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Review

Does mindfulness-based intervention improve cognitive function?: A meta-analysis of controlled studies

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ABSTRACT

Theoretical accounts and preliminary evidence suggest that Mindfulness-Based Interventions (MBIs) improve cognitive function, but reviews of empirical studies have provided mixed results. To clarify empirical evidence, we conducted a meta-analysis of 25 studies (n = 1439) and examined the effects of MBIs on four cognitive domains: attention, working memory, long-term memory, and executive function. The summary effect sizes indicate that MBIs produce non-significant effects on attention (SMD = 0.07), working memory (SMD = 0.16), and long-term memory (SMD = −0.12), while a small effect was observed for executive function (SMD = 0.29). Given significant heterogeneity across studies, we conducted meta-regression analyses with sample characteristics, age, number of treatment sessions, treatment duration, intervention type, control group type, and study design. We found moderating effects of intervention type on attention and executive function. Although the current study highlights preliminary evidence for improvements in executive function, overall results suggest non-significant findings for attention, working memory, and long-term memory. To draw a firm conclusion, further research is needed to address methodological challenges in meta-analysis and the limitations of existing studies.

1. Introduction

Over the past several decades there has been a growing body of research on mindfulness-based interventions (MBIs). Mindfulness is defined as the ability to bring attention to internal (i.e., thoughts, feelings, and bodily sensations) and external (i.e., immediate surroundings) experiences in the present moment with an open and non-judgmental attitude (Kabat-Zinn, 2013). Futhermore, within recent years, mindfulness has been incorporated into a variety of clinically oriented programs such as Mindfulness-Based Stress Reduction (MBSR; Kabat-Zinn, 2013) and Mindfulness-Based Cognitive Therapy (MBCT; Segal, Williams, & Teasdale, 2013). MBIs have been found to provide significant benefits for a wide range of clinical conditions, such as medical illnesses (Speca, Carlson, Goodey, & Angen, 2000), anxiety and stress (Shapiro, Schwartz, & Bonner, 1998; Williams, Kolar, Reger, & Pearson, 2001), coping with chronic pain (Rosenzweig et al., 2010), and depression (Ma & Teasdale, 2004). Research also suggests that MBIs can improve various aspects of life in non-clinical populations by serving as a buffer against psychological distress and by facilitating self-compassion and empathy (Chiesa & Serretti, 2011; Shapiro et al., 1998). While the clinical benefits of MBIs have been well documented, the mechanisms by which they arise are not fully understood.

A number of potential mechanisms have been documented that may underlie the positive effects of MBIs (Chambers, Gullone, & Allen, 2009a, 2009b; Lee & Orsillo, 2014; Lim, Condon, & DeSteno, 2015). Among them, mindful attention and cognitive control have received considerable theoretical and research attention. For example, Bishop et al. (2004) proposed a two-component model of mindfulness consisting of self-regulation of attention and an open and accepting attitude toward experiences in the present moment. The two-factor model posits that mindfulness involves sustained attention to maintain awareness of current experience, attention switching to bring focus back to the

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present moment (e.g., one's own breath), and inhibition of elaborative processing (e.g., ruminating on negative thoughts or feelings) that diverts from the present moment. Likewise, Shapiro, Carlson, Astin, and Freedman (2006) proposed that attention encompases one of the three core components of mindfulness. In this view, mindfulness practice promotes the ability to maintain present moment awareness.

From a neuroscience perspective, Hölzel et al. (2011) proposed five mechanisms through which mindfulness mediates its effects, and among them, attention regulation was theorized to promote sustained and selective attention and executive control of cognitive resources. For instance, Hölzel et al. (2007) found increased activation in the anterior cingulate cortex (ACC), the locus of executive function, among experienced meditators compared with age- and gender-matched controls. Furthermore, Larson, Steffen, and Primosch (2013) argue that mindfulness practice promotes the ability to be aware of attentional focus in a given moment and allocates cognitive resources in a goal-directed manner. Preliminary studies also suggest that participants in MBIs report improvements in cognitive function, such as increased sustained attention (Morrison, Goolsarran, Rogers, & Jha, 2014) and working memory (Jha, Stanley, Kiyonaga, Wong, & Gelfand, 2010), and reduced emotional interference on cognitive tasks (Ortner, Kilner, & Zelazo, 2007).

A challenge to investigating cognitive function by meta-analyzing a large number of studies is identifying and differentiating various cognitive tasks and systematically matching them to corresponding cognitive functions. During our review, we found that the same cognitive task was conceptualized and categorized differently across the studies under investigation. In addition, literature documents controversy over the definition and identification of specific cognitive functions (Johnston & Dark, 1986). For example, executive function is conceptualized as the capacity to control cognitive resources and execute higher-order processes, such as decision making and planning (Chan, Shum, Toulopoulou, & Chen, 2008). However, Petersen and Posner (2012) proposed executive function as part of a broader attention network. Although there is much debate about how cognitive functions are differentiated and interconnected, it is beyond the scope of this review. To provide clarity and interpretability of our findings, it is worth describing how we conceptualized cognitive functions and categorized cognitive tasks.

As the most basic and integral part of the cognitive system, attention is defined as the limited capacity to allocate cognitive resources to stimuli, thus serving as a gate by selecting information of significance and relaying that information into working memory for higher-order processing. Since most cognitive scientists do not conceptualize attention as a unitary construct, but rather as a multi-faceted system (Parasuraman, 2000; Petersen & Posner, 2012), we categorized attention into three sub-types: sustained attention, selective attention, and miscellaneous attention. First, sustained attention involves maintaining vigilance and wakefulness with regard to ever-changing internal and external environments for a continuous amount of time (Zimmermann & Leclercq, 2002). Next, selective attention refers to the ability to select a specific sensory stimulus or its feature or location while filtering out irrelevant sensory inputs (Johnston & Dark, 1986; Petersen & Posner, 2012). Selective attention is often directed toward preconceived goals, thus requiring an interplay between stimulus-driven, bottom-up processing and goal-oriented, top-down control. For example, when inundated by both target and non-target stimuli, attention needs to be deployed to the search target for further processing while ignoring non-target stimuli. Lastly, we found that some reviewed studies included attention tasks that do not fall into one of the two attention sub-types discussed above (e.g., attentional blink task and attentional capture task). Thus, we created a miscellaneous category to encompass these attention measures.

Working memory is defined as the capacity to retain and manipulate relevant information over a short duration, and to update old information with new (Baddeley & Hitch, 1994; Smith & Jonides, 1999). While attention guides cognitive resources to select goal-relevant information, the relayed information is held in working memory for encoding and updating. Oberauer (2009) suggests six distinct functions of working memory. These functions include structural representations, manipulation, flexible reconfiguration, partial decoupling from long-term memory, and encoding of structural information into long-term memory. Working memory differs from long-term memory in that although previous knowledge and episodic memory in long-term memory can be retrieved into working memory, information in working memory decays rapidly without being continuously rehearsed or stored into long-term memory.

On the other hand, long-term memory primarily concerns the storage and retrieval of information over extended time intervals. Various types of long-term memory are identified in the literature, including declarative memory, episodic memory, semantic memory, autobiographical memory, and procedural memory. In laboratory-based experiments, long-term memory is often tested by presenting the test-taker with a story or a list of items and asking the individual to recall certain information immediately (immediate recall) or after a short interval (delayed recall) (Cowan, 2008).

Lastly, executive function refers to a set of higher order cognitive processes that facilitate cognitive control of behavior with regard to personal goals. Executive function often involves the simultaneous and flexible use of executive abilities such as inhibitory control, conflict monitoring, planning, reasoning, problem solving, decision making, and cognitive flexibility (see Chan et al., 2008 for review). Some theoretical models suggest executive function as part of attention or working memory (Baddeley & Hitch, 1994; Petersen & Posner, 2012), where executive function plays a supervisory role, and the functional relationship between executive function and other cognitive functions may change depending on the model. However, we found that "executive attention" or "central executive" conceptually overlap with models that consider executive function a distinct, integral system. Thus, we analyzed executive function as a separate functional category.

In sum, the current evidence is mixed with regard to whether MBIs promote improvements in the four subtypes of the cognitive system (i.e. attention, working memory, long-term memory, and executive function). While some studies report cognitive improvements following an MBI (Becerra, Dandrade, & Harms, 2017; Chambers et al., 2008; Esch et al., 2017), others document non-significant effects of MBIs (Manglani, Samimy, Schirda, Nicholas, & Prakash, 2019; Meland et al., 2015; Tang, Hölzel, & Posner, 2015). One recent meta-analysis provided preliminary evidence for improvements in working memory, long-term memory, and executive function, but null findings for attention and executive function (Lao, Kissane, & Meadows, 2016). Despite its promising results, the inclusion of only MBCT and MBSR programs limit the generalizability of the findings, along with the lack of examination of variables that could have moderated the effects of MBIs. Thus we tested the hypothesis that MBIs are an effective treatment for enhancing the four cognitive functions compared to active or waitlist controls. Furthermore, we included both randomized and non-randomized controlled studies and explored whether main effects were moderated by sample characteristics, age, number of treatment sessions, treatment duration, intervention type, control group type, and study design.

2. Methods

2.1. Eligibility criteria

2.1.1. Participants

We sought a maximally generalizable data set by avoiding potential confounds of rapidly changing brain development and cognitive decline. We therefore included participants between ages 18 and 59 years. We also included studies that involved individuals with psychiatric (e.g., anxiety disorders) and medical (e.g., diabetes) conditions, as well as healthy adults to maximize the generalizability of our findings. Child and adolescent participants were not considered because brain development and cognitive maturation changes rapidly in these age groups (McArdle, Ferrer-Caja, Hamagami, & Woodcock, 2002). Studies with participants over 59 years of age were also excluded because of the commonality of cognitive decline, and thus possible ceiling effects of MBIs on cognitive function (Starr, Deary, Inch, Cross, & Maclennan, 1997).

2.1.2. Mindfulness-based interventions

The study must be a controlled study where participants either received an MBI or were subject to a control condition, such as a waitlist group or alternative intervention. Interventions must be delivered via the traditional face-to-face, in-person method, and thus the studies providing remote instructions or smartphone applications were excluded. In the current meta-analysis, an MBI was characterized as formal training in promoting self-regulation of attention, present-moment awareness, and a non-judgmental attitude toward the experience (Kabat-Zinn, 2003). Eligible MBIs emphasized mindfulness as a primary component of the intervention and devote a substantial amount of time learning and practicing mindfulness skills during treatment. For instance, mindful breathing, formal sitting meditation, body scan, and exercises involving body movement (e.g., walking meditation and Hatha Yoga) are the most common mindfulness practices among the included studies. However, programs that did not teach formal meditative practices (e.g., Acceptance and Commitment Therapy and Dialectical Behavior Therapy) and those that solely focused on yoga or body movement were excluded because the presence of additional active treatment components can confound treatment effects and reduce internal validity. Finally, we included studies that were delivered for more than one session with a minimum total treatment duration of one hour.

2.1.3. Cognitive tasks

The study must include at least one cognitive task in the domains of attention, working memory, long-term memory, or executive function (See Table 1.). The task was either administered via a computer or by paper and pencil in a controlled laboratory setting, and must have produced objective and quantifiable behavioral data, such as reaction time and accuracy. Thus, tests involving self- or other-rated scores or neurobiological measurements such as blood-oxygen-level-dependent (BOLD) signals and electroencephalography (EEG) were not considered in this study.

2.1.4. Additional criteria

Selected articles must be written in English, published in a peer-reviewed journal until August 2020, and report data from empirical studies with a minimum sample size of 20.

2.2. Search strategy and data extraction

Five electronic databases, including PsycINFO, Medline, PubMed, Web of Science, and Google Scholar were searched by using the following keywords: mindfulness, meditation, attention, working memory, long-term memory, executive function, cognitive ability, awareness, concentration, and cognitive control (see Appendix 1 for the full search strategy). Additionally, we reviewed the reference list of selected articles (backward search) as well as articles that cited eligible studies (forward search). The search was performed by three trained research assistants under the supervision of the first author (S.I.).

2.2.1. Study selection

As shown in the PRISMA flow diagram (see Fig. 1), a total of 5446 records were identified through database searching. After removing duplicate entries, initial screening was performed by checking abstracts and study information (e.g., age and language) from the database. Then a full text review was performed to ascertain whether the remaining studies met the eligibility criteria. To ensure objectivity and avoid mistakes in our study selection, two trained reviewers independently evaluated each study for the inclusion criteria. When any discrepancy was noted, the first author performed the third review and discussed the final determination with the reviewers.

Table 1
List of cognitive tasks.

Cognitive function	Task	Outcome measure
Sustained attention	Attentional Network Test - Alerting	Reaction time
	Choice reaction time	Accuracy, reaction time
	Continuous Performance Test	Omission error, reaction time, d'
	Digit Vigilance Task	Accuracy, reaction time
	Go-Nogo Task	Accuracy, reaction time
	Stroop Task	Reaction time-congruent
	Sustained Attention to Response (SART)	Accuracy, reaction time, commission error, omission error, A'
Selective attention	Attentional Network Test - Orienting	Reaction time
	Digit Cancellation Test	Accuracy
	Digit Symbol-Coding	Accuracy
	Discrimination Task	Accuracy
Miscellaneous attention	Attentional Blink Task	Accuracy
	Attentional Capture Test	Accuracy
	Concentrated Attention Task	Accuracy, error rate
	Letter Substitution Test	Accuracy
Working memory	Arithmetic subtest from WAIS-III	Accuracy
	Automated version of Ospan (AOSPAN) Task	Accuracy
	Computer-based memory test	Accuracy
	Delayed Recognition	Accuracy
	Digit Span	Accuracy
	Letter Number Sequencing	Accuracy
	Memory Scanning Task	Accuracy
	N back task	Accuracy
	Operation Span	Accuracy
	Paced auditory serial addition test	Accuracy
	Spatial Working Memory Task	Accuracy
	Symbol Digit Modalities	Accuracy
Long-term memory	Deese-Roediger-McDermott Paradigm	d', false alarm, hit rate
	Episodic memory task	Source d'
	Memory Retrieval Task	Accuracy
Executive function	Attentional Network Test - Executive	Accuracy, reaction time, omission error
	Backward Inhibition	Reaction time
	Competitor Rule Suppression	Reaction time
	Continuous Performance Test	Comission error
	Error Awareness Task	Error rate
	Go-Nogo Task	False alarm percent
	Internal Switching Task	Reaction time
	Iowa Gambling Task	Accuracy
	Key Search Task	Accuracy
	Response Inhibition Task	Reaction time
	Stroop Task	Reaction time-interference and incongruent
	Sustained Attention to Response (SART)	Commission error
	Trail Making Test B	Reaction time
	Zoo Map	Accuracy

2.2.2. Data extraction

In accordance with the PRISMA guidelines (Moher, Liberati, Tetzlaff, & Altman, 2009), the following information was extracted: (1) author names and publication year; (2) sample size; (3) mean ages and standard deviation; (4) sample characteristics; (5) previous meditation

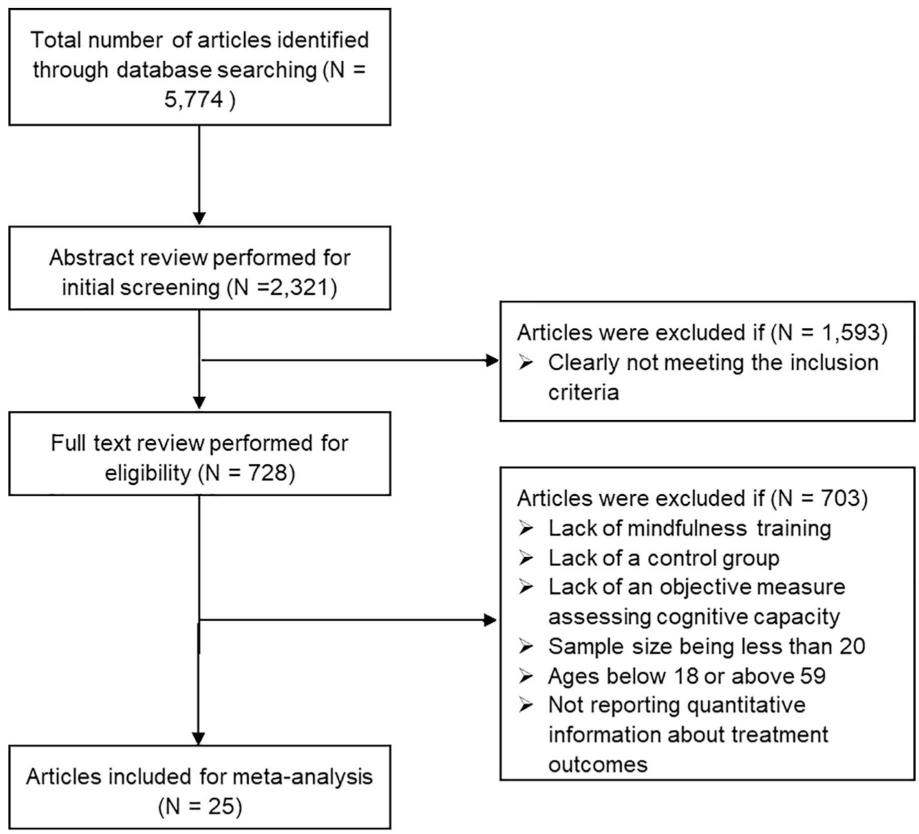

Fig. 1. Flow of information through the different phases of a meta-analysis.

experience; (6) cognitive task characteristics; (7) detailed information about intervention and control conditions; (8) intervention type (standard MBSR or MBCT, modified MBSR or MBCT, or other types of MBI); (9) number of session; (10) total treatment duration; (11) study design (randomized controlled trial and non-randomized controlled trial); and (12) pre-post difference score and standard deviation. Data extraction was performed by the third and fourth authors, and when data were not available, we requested the missing data from the corresponding authors of the study.

2.3. Data analysis

Data were analyzed using the R package "meta" (Schwarzer, 2007). Using a random effects model, standard mean differences (SMDs) with 95% confidence intervals were computed as a principal summary measure. Since different cognitive tasks and outcome measures were often used across studies, SMD allowed for the direct comparison among studies by standardizing each study's results to a uniform scale. One reviewer pointed out that some included studies used multiple outcome measures for the same cognitive function, which produced correlated estimates. To control for such dependency, we applied the robust variance estimation method (Hedges, Tipton, & Johnson, 2010) with small sample corrections using the R package "robumeta" (Fisher & Tipton, 2015).

The selected studies were first categorized into one of the four cognitive domains as discussed above. When a study involved multiple types of cognitive tasks, cognitive outcomes were grouped for each cognitive type. Using the robumeta function, we computed dependency-corrected effect sizes and their variances, and these statistics for multiple outcome variables were averaged within a study. Effect sizes were interpreted using Cohen's guidelines (Cohen, 1988); That is, SMD = 0.2, 0.5, and 0.8 indicate small, medium, and large effects, respectively.

Next, we assessed the heterogeneity (I^2) of pooled effect sizes via the methods proposed by Sidik and Jonkman (2005). When significant heterogeneity was found in a summary effect size, we performed meta-regression to evaluate if potential moderators would account for such variability in effect sizes across studies. Since previous research suggests that age, mental illness, and health status are associated with cognitive function (Bond et al., 2006; Gualtieri & Morgan, 2008; McArdle et al., 2002), we tested the meta-regression models with sample characteristics (healthy adults versus individuals with psychiatric or medical conditions), age, number of treatment sessions, treatment duration (hours), intervention type (standard MBCT and MBSR, vs. abbreviated or modified MBCT and MBSR, vs. other intervention type), control group type (active control vs. waitlist), and study design (randomized vs. non-randomized controlled studies). Furthermore, since we hypothesized non-uniform effects of MBIs on three subsystems of attention, we performed a subgroup analysis by computing pooled effect sizes for sustained, selective, and miscellaneous attention separately.

2.4. Risk of Bias

First, we created funnel plots for each cognitive domain and visually examined them for the influence of publication bias on meta-analysis results. To further quantify and evaluate the asymmetry of effect size distributions, we performed Egger's test of the intercept (Egger, Smith, Schneider, & Minder, 1997). Finally, we performed a risk of bias assessment using the Cochrane Risk of Bias tool (ROB 2.0; Higgins et al., 2011) in the following domains: 1) randomizing process, 2) deviations from intended interventions, 3) missing outcome data, 4) measurement of the outcome, and 5) selection of the reported results.

3. Results

3.1. Study and sample characteristics

After full text review, 25 studies were found to meet the inclusion criteria with all necessary information (e.g., sample size in each group, mean, and standard deviation) for meta-analysis (see Table 2 for details). The included studies were published between 2008 and 2020, with the majority (56.0%) published within the last 5 years. The final sample consists of 1439 participants with a mean age of 23.30 years (*SD* = 10.2). Most studies included healthy adults (80.0%), followed by individuals with psychological and medical conditions (16.0% and 4.0%, respectively). Participants received an average of 8.32 sessions (*SD* = 6.08) during 14.76 h (*SD* = 13.40). Seventy-six percent of the included studies (*n* = 924) were randomized controlled trials while the rest (*n* = 513) were non-randomized controlled studies.

3.2. Cognitive domains

3.2.1. Attention

Among the 25 studies included in the meta-analysis, 16 studies (*n* = 1014) included measures of attention such as Attention Network Test (ANT), Continuous Performance Test (CPT), and Sustained Attention to Response (SART). Fig. 2 presents weighted average effect sizes and measures of heterogeneity, and a random effects analysis revealed an effect size of 0.07 (95% CI = [.-0,12, 0.27]), indicating a non-significant effect of MBIs on performance in attention tasks. Based on the aforementioned categories of sustained attention (*n* = 879), selective attention (*n* = 306), and miscellaneous attention (*n* = 94) measures, we performed a subgroup analysis to ascertain differential effects of each subtype of attention. The results indicated non-significant effects for sustained attention (SMD = 0.29, 95% CI = [−0.22, 0.79], selective attention (SMD = −0.06, 95% CI = [−0.30, 0.19]), and miscellaneous attention (SMD = 0.07, 95% CI = [−0.12, 0.27]).

3.2.2. Working memory

Of included studies, 6 studies (*n* = 500) administered working memory tasks such as Digit Span, Letter Number Sequencing, and Operation Span Task. As shown in Fig. 3, the analysis revealed a non-significant effect of MBIs on working memory (SMD = 0.16, 95% CI = [−0.15, 0.47]).

3.2.3. Long term memory

Three studies (*n* = 141) included measures of long-term memory such as Delayed Recall Memory Task, Recognition Memory Task, and Autobiographical Memory Test. The random effect model estimated an effect size of −0.12 (95% CI = [−1.12, 0.88]), indicating a non-significant but more favorable effect of control conditions on long-term memory (see Fig. 4).

3.2.4. Executive function

Thirteen studies (*n* = 668) assessed various aspects of executive function involving conflict monitoring, inhibitory control, cognitive flexibility, planning, and decision making, and tasks included Stroop Task, Flanker Task, Go-Nogo Task, and Category and Letter Fluency Task. The analysis revealed an effect size of 0.29 (95% CI = [0.08, 0.51]), suggesting a small impact of MBIs on executive function (see Fig. 5).

3.3. Meta-regression analyses

To evaluate the degree of heterogeneity across studies, Cochran's Q-Statistics and I^2 Index were computed (Higgins & Thompson, 2002; Sidik & Jonkman, 2005). Significant inconsistencies were observed for attention and executive function (all *p*'s < 0.05), but not for working memory and long-term memory, with a range of Q and I^2 values (Q = 48.17 and I^2 = 54.3 for attention; Q = 5.98 and I^2 = 16.4 for working memory; Q = 3.59 and I^2 = 44.3 for long-term memory; and Q = 21.0 and I^2 = 42.9 for executive function, respectively).

Given the significant heterogeneity of effect sizes, meta-regression analyses were conducted to test whether the hypothesized moderating variables such as sample characteristics, age, number of treatment sessions, treatment duration, intervention type, control group type, and study design account for variance in the observed effects of MBIs across studies (see Table 3). The results indicated significant moderating effects for intervention type on attention (SMD = −0.79, 95% CI = [−1.51–0.06]) and executive function (SMD = −0.51, 95% CI = [−0.94–0.07]). In other words, the effects of MBSR or MBCT-based interventions were significantly greater compared to other types of interventions. However, non-significant moderating effects were found for the rest of the moderating variables (all *p*'s > 0.05). (See Table 4.)

3.4. Risk of Bias

As shown in Fig. 6, funnel plots were visually inspected for publication bias, and the overall pattern of effect sizes showed a symmetrical distribution for attention, working memory, and long-term memory, but a moderate asymmetrical distribution for executive function. These results were further corroborated by Egger's regression tests that resulted in non-significant asymmetry for attention, working memory, and long-term memory (all *p*'s > 0.05), but a significant asymmetry for executive function (intercept = −3.96, *p* = .038). We identified the Greenberg, Reiner, and Meiran (2013) study as a potential outlier and performed parallel analyses after its omission, which yielded comparable test results (ES = 0.21, 95% CI = [0.04, 0.47]).

Furthermore, most studies were rated a high overall risk of bias while the four remaining studies indicated an unclear risk of bias (see Table 3). On one hand, only a few studies provided sufficient information to enable assessment for randomization (*n* = 2) and deviations from intended interventions (*n* = 5). On the other hand, almost all studies were rated a low risk of bias for missing outcome data (*n* = 25), measurement of the outcome (*n* = 25), and selection of the reported result (*n* = 24).

4. Discussion

The current paper reports a comprehensive meta-analysis of 25 controlled studies that examined effects of MBIs on the cognitive function domains of attention, working memory, long-term memory, and executive function. Overall, the findings of the meta-analysis indicate that MBIs produce non-significant effects for attention, working memory, and long-term memory, however, they provide evidence for small improvements in executive function. Significant heterogeneity in effect sizes was observed among studies, and intervention type was found to moderate treatment effects.

Contrary to theoretical expectations (Bishop et al., 2004; Williams, Teasdale, Segal, & Soulsby, 2000), our results provide little support that mindfulness training improves attentional capacity. To perform optimally on measures of sustained attention such as Continuous Performance Test (CPT) and Sustained Attention to Response (SART), one is required to monitor the occurrence of target events over extended periods of time and execute an appropriate response (e.g., key press) while avoiding commission errors to non-target stimuli and suppressing distraction. However, mindfulness exercises such as mindful breathing and body scan typically involve attention toward internal representations while attention tasks used in included studies are designed to assess visual attention. Thus, it is possible that visual attention tasks may not capture the complete aspects of improvements in attention promoted by MBIs. Aother possible explanation is that meditation styles and practice-specific effects have differential effects on subsystems of attention. In general, meditation practice is categorized into focused attention meditation (FAM) or open monitoring meditation (OMM)

Table 2
Description of included studies ($N = 25$).

Author, year	Sample size	Mean age	Sample	Intervention group	Control group	Number of session	Treatment duration (hour)	Study design
Ainsworth et al., 2013	51	20.3	College students	Focused attention and opening monitoring meditation	Relaxation training	3	3	RCT
Allen et al., 2012	38	26.5	College students	Mindfulness program focusing on breath awareness, body scaning, compassion, and open-monitoring practice	Shared reading and listening	6	12	RCT
Bachmann et al., 2018	40	40.1	Adults with ADHD	Mindfulness intervention with emphasis on present-moment awareness, non-judgement, and acceptance	Psychoeducation on coping with ADHD symptoms and improving organizational and stress management skills	8	17	RCT
Baird et al., 2014	50	20.5	College students	Meditation training focusing on the physical posture and mental strategies of focused attention (Samatha) meditation	Nutrition science and applied strategies for healthy eating	8	6	RCT
Becerra et al., 2017	46	33.9	College students	Mindfulness training on shamantha skills	Waitlist	4	4	RCT
Bueno et al., 2015	43	29.6	Adults with ADHD	ADHD-focused mindful awareness practices (MAP)	Waitlist	8	20	NRCT
Chambers et al., 2008	40	32.8	Healthy adults	Vipassana meditation retreat	Waitlist	10	20	NRCT
Ching et al., 2015	282	18.5	College students	Mindfulness-based class consisting of mindful breathing, body scan, eating and walking meditation	Waitlist	18	15	NRCT
Esch et al., 2017	31	26.6	College students	Combined breathing and mindfulness meditation technique	Waitlist	5	7.5	RCT
Greenberg et al., 2013	76	25.5	College students	Modified MBCT	Waitlist	8	18	RCT
Jha et al., 2017	40	31.0	Military personnel	Mindfulness-based mind fitness training (MMFT)	Waitlist	8	16	RCT
Johansson et al., 2015	21	48.5	Healthy adults with mental fatigue after suffering from a storke or traumatic brain injury	MBSR	Peaceful walking group	8	24.5	RCT
Josefsson et al., 2014	50	47.0	Healthy adults	Modified MBSR	Relaxation training	8	6	RCT
Manglani et al., 2019	40	45.7	Patients with multiple sclerosis	Modified MBSR	Adaptive cognitive training (aCT)	4	8	RCT
Meland et al., 2015	40	37.5	Military personnel	MBSR	Waitlist	33	68.6	NRCT
Menezes et al., 2015	33	24.4	College students	Mindfulness training with emphasis on focused attention	Waitlist	5	7.5	RCT
Menezes et al., 2013	63	25.0	College students	Mindfulness training consisting of focused meditation on emotion and attention regulation	Waitlist	6	9	RCT
Morrison et al., 2014	48	18.2	College students	Modified MBSR	Waitlist	7	7	RCT
Nyhus et al., 2020	40	20.0	College students	Modified MBSR	Waitlist	4	4	RCT
Rosenstreich, 2016	51	25.7	College students	Mindfulness training with unknown components	Waitlist	5	2.5	RCT
Schoenberg et al., 2014	44	47.8	Patients with depression	Modified MBSR	Waitlist	8	25.5	RCT
Tang et al., 2015	54	18.2	College students	Mindfulness training involving breath focus, body scan, loving-kindness, open monitoring	Developmental psychology class	14	14	NRCT
Rodriguez Vega et al., 2014	101	28.4	Hospital psychotherapists	MBSR	Wait-list	8	20	RCT
Verhoeven et al., 2014	54	48.0	Remitted depressed patients	MBCT	Wait-list	8	26	NRCT
Zanesco et al., 2019	61	33.1	Military personnel	Mindfulness training focusing on concentration, body scan, open monitoring, connection with others	Waitlist	4	8	RCT

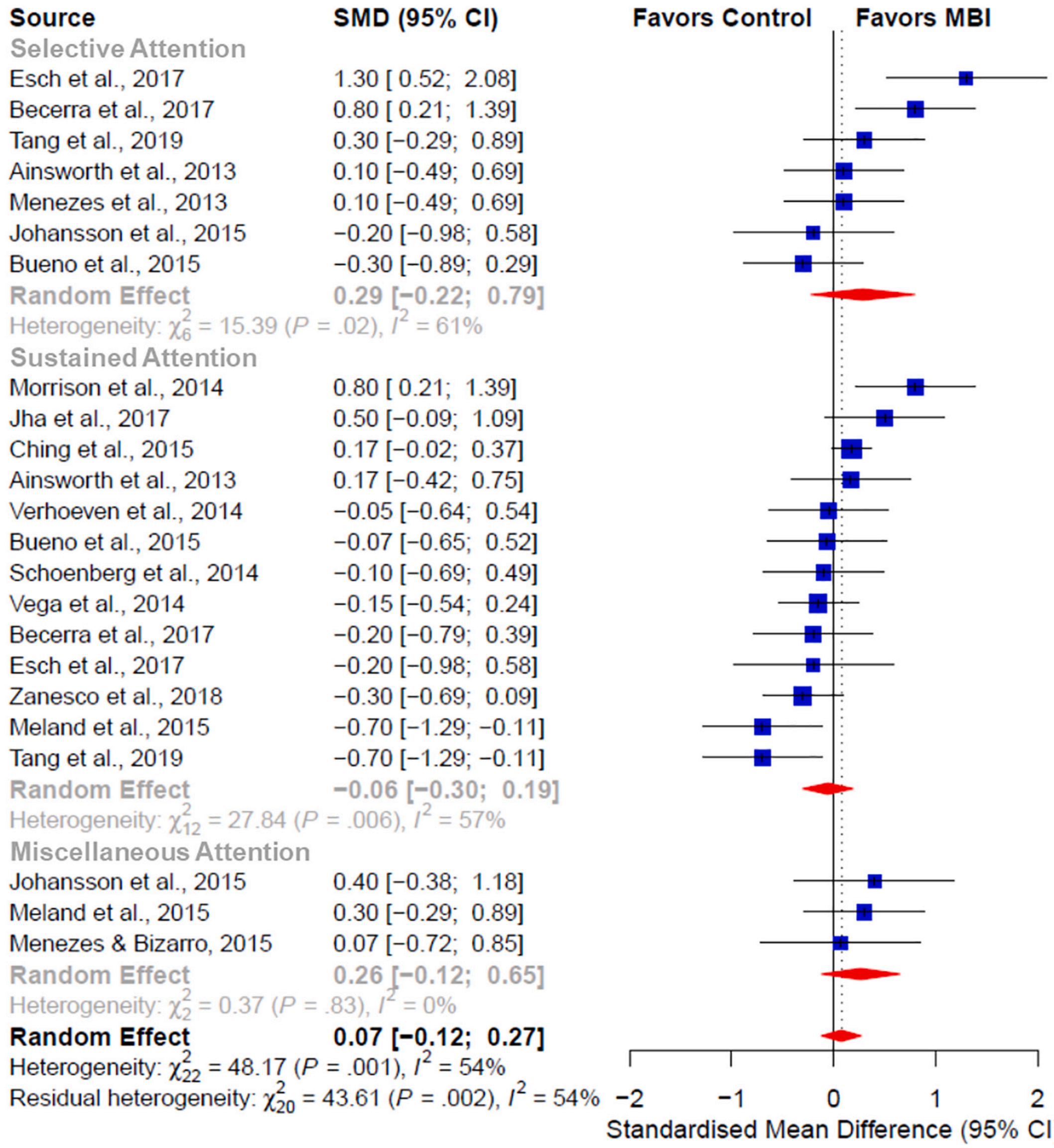

Fig. 2. Random effect of mindfulness-based intervention on attention ($N = 23$).

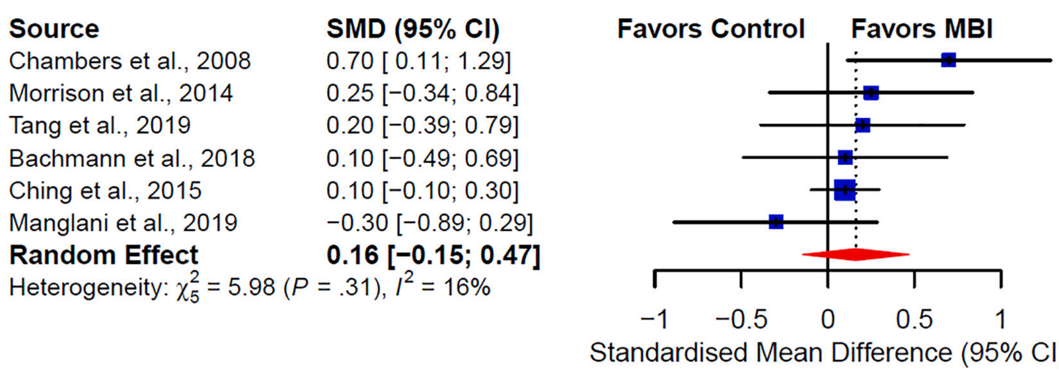

Fig. 3. Random effect of mindfulness-based intervention on working memory ($N = 6$).

(Lippelt, Hommel, & Colzato, 2014). On one hand, FAM involves sustaining attention on a predetermined object such as a candle flame. On the other hand, OMM emphasizes maintaining attention in a receptive mode while one remains attentive to moment by moment experience as it arises, thus facilitating a broader attentional focus (Lutz, Slagter, Dunne, & Davidson, 2008; Vago & David, 2012). Interventions that we reviewed typically started with FAM (e.g., mindful breathing) and progressed toward the cultivation of opening monitoring awareness through techniques such as noting and verbal labeling (Britton et al., 2018). Consistent with this line of reasoning, preliminary studies report

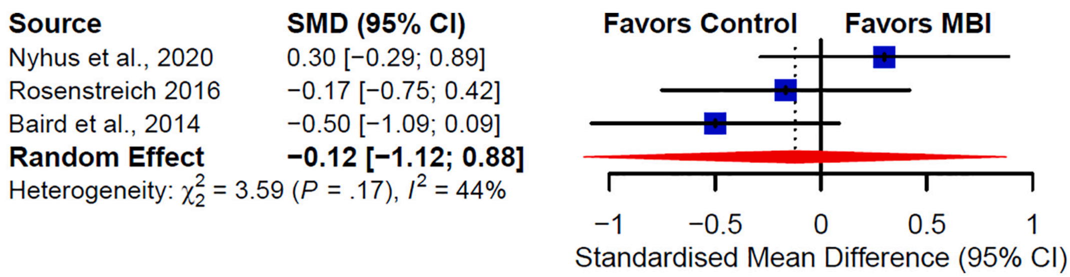

Fig. 4. Random effect of mindfulness-based intervention on long-term memory ($N = 3$).

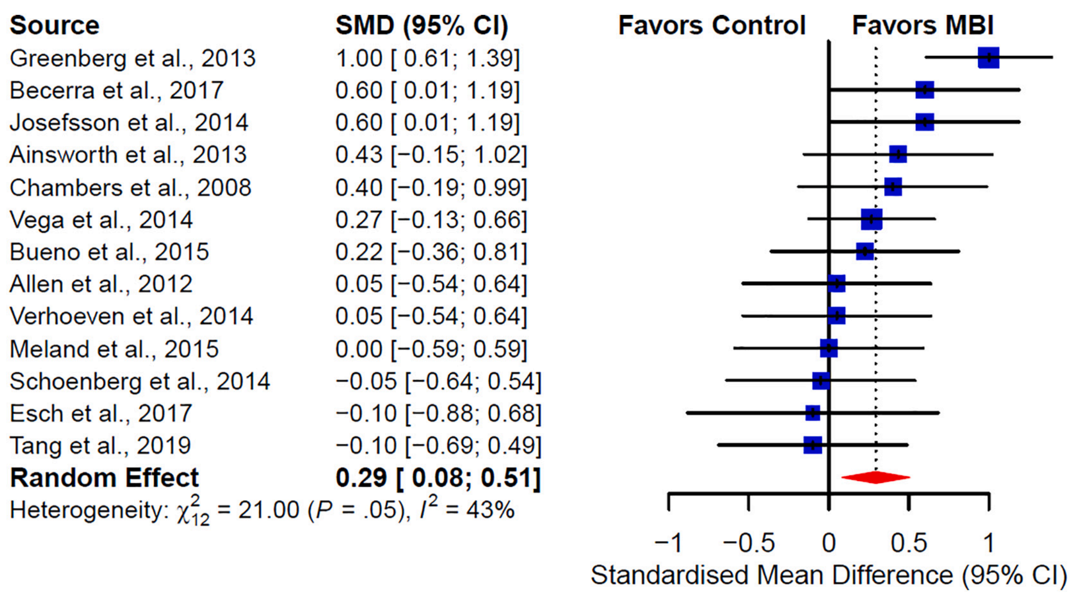

Fig. 5. Random effect of mindfulness-based intervention on executive function ($N = 13$).

Table 3
Assessment of risk of bias ($N = 25$).

Reference	Randomization process	Deviations from intended interventions	Missing outcome data	Measurement of the outcome	Selection of the reported result	Overall bias
Ainsworth et al., 2013	High	Low	Low	Low	Low	High
Allen et al., 2012	High	Low	Low	Low	High	High
Bachmann et al., 2018	Low	Unclear	Low	Low	Low	Unclear
Baird et al., 2014	High	Low	Low	Low	Low	Unclear
Becerra et al., 2017	High	Low	Low	Low	Low	High
Bueno et al., 2016	High	Unclear	Low	Low	Low	Unclear
Chambers et al., 2008	High	Unclear	Low	Low	Low	High
Ching et al., 2015	High	Unclear	Low	Low	Low	High
Esch et al., 2017	High	Unclear	Low	Low	Low	High
Greenberg et al., 2013	High	Unclear	Low	Low	Low	High
Jha et al., 2017	High	Unclear	Low	Low	Low	High
Johansson et al., 2015	High	Unclear	Low	Low	Low	High
Josefsson et al., 2014	High	Unclear	Low	Low	Low	High
Manglani et al., 2019	High	Low	Low	Low	Low	High
Meland et al., 2015	High	Unclear	Low	Low	Low	High
Menezes et al., 2015	High	Unclear	Low	Low	Low	High
Menezes et al., 2013	High	Unclear	Low	Low	Low	High
Morrison et al., 2014	High	Unclear	Low	Low	Low	High
Nyhus et al., 2020	High	Unclear	Low	Low	Low	High
Rosenstreich, 2016	Low	Unclear	Low	Low	Low	Unclear
Schoenberg et al., 2014	High	Unclear	Low	Low	Low	High
Tang et al., 2019	High	Unclear	Low	Low	Low	High
Rodriguez Vega et al., 2014	High	Unclear	Low	Low	Low	High
Verhoeven et al., 2014	High	Unclear	Low	Low	Low	High
Zanesco et al., 2019	High	Unclear	Low	Low	Low	High

Table 4
Summary effect sizes and measures of heterogeneity and bias ($N = 25$).

	Attention	Working memory	Long-term memory	Executive function
No. of subjects	1014	500	141	668
No. of studies	16	6	3	13
Random effect	0.07 [−0.12, 0.27]	0.16 [−0.15, 0.47]	−0.12 [−1.12, 0.88]	0.29 [0.08, 0.51]
Heterogeneity (I^2)	54.3% ($p = .001$)	16.4% ($p = .308$)	44–3% ($p = .166$)	42.9% ($p < .001$)
Egger's regression intercept	0.02 ($p = .980$)	0.91 ($p = .707$)	−0.89 ($p = .681$)	−3.96 ($p = .038$)
Moderation effect				
Sample characteristics	−0.18 [−0.73 0.37]	−0.11 [−0.23 0.66]	–	−0.20 [−0.70 0.31]
Age	−0.01 [−0.03 0.02]	−0.01 [−0.04 0.03]	0.08 [−1.62 1.78]	0.01 [−0.02 0.03]
Session number	−0.01 [−0.04 0.02]	0.02 [−0.06 0.09]	−0.22 [−1.24 0.79]	−0.02 [−0.04 0.02]
Treatment duration	−0.01 [−0.02 0.01]	0.05 [−0.01 0.010]	−0.26 [−1.45 0.92]	−0.01 [−0.02 0.01]
Intervention type	−0.79 [−1.51–0.06]	0.37 [−0.28 1.03]	−0.35 [−10.25 9.55]	−0.51 [−0.94–0.07]
Control group type	0.21 [−0.31 0.73]	0.22 [−0.49 0.92]	0.85 [−0.25 1.95]	0.18 [−0.28 0.64]
Study design	0.38 [−0.08 0.85]	−0.32 [−0.93 0.29]	–	0.34 [−0.05 0.73]

Note: Publication bias asymmetry estimates were computed from Egger's and rank correlation test.

an increase in sustained attention after FAM, but not after OEM (Brefczynski-Lewis, Lutz, Schaefer, Levinson, & Davidson, 2007; Carter et al., 2005). Neuroimaging evidence corroborates these results that FAM was significantly correlated with increased activity in the dorsolateral prefrontal cortex, indicative of keeping the mental representation of the goal in mind and sustaining attention to the object of focus (Hasenkamp, Wilson-Mendenhall, Duncan, & Barsalou, 2012). Furthermore, although the mean treatment duration in the included studies was 14.76 h, with a range between 2.5 and 68.6 h, a greater amount of meditation practice might be necessary to affect meaningful changes in certain attention networks. To evaluate these possibilities, further research is needed to compare the effects of FAM and OMM and examine the time course of changes in cognitive function in a longitudinal design.

While a recent meta-analysis using standardized mindfulness interventions such as MBSR and MBCT documents protective effects of working memory deterioration (Lao et al., 2016), our results suggest a positive but non-significant summary effect on performance in working memory tasks. There is also evidence that MBIs could reduce intrusive thoughts (Shipherd & Fordiani, 2015). During mindfulness practice, participants are often asked whether the mind is dwelling on goal-irrelevant thoughts and then are guided to redirect attention to the object of meditation (Kabat-Zinn, 2003). Such practice may not expand the working memory capacity per se, but instead reduces distracting information that is competing for capacity-limited resources. However, current evidence does not support this hypothesis. The discrepancy in findings between the two meta-analyses could be due to differences in inclusion criteria (i.e., the inclusion of non-manualized interventions and modified versions of MBCT and MBSR) and methodological approaches to compute effect sizes (i.e., the use of post-treatment scores vs. pre-post difference scores in the current study).

Likewise, we found no evidence for improvements in long-term memory. Classical models of long-term memory specify three sequential stages: encoding, storage, and retrieval of information (Tulving & Murray, 1985), and in particular, MBIs may contribute to encoding and retrieval. The present-moment focus of MBIs may improve the efficiency

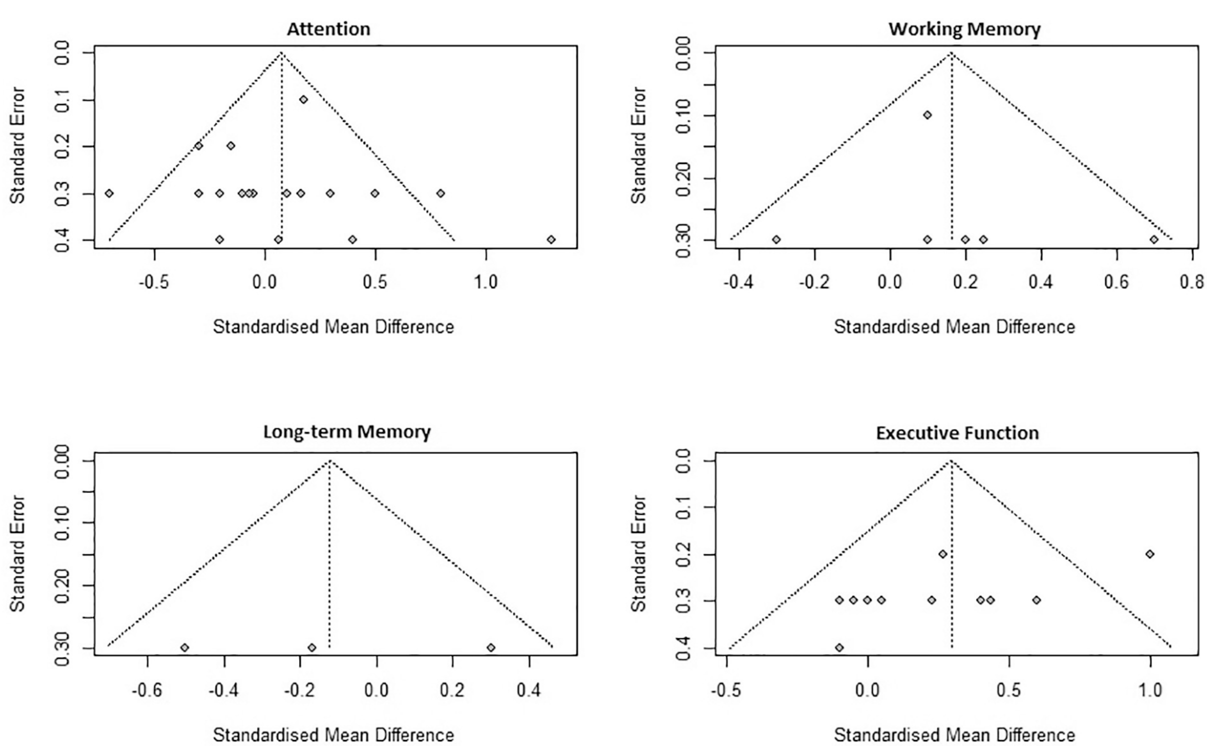

Fig. 6. Funnel plots for publication bias in random effects estimates ($N = 25$).

to encode information in detail and store a greater number of retrieval cues in long-term memory when one devotes undivided attention to the source of information with minimal distraction. Moreover, MBIs may enhance the ability to suppress irrelevant information and help block its storage in long-term memory. Consistent with this line of reasoning, Hölzel, Lazar, et al. (2011) followed participants in an MBSR program and reported an increase in gray matter concentration within the left hippocampus, which is closely associated with memory and learning process (Squire, 1992). Despite null-findings, it is worthwhile to perform further investigation because our summary effect size was estimated based on three studies and thus its generalizability is limited.

The current meta-analysis includes various executive function tasks involving conflict monitoring, inhibitory control, planning, cognitive flexibility, decision making, and problem-solving, and small overall effect sizes were observed. We can offer two explanations for these results. First, participants in an MBI are guided to monitor where the mind dwells in each moment and when needed, to redirect attention back to the object of meditation. The increased sensitivity to an incongruity between the present and expected goal states can bolster conflict monitoring (Teper, Segal, & Inzlicht, 2013). Furthermore, certain mindfulness exercises (e.g., yoga and walking) involve a process called deautomatization that can facilitate inhibitory control. As a result, increased awareness of habituated response patterns strengthens voluntary control over behaviors (Teper & Inzlicht, 2012). As Bishop et al. (2004) noted, one cardinal component of mindfulness is self-regulation of attention, which represents the ability to allocate cognitive resources efficiently based on situational demands and current goals. Thus, our results provide support for theorized effects of MBIs on executive function.

Substantial heterogeneity in effect sizes were observed for attention and executive function across studies, and our meta-regression analyses yielded significant moderating effects by intervention type. Compared with standard and modified MBSR and MBCT interventions, other types of MBIs showed lower treatment effects. These findings could be explained by the fact that the former had relatively longer treatment durations. It is also likely that MBSR- and MBCT-based interventions may have higher adherence to the treatment protocols with greater potency in their effectiveness. Despite the significant findings for intervention type, little evidence was found for the remaining moderating variables. The literature documents the application of mindfulness-based approaches to broad areas of physical and mental health across various age groups (Burke, 2010; Chiesa & Serretti, 2011; Keng, Smoski, & Robins, 2011). Our null findings for age and sample characteristics may corroborate MBI's broad applicability in cognitive domains such that MBIs may benefit cognitive performance in individuals of all ages with or without psychiatric or physical conditions. Contrary to our hypotheses, the number of treatment sessions and treatment duration did not account for heterogeneity in effect sizes across studies. It is possible that a relative narrow range of treatment duration and session numbers among included studies was not sufficient enough to account for otherwise large variability with interventions with longer treatment durations. Furthermore, although included MBIs carried shared emphasis on mindfulness as their primary component, the included studies considerably varied in session structure and content. One exemplary study by Britton et al. (2018) compared the effects of mechanistic targets (i.e., attentional control for FAM and emotional non-reactivity for OMM) while ensuring the equivalence in participant- and instructor-level variables between groups. Future research is warranted to categorize existing MBIs into distinct types and test whether such categorization can account for heterogeneity and differential effects on cognitive functions.

Identifying the specific cognitive effects of MBIs on clinical outcomes is a crucial next step for the field of clinical psychology. There is a large body of evidence that cognitive functions are impaired in psychological disorders. Poor inhibitory control, set-shifting, cognitive flexibility, and working memory updating were associated with symptom severity of generalized anxiety disorder and eating disorders (Tchanturia et al., 2004; Zainal & Newman, 2018). Furthermore, a meta-analysis by Snyder (2013) estimated moderately impaired performance in neuropsychological tests of executive function (Cohen's $d = 0.45–0.58$) for patients with major depressive disorder, compared to healthy control participants. Likewise, working memory deficits were documented among individuals with schizophrenia (see Forbes, Carrick, McIntosh, & Lawrie, 2009 for a meta-analysis). As evidence grows for the role of cognitive function in psychopathology, psychotherapists are increasingly turning to mindfulness interventions to treat various psychological disorders. Depressed individuals tend to ruminate on feelings of inadequacy and past failures, which may disrupt goal maintenance and working memory (MacLeod, Mathews, & Tata, 1986; Nolen-Hoeksema & Watkins, 2011). MBIs may improve the ability to monitor where the mind dwells in a given moment (also called meta-awareness), align cognitive resources with goal-relevant tasks efficiently, and reduce overgeneral autobiographical memory (Van der Velden et al., 2015; Williams et al., 2000). Since executive function and emotion regulation systems closely interact with each other and overlap anatomically and functionally, impaired executive function may adversely impact emotion regulation (Chambers et al., 2009a, 2009b). When the mind is already occupied by cognitively demanding tasks or perseverative negative thinking, such as worry and rumination, limited cognitive resources are available for emotion regulation. MBIs may facilitate the tendency to perceive thoughts and feelings as transient mental events and promote cognitive flexibility (Hayes & Wilson, 2003; Masuda, Hayes, Sackett, & Twohig, 2004), thus preventing such elaborative processing and reducing the burden on the emotion regulation system (Chambers et al., 2009a, 2009b).

5. Limitations and recommendations for future direction

The current meta-analysis synthesizes data across studies on MBIs with diverse populations and presents a balanced estimate of MBI's effects on cognitive function. However, we noticed several methodological issues within subsets of the included studies, thus it is worth highlighting these limitations and providing recommendations for further research. First, we noticed significant differences in conceptualizations and operational definitions of mindfulness. Without solid theoretical frameworks and validated measurement instruments, researchers risk creating "pseudo" mindfulness programs that lack clinical potency, specificity of behavioral effects, and coherence among the components of intervention. Although mindfulness research is still in a relatively early stage, researchers should prioritize specifying active ingredients of mindfulness-based treatment programs and develop objective measures to assess both meditation-induced and trait mindfulness (Davidson, 2010). These combined efforts will improve the quality of MBIs and strengthen empirical evidence of mindfulness research.

Second, most reviewed studies did not demonstrate whether participants had an improvement in mindfulness skills after receiving an MBI. The basic tenet is that MBIs enhance mindfulness skills, which in turn leads to improvements in cognitive function. However, only two studies assessed the direct effects of MBIs on levels of mindfulness. Without such information, internal validity of an MBI program becomes weak and significant findings cannot be solely attributed to the treatment effect. Likewise, null findings could indicate either lack of potency of a particular MBI program or the confirmation of the null hypothesis. Thus, MBI researchers need to develop and include a measure of state mindfulness that is sensitive to momentary fluctuations in mindfulness levels.

Third, some studies under review were underpowered and deemed exploratory in nature. Sample sizes in five studies were small, with having 40 or less participants in total. Using G power (Faul, Erdfelder, Buchner, & Lang, 2009), we estimated that 102 or 42 total participants are required to detect medium or large effect sizes with power at 0.8, respectively. When multiple correlated outcome measures are used, the estimated sample size needs to be increased further. Given that the summary effect sizes were insignificant to small, most included studies were not designed to detect hypothesized effects of their MBI program. To address this shortcoming and provide balanced estimates, we used the weighted mean effect sizes of individual studies for meta-analysis. However, studies with small sample sizes significantly reduce replicability due to insufficient power, and thus we recommend performing power analysis and using the adequate sample size in future studies.

Fourth, studies include many outcomes of cognitive function without providing clear justification for the link between an MBI and the selected outcome variables. For example, 17 out of 25 studies used multiple outcome measures. Since all outcome variables were nested within the cognitive task and correlations among these variables were likely to be high, significant results for a large number of variables should be interpreted with caution. Despite the inclusion of multiple outcome measures, none of the studies adjusted Type I error rates for multiple comparisons, nor provided explanation for the non-significant results in the majority of the cognitive measures. Thus, future investigation should implement a confirmatory analysis based on clear a priori hypotheses about the relation among study variables rather than a data-driven, exploratory approach.

Fifth, our study results must be interpreted with caution due to a possible ceiling effect on outcome measures. Participants in the included studies were young (mean age = 23.30, $SD = 10.2$) and primarily college students. Empirical evidence suggests that brain development is complete in the early twenties and cognitive functions tend to peak at this age range (Glisky, 2007; Mills et al., 2016). It is possible that the impact of an MBI was lower in young adulthood, and the ceiling effect may explain inconsistent findings in the studies using young participants. However, our results do not support for the moderatating effect of age. Thus, further research is needed to systematically evaluate the impact of MBIs on various age groups.

The last limitation of the reviewed studies is the lack of active control groups to account for the effects of nonspecific factors such as demand characteristics, social desirability, placebo effect, group differences in expectation, motivation, and face-to-face contact hours with the group members and therapist. In this meta-analysis, we computed an effect size by calculating standardized differences in pre-post treatment difference scores between MBI and control groups. When the groups were not equalized on the above factors, the internal validity of the study results became weak, which is corroborated by our risk of bias assessment. Thus, research may consider including a comparable treatment group without teaching substantive mindfulness skills, such as a cognitive enhancement program or "sham" meditation program that controls for confounding variables (Tang et al., 2015).

In sum, our meta-analysis offers empirical support that MBIs can benefit executive function. However, little evidence was found for other cognitive functions such as attention, working memory, and long-term memory. Furthermore, intervention type had significant moderating effects on improvements in attention and executive function. However, no moderating effects were observed for sample characteristics, age, number of treatment sessions, treatment duration, control group type, and study design. The aforementioned limitations warrant caution in interpreting the present findings as potential confounders and unexplained error variance may have biased the results of individual studies, and thus affected the current meta-analysis results. Thus, there is a clear need for methodologically sound and sufficiently powered randomized controlled studies that can establish a clear link between mindfulness components and cognitive functions. Many of the limitations we observed in these reviewed studies were found in the mindfulness meditation literature. Consistent with the criticisms of Van Dam et al. (2018), we found that this literature suffered methodological challenges including "haphazard variability" across MBIs as well as the need for replication of specific effects and increased internal validity from the use of active control groups. Many of their prescribed suggestions for future research apply here, such as the use of a multimodal approach, clearer operationalization of MBIs and outcome measures, replication with randomized designs and active control groups, and research conducted by multidisciplinary teams of investigators to minimize allegiance effects and confirmation bias (Van Dam et al., 2018).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cpr.2021.101972.

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