1573-1590. https://doi.org/10.1037/xge0001143

Carpenter, J., Sherman, M. T., Kievit, R. A., Seth, A. K., Lau, H., & Fleming, S. M. (2019). Domain-general enhancements of metacognitive ability through adaptive training. *J Exp Psychol Gen, 148*(1), 51-64. https://doi.org/10.1037/xge0000505

Carretti, B., Caldarola, N., Tencati, C., & Cornoldi, C. (2014, Jun). Improving reading comprehension in reading and listening settings: the effect of two training programmes focusing on metacognition and working memory. *Br J Educ Psychol, 84*(Pt 2), 194-210. https://doi.org/10.1111/bjep.12022

Carter, E. C., Schönbrodt, F. D., Gervais, W. M., & Hilgard, J. (2019). Correcting for Bias in Psychology: A Comparison of Meta-Analytic Methods. *Adv Methods Pract Psychol Sci, 2*(2), 115-144. https://doi.org/10.1177/2515245919847196

Chen, B., Mundy, M., & Tsuchiya, N. (2019). Metacognitive Accuracy Improves With the Perceptual Learning of a Low- but Not High-Level Face Property. *Front Psychol, 10*, 1712. https://doi.org/10.3389/fpsyg.2019.01712

Cheung, M. W. (2014, Jun). Modeling dependent effect sizes with three-level meta-analyses: a structural equation modeling approach. *Psychol Methods, 19*(2), 211-229. https://doi.org/10.1037/a0032968

Cho, Y. S., & Linderman, K. (2019). Metacognition-based process improvement practices. *Int J Prod Econ, 211*, 132-144. https://doi.org/10.1016/j.ijpe.2019.01.030

Cogliano, M., Bernacki, M. L., & Kardash, C. M. (2021). A metacognitive retrieval practice intervention to improve undergraduates' monitoring and control processes and use of performance feedback for classroom learning. *J Educ Psychol, 113*(7), 1421-1440. https://doi.org/10.1037/edu0000624

Cortese, A., Amano, K., Koizumi, A., Kawato, M., & Lau, H. (2016). Multivoxel neurofeedback selectively modulates confidence without changing perceptual performance. *Nat Commun, 7*, 13669. https://doi.org/10.1038/ncomms13669

Creswell, J. D. (2017). Mindfulness Interventions. *Annu Rev Psychol, 68*, 491-516. https://doi.org/10.1146/annurev-psych-042716-051139

Cunningham, P., Matusovich, H., Hunter, D., & Morelock, J. (2016). *Beginning to Understand and Promote Engineering Students' Metacognitive Development*.

Desoete, A. (2009). Metacognitive prediction and evaluation skills and mathematical learning in third-grade students. *Educ Res Eval, 15*(5), 435-446. https://doi.org/10.1080/13803610903444485

Desoete, A., Roeyers, H., & Buysse, A. (2001). Metacognition and mathematical problem solving in grade 3. *J Learn Disabil, 34*(5), 435-447. https://doi.org/10.1177/002221940103400505

Dinsmore, D. L., Alexander, P. A., & Loughlin, S. M. (2008). Focusing the conceptual lens on metacognition, self-regulation, and self-regulated learning. *Educ Psychol Rev, 20*(4), 391-409. https://doi.org/10.1007/sl0648-008-9083-contains

Egger, M., Davey Smith, G., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *BMJ, 315*(7109), 629-634. https://doi.org/10.1136/bmj.315.7109.629

Filevich, E., Forlim, C. G., Fehrman, C., Forster, C., Paulus, M., Shing, Y. L., & Kühn, S. (2020, Feb). I know that I know nothing: Cortical thickness and functional connectivity underlying meta-ignorance ability in pre-schoolers. *Dev Cogn Neurosci, 41*, 100738. https://doi.org/10.1016/j.dcn.2019.100738

Flavell, J. H. (1979). Metacognition and cognitive monitoring: A new area of cognitive-developmental inquiry. *Am Psychol, 34*(10), 906-911. https://doi.org/10.1037/0003-066x.34.10.906

Fleming, S. M., & Lau, H. C. (2014). How to measure metacognition. *Front Hum Neurosci, 8*, 443. https://doi.org/10.3389/fnhum.2014.00443

Fleming, S. M., Ryu, J., Golfinos, J. G., & Blackmon, K. E. (2014). Domain-specific impairment in metacognitive accuracy following anterior prefrontal lesions. *Brain, 137*(Pt 10), 2811-2822. https://doi.org/10.1093/brain/awu221

Fleming, S. M., Weil, R. S., Nagy, Z., Dolan, R. J., & Rees, G. (2010). Relating Introspective Accuracy to Individual Differences in Brain Structure. *Science, 329*(5998), 1541-1543. https://doi.org/10.1126/science.1191883

Fleur, D. S., Bredeweg, B., & van den Bos, W. (2021, Jun 8). Metacognition: ideas and insights from neuro- and educational sciences. *NPJ Sci Learn, 6*(1), 13. https://doi.org/10.1038/s41539-021-00089-5

Folke, T., Jacobsen, C., Fleming, S. M., & De Martino, B. (2016). Explicit representation of confidence informs future value-based decisions. *Nat Hum Behav, 1*(1). https://doi.org/10.1038/s41562-016-0002

Fox, K. C., Zakarauskas, P., Dixon, M., Ellamil, M., Thompson, E., & Christoff, K. (2012). Meditation experience predicts introspective accuracy. *PLoS One, 7*(9), e45370. https://doi.org/10.1371/journal.pone.0045370

Fu, R., Gartlehner, G., Grant, M., Shamliyan, T., Sedrakyan, A., Wilt, T. J., Griffith, L., Oremus, M., Raina, P., Ismaila, A., Santaguida, P., Lau, J., & Trikalinos, T. A. (2011). Conducting quantitative synthesis when comparing medical interventions: AHRQ and the Effective Health Care Program. *J Clin Epidemiol, 64*(11), 1187-1197. https://doi.org/10.1016/j.jclinepi.2010.08.010

Galvin, S. J., Podd, J. V., Drga, V., & Whitmore, J. (2003). Type 2 tasks in the theory of signal detectability: discrimination between correct and incorrect decisions. *Psychon. Bull. Rev, 10*, 843-876. https://doi.org/10.3758/BF03196546

Goldhacker, M., Rosengarth, K., Plank, T., & Greenlee, M. W. (2014, Jun). The effect of feedback on performance and brain activation during perceptual learning. *Vision Res, 99*, 99-110. https://doi.org/10.1016/j.visres.2013.11.010

Goupil, L., & Kouider, S. (2019). Developing a Reflective Mind: From Core Metacognition to Explicit Self-Reflection. *Curr Dir Psychol Sci, 28*(4), 403-408. https://doi.org/10.1177/0963721419848672

Goupil, L., Romand-Monnier, M., & Kouider, S. (2016). Infants ask for help when they know they don't know. *Proc Natl Acad Sci U S A, 113*(13), 3492-3496. https://doi.org/10.1073/pnas.1515129113

Gutierrez de Blume, A. P. (2022). Calibrating calibration: A meta-analysis of learning strategy instruction interventions to improve metacognitive monitoring accuracy. *J Educ Psychol, 114*(4), 681-700. https://doi.org/10.1037/edu0000674

Haddara, N., & Rahnev, D. (2022). The Impact of Feedback on Perceptual Decision-Making and Metacognition: Reduction in Bias but No Change in Sensitivity. *Psychol Sci, 33*(2), 259-275. https://doi.org/10.1177/09567976211032887

Hedges, L. V. (1984). Aduances in Statistical Methods for MetaAnalysis *New Directions for Program Evaluation, 24*, 25-40. https://doi.org/10.1002/ev.1376

Heyes, C., Bang, D., Shea, N., Frith, C. D., & Fleming, S. M. (2020). Knowing Ourselves Together: The Cultural Origins of Metacognition. *Trends Cogn Sci, 24*(5), 349-362. https://doi.org/10.1016/j.tics.2020.02.007

Hofmann, S. G., Doan, S. N., Sprung, M., Wilson, A., Ebesutani, C., Andrews, L. A., Curtiss, J., & Harris, P. L. (2016). Training children's theory-of-mind: A meta-analysis of controlled studies. *Cognition, 150*, 200-212. https://doi.org/10.1016/j.cognition.2016.01.006

Judd, C. H. (1905). Practice without knowledge of results. *The Psychological Review: Monograph Supplements, 7*(1), 185-198. https://doi.org/record/1926-02662-001

Kallapiran, K., Koo, S., Kirubakaran, R., & Hancock, K. (2015). Review: Effectiveness of mindfulness in improving mental health symptoms of children and adolescents: a meta-analysis. *Child Adolesc Ment Health, 20*(4), 182-194. https://doi.org/10.1111/camh.12113

Kelemen, W. L., Frost, P. J., & Weaver, C. A., 3rd. (2000). Individual differences in metacognition: evidence against a general metacognitive ability. *Mem Cognit, 28*(1), 92-107. https://doi.org/10.3758/bf03211579

Knapp, G., & Hartung, J. (2003). Improved tests for a random effects meta-regression with a single covariate. *Stat Med, 22*(17), 2693-2710. https://doi.org/10.1002/sim.1482

Lipsey, M. W., & Wilson, D. B. (2001). *Practical meta-analysis*. Sage Publications, Inc.

Maniscalco, B., & Lau, H. (2012, Mar). A signal detection theoretic approach for estimating metacognitive sensitivity from confidence ratings. *Conscious Cogn, 21*(1), 422-430. https://doi.org/10.1016/j.concog.2011.09.021

Mann., L., Radford., M., Burnett., P., Ford., S., Leung., M. B. a. K., Nakamura., H., Vaughan., G., &

Yang., K.-S. (1998). Cross-cultural differences in self-reported decision-making style and confidence. *Int J Psychol, 33*(5), 325–335. https://doi.org/10.1080/002075998400213

McCurdy, L. Y., Maniscalco, B., Metcalfe, J., Liu, K. Y., de Lange, F. P., & Lau, H. (2013). Anatomical coupling between distinct metacognitive systems for memory and visual perception. *J Neurosci, 33*(5), 1897-1906. https://doi.org/10.1523/JNEUROSCI.1890-12.2013

Molin, F., Bruin, A., & Haelermans, C. (2022). A conceptual framework to understand learning through formative assessments with student response systems: The role of prompts and diagnostic cues. *Soc Sci Humanit Open, 6*(1). https://doi.org/10.1016/j.ssaho.2022.100323

Morales, J., Lau, H., & Fleming, S. M. (2018, Apr 4). Domain-General and Domain-Specific Patterns of Activity Supporting Metacognition in Human Prefrontal Cortex. *J Neurosci, 38*(14), 3534-3546. https://doi.org/10.1523/jneurosci.2360-17.2018

Moritz, S., Andreou, C., Schneider, B. C., Wittekind, C. E., Menon, M., Balzan, R. P., & Woodward, T. S. (2014). Sowing the seeds of doubt: a narrative review on metacognitive training in schizophrenia. *Clin Psychol Rev., 34*(4), 358-366. https://doi.org/10.1016/j.cpr.2014.04.004

Moritz, S., Klein, J. P., Lysaker, P. H., & Mehl, S. (2019, Sep). Metacognitive and cognitive-behavioral interventions for psychosis: new developments *Dialogues Clin Neurosci, 21*(3), 309-317. https://doi.org/10.31887/DCNS.2019.21.3/smoritz

Moritz, S., & Woodward, T. S. (2007). Metacognitive training in schizophrenia: from basic research to knowledge translation and intervention. *Curr Opin Psychiatry, 20*(6). https://doi.org/10.1097/YCO.0b013e3282f0b8ed

Nelson, T. O. (1990). Metamemory: A Theoretical Framework and New Findings. In G. H. Bower (Ed.), *Psychol Learn Motiv* (Vol. 26, pp. 125-173). Academic Press. https://doi.org/10.1016/S0079-7421(08)60053-5

Nonose, K., Kanno, T., & Furuta, K. (2012). A team cognition model derived from an analysis of reflection on cooperation. *Cognition, Technology & Work, 14*, 83-92. https://doi.org/10.1007/s10111-011-0179-2

Normann, N., van Emmerik, A. A., & Morina, N. (2014, May). The efficacy of metacognitive therapy for anxiety and depression: a meta-analytic review. *Depress Anxiety, 31*(5), 402-411. https://doi.org/10.1002/da.22273

Park, C. (2003). Engaging Students in the Learning Process: The learning journal. *Journal of Geography in Higher Education, 27*(2), 183-199. https://doi.org/10.1080/03098260305675

Penney, D., Sauve, G., Mendelson, D., Thibaudeau, E., Moritz, S., & Lepage, M. (2022). Immediate and Sustained Outcomes and Moderators Associated With Metacognitive Training for Psychosis: A Systematic Review and Meta-analysis. *JAMA Psychiatry, 79*(5), 417-429. https://doi.org/10.1001/jamapsychiatry.2022.0277

Petrov, A. A., Dosher, B. A., & Lu, Z. L. (2006, Oct). Perceptual learning without feedback in non-stationary contexts: data and model. *Vision Res, 46*(19), 3177-3197. https://doi.org/10.1016/j.visres.2006.03.022

Pham, B., Platt, R., McAuley, L., Klassen, T. P., & Moher, D. (2001). Is There a "Best" Way to Detect and Minimize Publication Bias?:An Empirical Evaluation. *Eval Health Prof, 24*(2), 109-125. https://doi.org/10.1177/016327870102400202

Pintrich, P. R. (2010). The Role of Metacognitive Knowledge in Learning, Teaching, and Assessing. *Theory Pract, 41*(4), 219-225. https://doi.org/10.1207/s15430421tip4104_3

Purcell, B. A., & Kiani, R. (2016). Hierarchical decision processes that operate over distinct timescales underlie choice and changes in strategy. *Proc Natl Acad Sci U S A, 113*(31), E4531-E4540. https://doi.org/10.1073/pnas.1524685113

Qiu, L., Su, J., Ni, Y., Bai, Y., Zhang, X., Li, X., & Wan, X. (2018). The neural system of metacognition accompanying decision-making in the prefrontal cortex. *PLoS Biol, 16*(4), e2004037. https://doi.org/10.1371/journal.pbio.2004037

Raudenbush, S. W., & Bryk, A. S. (2002). *Hierarchical linear models: Applications and data analysis methods* (Vol. 1). sage.

Rochat, L., Manolov, R., & Billieux, J. (2018, Jun). Efficacy of metacognitive therapy in improving mental health: A meta-analysis of single-case studies. *J Clin Psychol, 74*(6), 896-915. https://doi.org/10.1002/jclp.22567

Rothstein, H. R., Sutton, A. J., & Borenstein, M. (2005). Publication Bias in Meta-Analysis. In *Publication Bias in Meta‐Analysis* (pp. 1-7). https://doi.org/https://doi.org/10.1002/0470870168.ch1

Rouault, M., Dayan, P., & Fleming, S. M. (2019). Forming global estimates of self-performance from local confidence. *Nat Commun, 10*(1), 1141. https://doi.org/10.1038/s41467-019-09075-3

Samaha, J., & Postle, B. R. (2017). Correlated individual differences suggest a common mechanism underlying metacognition in visual perception and visual short-term memory. *Proc Biol Sci, 284*(1867). https://doi.org/10.1098/rspb.2017.2035

Schmidt, C., Reyes, G., Barrientos, M., Langer, A. I., & Sackur, J. (2019). Meditation focused on self-observation of the body impairs metacognitive efficiency. *Conscious Cogn, 70*, 116-125. https://doi.org/10.1016/j.concog.2019.03.001

Schraw, G., & Dennison, R. S. (1994). Assessing Metacognitive Awareness. *Contemp Educ Psychol, 19*(4), 460-475. https://doi.org/10.1006/ceps.1994.1033

Shibata, K., Yamagishi, N., Ishii, S., & Kawato, M. (2009, Oct). Boosting perceptual learning by fake feedback. *Vision Res, 49*(21), 2574-2585. https://doi.org/10.1016/j.visres.2009.06.009

Stanley, T. D. (2017). Limitations of PET-PEESE and Other Meta-Analysis Methods. *Soc Psychol Personal Sci, 8*(5), 581-591. https://doi.org/10.1177/1948550617693062

Thorndike, E. L. (1927). The Law of Effect. *Am J Psychol, 39*(1/4), 212-222. https://doi.org/10.2307/1415413

Van den Bussche, E., Van den Noortgate, W., & Reynvoet, B. (2009, May). Mechanisms of masked priming: a meta-analysis. *Psychol Bull, 135*(3), 452-477. https://doi.org/10.1037/a0015329

Veenman, M. V. J., Kok, R., & Blöte, A. W. (2005). The relation between intellectual and metacognitive skills in early adolescence. *Instr Sci, 33*(3), 193-211. https://doi.org/10.1007/s11251-004-2274-8

Viechtbauer, W., & Cheung, M. W. (2010, Apr). Outlier and influence diagnostics for meta-analysis. *Res Synth Methods, 1*(2), 112-125. https://doi.org/10.1002/jrsm.11

Vo, V. A., Li, R., Kornell, N., Pouget, A., & Cantlon, J. F. (2014). Young children bet on their numerical skills: metacognition in the numerical domain. *Psychol Sci, 25*(9), 1712-1721. https://doi.org/10.1177/0956797614538458

Ye, Q., Zou, F., Dayan, M., Lau, H., Hu, Y., & Kwok, S. C. (2019, Sep). Individual susceptibility to TMS affirms the precuneal role in meta-memory upon recollection. *Brain Struct Funct, 224*(7), 2407-2419. https://doi.org/10.1007/s00429-019-01909-6

Ye, Q., Zou, F., Lau, H., Hu, Y., & Kwok, S. C. (2018, Jul 11). Causal Evidence for Mnemonic Metacognition in Human Precuneus. *J Neurosci, 38*(28), 6379-6387.

https://doi.org/10.1523/jneurosci.0660-18.2018
Zenner, C., Herrnleben-Kurz, S., & Walach, H. (2014). Mindfulness-based interventions in schools-a systematic review and meta-analysis. *Front Psychol, 5*, 603. https://doi.org/10.3389/fpsyg.2014.00603
Zepeda, C. D., Richey, J. E., Ronevich, P., & Nokes-Malach, T. J. (2015). Direct instruction of metacognition benefits adolescent science learning, transfer, and motivation: An in vivo study. *J Educ Psychol, 107*(4), 954-970. https://doi.org/10.1037/edu0000022
Zimmerman, B. J., & Pons, M. M. (1986). Development of a Structured Interview for Assessing Student Use of Self-Regulated Learning Strategies. *Am Educ Res J, 23*(4), 614-628. https://doi.org/10.3102/00028312023004614