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REVIEW

Mindfulness and Attention: Current State-of-Affairs and Future Considerations

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Abstract
This review examines longitudinal studies of changes in components of attention following mindfulness training. A total of 57 retreat studies, non-randomized trials, and randomized controlled trials were identified. Employing the classical taxonomy proposed by Posner and Petersen (*Annual Review of Neuroscience, 13*(1), 25–42, 1990), outcome measures were broadly categorized based on whether they involved maintenance of an aroused state (alerting), selective prioritization of attention to target items (orienting), or assessed conflict monitoring (executive attention). Although many non-randomized and retreat studies provide promising evidence of gains in both alerting and conflict monitoring following mindfulness training, evidence from randomized controlled trials, especially those involving active control comparison groups, is more mixed. This review calls attention to the urgent need in our field of contemplative sciences to adopt the methodological rigor necessary for establishing mindfulness meditation as an effective cognitive rehabilitation tool. Although studies including wait-listed control comparisons were fruitful in providing initial feasibility data and pre-post effect sizes, there is a pressing need to employ standards that have been heavily advocated for in the broader cognitive and physical training literatures. Critically, inclusion of active comparison groups and explicit attention to the reduction of demand characteristics are needed to disentangle the effects of placebo from treatment. Further, detailed protocols for mindfulness and control groups and examination of theoretically guided outcome variables with established metrics for reliability and validity are key ingredients in the systematic study of mindfulness meditation. Adoption of such methodological rigor will allow for causal claims supporting mindfulness training as an efficacious treatment modality for cognitive rehabilitation and enhancement.

Keywords Mindfulness · Meditation · Attention · Rigorous randomized controlled trials

Introduction

> "Mindfulness means paying attention in a particular way: on purpose, in the present moment, and non-judgmentally."
> Jon Kabat-Zinn (1983)

> "Mindfulness is an innate human capacity to deliberately pay full attention to where we are, to our actual experience, and to learn from it."
> Jack Kornfield (2005)

> "Mindfulness is an open attentiveness to whatever arises."
> Pema Chödron (2001)

> "Mindfulness is a receptive attention to and awareness of present events and experiences."
> Brown and Ryan (2003)

Attention is considered central to the construct of mindfulness. The lessons of leading mindfulness teachers frequently note the use of attentional processes to alter information processing and influence emotional experiences, thought processes, and sensations (Chödron 2001; Hanh 1999; Kabat-Zinn 1990; Rosenberg 2004). The key practices taught in mindfulness

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training programs, such as breath awareness practices, body scan practices, walking meditation, and choiceless awareness, rely upon attentional processes to focus on a specific anchor, such as the breath, or various other phenomena, such as thoughts, emotions, and sensations, as they arise. Additionally, although measures of trait mindfulness differ with regard to the facets of mindfulness they include, the ability to sustain attention is common to the majority of these measures, particularly those garnering the most empirical support (Baer et al. 2006; Brown and Ryan 2003).

Despite the great interest in examining the impact of mindfulness on attention, evidence for a beneficial impact of training in skills and principles of mindfulness on attention is currently mixed. In this narrative review, our aim is to appraise the longitudinal training literature in which mindfulness practices are taught to improve performance on measures involving attentional functioning. We synthesize the results of these studies with the goal of clarifying the extent to which such training offers prophylaxis for the various components of attention. To review preliminary evidence of attentional benefits associated with mindfulness, we included non-randomized trials of short-term training and retreat studies—those examining the effects of mindfulness training without a comparison group or those that allowed for self-selection of training groups. In order to examine whether mindfulness training causally impacts attention, we included studies that randomized participants to a mindfulness group and at least one other comparison group.

Although prior reviews synthesizing the impact of mindfulness training on attention exist (Chiesa and Serretti 2010; Chiesa et al. 2011; Keng et al. 2011), there is an impressive body of literature that has emerged since these reviews were published that would contribute to our understanding of whether and how mindfulness impacts components of attention. Only one existing review of the mindfulness and attention literature has employed an organizational scheme for the attentional outcome variables (Chiesa et al. 2011), separating findings into alerting, orienting, and conflict monitoring domains (Posner and Petersen 1990). The other two reviews do not provide exhaustive summaries of the impact of mindfulness on attention, but instead, include attention as a secondary or tertiary area of interest within the wider domains of neurobiological evidence (Chiesa and Serretti 2010) or psychological evidence (Keng et al. 2011) for mindfulness training. The current review expands upon these previous reviews by organizing and discussing measures of attention by employing the well-established theoretical and descriptive networks-based model of attention proposed by Posner and Petersen (Posner and Petersen 1990; Petersen and Posner 2012). Herein, attention is decomposed into three independent processes of alerting, orienting, and executive control of attention, with each of these components relying on distinct neuroanatomical maps and served via different neuromodulators (Fan et al. 2005; Petersen and Posner 2012).

Although attention has been the focus of studies in cognitive science for many decades, it has been considered a rather elusive construct, underlying multiple perceptual and cognitive systems (Chun et al. 2011). Attention plays a key role in operations ranging from simple sensory processing to higher-order decision-making and long-term encoding and retrieval (Chun and Turk-Browne 2007). Given this versatility, it is no surprise that a myriad of attention measures have been employed in the mindfulness training literature. As such, categorizing the outcomes of these studies based on the well-established taxonomy of alerting, orienting, and executive attention will provide a framework for synthesizing the current literature and understanding the neurobiological mechanisms mediating the effects of mindfulness training on attention, subsequently aiding in future directions.

Another aim of this review, which sets it apart from existing reviews, is to highlight key methodological differences in study design and outcome variables that may help explain discrepant findings and provide suggestions for future mindfulness training studies. This discussion expands upon previous reviews examining the impact of mindfulness on attention, which have placed a much smaller emphasis on study design issues (Chiesa et al. 2011; Chiesa and Serretti 2010; Keng et al. 2011). In addition, all existing reviews have synthesized findings across both longitudinal training studies and cross-sectional comparisons of experienced meditators and naïve controls, thereby introducing heterogeneity in sample characteristics and conflating findings across studies that can and cannot infer causality. By narrowing the focus to longitudinal training studies, this review speaks directly to whether mindfulness training causally facilitates attentional functioning.

Given the increasing public interest in using mindfulness meditation to confer cognitive benefits in both healthy and clinical populations, it is imperative that the field of contemplative sciences adopts rigorous study designs that will provide unequivocal evidence of attentional benefits following mindfulness training. In this review, we synthesize the results of existing studies with the goal of clarifying the extent to which such training in mindfulness meditation yields benefits for the various components of attention. We also draw upon the broader training literature, which has been plagued by similar threats to internal validity, to critically evaluate existing studies and provide concrete suggestions for addressing such concerns in future studies.

Method

Literature Search

We conducted an electronic search in *PubMed*, *PsycINFO*, and *Web of Science* using the keywords *mindfulness*, *meditation*, *training*, *cognition*, *attention*, and *attentional* *control*. We then inspected the References sections of all retrieved articles for a cross-reference. We included peer-reviewed journal articles written in English and published prior to February 2019.

Selection of Trials

We excluded studies that were (1) case studies, (2) qualitative reports, (3) reviews, (4) meta-analyses, or (5) commentaries/editorials. Given that the primary aim of this review is to assess the current state-of-affairs regarding the impact of mindfulness training on attention, we did not impose restrictions on the populations from which study samples were drawn. Thus, studies targeting both community participants as well as clinical populations were included. We included non-randomized trials, retreat studies, and randomized controlled trials (RCTs) in which participants engaged in a mindfulness intervention involving more than one session of in-person training. The term "mindfulness training" can refer to training in a number of fairly distinct practices, but for the purposes of this review, we included studies in which training involved practices requiring sustained or selective attention to a particular object (i.e., focused attention) or receptive attention to the transient occurrence of sensations, thoughts, or emotions (i.e., open monitoring). The majority of studies employed standardized or adapted versions of mindfulness-based stress reduction (MBSR), or described training as "mindfulness training," "mindfulness awareness practices," "open monitoring," or "focused attention meditation." Other training included mindfulness-based cognitive therapy (MBCT), attentional control training, integrative body-mind training, breathworks mindfulness training, the Benson mindfulness technique, open and calm, the school-based MindUp program, and mindfulness-based mind fitness training (see Table 1 A–C). We included RCTs—those where either a participant or a group of participants had an equal chance of being in any of the intervention or control groups—in the current review. Studies involving any type of comparison group, including active control groups and wait-listed control groups, were included. Additionally, non-randomized trials and retreat studies—those examining performance following mindfulness training without a comparison group or those that allowed for self-selection of training groups, including those involving quasi-randomized designs—were included to review preliminary evidence of attentional benefits following mindfulness training. Lastly, included studies assessed at least one measure of attention falling into the alerting, orienting, or executive control domains and investigated intervention effects by analyzing pre- and post-intervention data using within subjects change or interactions between group and timepoint.

Data Extraction and Synthesis

Attentional outcomes of interest were classified into three components: alerting, orienting, or executive attention. Tasks capturing alerting included visual discrimination tasks, tasks of visual search, and sustained attention. Tasks capturing orienting included both top-down selection of stimuli through endogenous processing or bottom-up direction of attention via exogenous processing. Finally, for executive control of attention, we restricted our search to tasks involving conflict monitoring, such as the Flanker task or the Stroop task. We did not include studies that assessed more higher-order cognitive control tasks, such as set-shifting and task-switching. Although there is debate in the literature regarding the differentiation of executive attention and cognitive control, we considered tasks of executive attention to be those that involved selection of sensory representations. In contrast, cognitive control, considered to be a super-set of attention, involves goal-directed selection of broader stimulus representations, such as attentional sets, decisions, and motor responses (Buschman and Kastner 2015). As such, tasks assessing cognitive flexibility, such as set-shifting, planning, and task-switching, were not included in the current review.

For each study, we coded the presence or absence of five design characteristics: (1) randomization of participants to groups; (2) inclusion of an active control group; (3) explicit attention to reduction of demand characteristics; (4) detailed discussion of content of the intervention and control groups; and (5) following of study reporting guidelines (such as CONSORT). We also reported sample characteristics including number of participants, mean age, and any clinical features; frequency and duration of training in intervention and control groups; presence and length of at-home practice; dependent variables of interest, including task name and outcome metrics; and the main longitudinal findings (Table 1 A–C).

Search Results

The database search retrieved 1409 papers; 420 were removed based on the above exclusionary criteria. From the remaining studies, 932 did not meet the above inclusionary criteria and 57 were selected for inclusion (see PRISMA Fig. 1). We identified 34 randomized controlled trials examining the effect of multi-session mindfulness training compared with a control group (see Table 1 A for study details), five non-randomized retreat

Table 1 (A–C) Brief summaries of studies that involved (A) randomized controlled trials examining the effects of training on attention; (B) non-randomized, longitudinal, retreat studies examining the effects of intensive mindfulness practices on attention; and (C) non-randomized short-term studies assessing the training effects of mindfulness programs on attention, but lacking the rigor of RCTs. For each of the studies, we have provided key study characteristics, such as the sample, details of the mindfulness group vs. the control group, engagement in home practices, and the attention-related dependent variables, classified as alerting (A), orienting (O), and executive attention (E). Each study is also rated on the five design characteristics discussed in the manuscript: (1) randomization of participants to groups; (2) inclusion of an active control group; (3) explicit attention to reduction of demand characteristics; (4) detailed discussion of content of the intervention and control groups; and (5) following of study reporting guidelines (such as CONSORT)

Table 1(A)

	Authors	Year	Design					Sample	Intervention Group(s)	Control Group(s)	Home Practice		Dependent Variables		Main Findings: Group Differences?
			1	2	3	4	5						Task	Metric	
1	Linden	1973	✓	✓	✓	✓		Third grade students § N = 90 recruited	Meditation. § 20-25 min. twice/week for 18 weeks § n = 30 assigned § n = 26 analyzed	1) Study skills guidance § 45 min. once/week for 18 weeks § n = 30 assigned --------------- 2) No intervention § n = 30 assigned	None	O	CEFT	Field independence: § Accuracy scores	Meditation group had higher field independence scores compared with both the active control group and the no intervention group.
2	McMillan, Robertson, Brock, & Chorlton	2002	✓	✓				Traumatic brain injury patients § N = 145 recruited § N = 130 analyzed § Mean age = 34	ACT § 45 min. once/week for 4 weeks. § n = 50 assigned § n = 44 analyzed § Mean age = 35	1) Physical exercise § 45 min. once/week for 4 weeks § n = 47 assigned § n = 38 analyzed § mean age = 31 --------------- 2) No intervention § n = 48 analyzed § Mean age = 36	Daily (audiotape)	A	TEA (all subtests)	Scaled scores	NS
3	Anderson, Lau, Segal, & Bishop	2007	✓					Healthy adults § N = 86 recruited § N = 72 analyzed § Mean age = 39.5	MBSR § 2 hr. once/week for 8 weeks § n = 46 assigned § n = 39 analyzed § Mean age = 37	Wait-list § n = 40 assigned § n = 33 analyzed § Mean age = 42	None: MBSR group encouraged to engage in at-home practice	A	Vigil CPT	Sustained attention: § Target discrimination (hits – false alarms) § Mean RT	NS
												E	Emotional Stroop Task	Affective response inhibition: § True errors (reading word, naming incorrect color) § False errors (non-word response) § Mean RT	NS
												A	Object Detection Task	Non-directed attention: § Mean accuracy § Mean RT	NS
4	Tang et al.	2007	✓	✓				Undergraduates at a Chinese university § N = 80 recruited and analyzed § Mean age = 22	IBMT § 20 min. once/day for 5 days § n = 40 assigned and analyzed	PMR § 20 min. once/day for 5 days § n = 40 assigned and analyzed	None	A O E	ANT	Alerting, Orienting, Conflict § Mean RT	IBMT showed greater improvement on conflict trials compared to PMR.

5	MacLean et al.*	2010	✓			✓		Healthy adults familiar with mindfulness practice § N = 60 recruited § N = 59 analyzed	Focused attention meditation retreat § 3 months § Mean = 5 hr./day Shamatha § Mean = 45 min./day complementary practices § n = 30 assigned	Wait-list § n = 30 assigned § Engaged in focused meditation retreat similar to the first group § Assessments completed at start and end of retreat	None	A O	Sustained Attention Task	Discrimination: § Target height Perceptual sensitivity: § A' = hits – false alarms Vigilance: § Slope of A'	§ Mindfulness training produced improvements in discrimination, but not vigilance when comparing Retreat 1 to wait-list participants. § Mindfulness training in Retreat 2 led to improvements in discrimination and vigilance.
	Sahdra et al.*	2011	✓			✓		Healthy adults familiar with mindfulness practice § N = 60 recruited § N = 59 analyzed	Focused attention meditation retreat § 3 months § Mean = 5 hr./day Shamatha § Mean = 45 min./day complementary practices § n = 30 assigned. § n = 29 analyzed	Wait-list § n = 30 assigned § Engaged in focused meditation retreat similar to the first group § Assessments completed at start and end of retreat	None	A O	Response Inhibition Task	Threshold § Average A' = hits – false alarms § Slope of A' across blocks	§ Retreat 1 participants showed significant improvements in perceptual sensitivity across training compared with wait-listed controls. § Retreat 2 participants also showed increases in perceptual sensitivity and vigilance.
	Zanesco, King, MacLean, & Saron*	2018	✓			✓			Follow-ups for retreat groups 1 and 2: § 6-month: n = 55 § 1.5-year: n = 44 § 7-year: n = 44	None: previously wait-listed participants completed retreat	None	A O	Sustained Attention Task	§ *A'* = hits – false alarms § Slope of A' § RT_CV	Across both retreats there were improvements in perceptual discrimination, response inhibition accuracy, vigilance, and RT_CV. There were no significant changes in response inhibition accuracy across 7-year follow-up, and gains were maintained above half the level of retreat-training gains for several years of follow-up. Age-related deficits were moderated by continued engagement in meditation practice.
6	Semple	2010	✓	✓	✓		✓	Healthy adults § N = 53 recruited § N = 45 analyzed § Mean age of those analyzed = 40	Benson Mindfulness Technique § Pretest 90 min. individual training session § Posttest 20 min. individual training session § n = 19 assigned § n = 15 analyzed	1) Jacobson PMR § Pretest 90 min. individual training session § Posttest 20 min. individual training session § n = 18 assigned § n = 14 analyzed --------------- 2) Wait-list § n = 16 assigned § n = 16 analyzed	20 min. twice/day for 4 weeks (audiotape)	A	CPT	Sustained attention: § Discriminability (log d)	Mindfulness group demonstrated greater discriminability than controls.
												E	Stroop Color-Word Task	Response inhibition: § Accuracy interference	NS
7	Allen et al.	2012	✓	✓	✓	✓		Students in Denmark § N = 61 recruited § N = 38 analyzed § Mean age = 26.5	Focused awareness and open monitoring practices § 2 hr. once/week for 6 weeks § n = 30 assigned § n = 19 analyzed § Mean age = 27	Shared reading and listening § 2 hr. once/week for 6 weeks § n = 31 assigned § n = 19 analyzed. § Mean age = 26	20 min./day	A	Error Awareness Task	Response inhibition: § Stop accuracy (commission errors) Error awareness: § Percent error awareness (aware/total errors)	NS
												E	Affective Number Counting Stroop Task	Stroop interference: § Incongruent trial RT-congruent trial RT	Greater reduction in Stroop interference RT for the mindfulness group.

8	Jensen, Vangkilde, Frokjaer, & Hasselbalch	2012	✓	✓	✓	✓	✓	Students in Denmark § N = 49 recruited § N = 47 analyzed	MBSR § 2.5 hr. once/week for 8 weeks plus 7-hr. retreat § n = 17 assigned § n = 16 analyzed	1) NMSR § 2.5 hr. once/week for 8 weeks § n = 16 assigned § n = 15 analyzed ---------------- 2) No intervention: § n = 16 assigned § At post-test n = 8 assigned to incentivized condition § At post-test n = 8 assigned to non-incentivized condition	45 min./day formal practice, 15 min./day informal practice	A	DART	Vigilance: § RT & RT_CV for frequent targets	MBSR and NMSR had lower RT_CV to frequent targets than non- incentivized controls. Also, incentivized controls had increased RT_CV at post-training.
												O	STAN	Spatial orienting: § RTs after invalidly cued, short temporal trials § RTs after neutral cues and neutral trial RT_CV	Incentivized controls improved more on neutral trial RT than both active groups. No group differences on RT_CV.
												E	Stroop Color-Word Task	Response inhibition: § Incongruent block error rate § Mean block RT § Block interference (incongruent RT – congruent RT)	MBSR and incentivized groups had fewer errors on incongruent blocks than non-incentivized controls. Incentivized controls improved most on RT on all blocks.
												E	d2 Test of Attention	§ Total error rate (commissions + omissions) § Error percentage (total errors/total trials) § Error distribution (error sums for three test sections)	MBSR improved error distributions more than all other groups.
												A O	CombiTVA	§ Number of correctly reported letters § Threshold of conscious perception (t0) § Maximum capacity of visual working memory (K) § Speed of visual processing (C) § Top-down controlled selectivity (α)	MBSR showed increased *t* 0 compared to non-incentivized controls. MBSR increased capacity of working memory more than inactive no-intervention groups (non-incentivized and incentivized controls). NMSR and incentivized controls had larger improvements on selectivity than MBSR.
9	Moore, Gruber, Derose, & Malinowsk i	2012	✓			✓	✓	Healthy adults § N = 40 recruited § N = 32 analyzed § Mean age = 35	Meditation training § 2 hr. training prior to T1 assessment § 1 hr. training prior to T2 assessment § n = 20 assigned § n = 14 analyzed § Mean age = 36.9	Wait-list § n = 20 assigned § n = 18 analyzed § Mean age = 34.6	10 min./day at least 5 days/week for 16 weeks prior to T3 assessment	E	Stroop Color-Word Task	Response inhibition: § Mean RT § Variability (SD) of RT § Inverse efficiency score (mean RT/ proportion correct responses)	NS
10	Ainsworth, Eddershaw, Meron, Baldwin, & Garner	2013	✓	✓				Healthy young adults § N = 76 recruited § N = 73 analyzed § Mean age = 20	1) Focused attention meditation § Three 60-min. sessions over 8 days § n = 24 assigned and analyzed ---------------- 2) Open monitoring meditation § Three 60-min. sessions over 8 days § n = 25 assigned and analyzed	Wait-list § n = 27 assigned § n = 24 analyzed	10 min./day	A O E	ANT	Alerting, Orienting, Conflict § Mean RT	Both active groups demonstrated improved performance on conflict trials (executive control) compared with the no intervention group.

11	Menezes et al.	2013	✓	✓		✓		Undergraduate students at a Brazilian university § N = 100 recruited § N = 74 analyzed § Mean age = 25	Focused attention meditation § 90 min./week for 6 weeks § n = 35 assigned § n = 26 analyzed	1) PMR § 90 min./week for 6 weeks § n = 37 assigned § n = 24 analyzed 2) Wait-list § n = 28 assigned § n = 24 analyzed	Time not specified (audiotape)	A	Concentrated Attention Test	Focused attention: § Correct answers § Errors § Omissions § Total score	Only meditation group reduced omission in concentrated attention test.
												A	Discrimination Task	Emotion interference: § RT to emotional images § Response bias (k) (tendency to respond similarly, regardless of trial)	Meditation reduced emotion interference in the easy condition, which was associated with practice time. Meditation and relaxation reduced response bias during high load.
12	Fan, Tang, Tang, & Posner	2014	✓	✓				Undergraduates at a Chinese university § N = 43 recruited and analyzed § Mean age = 21	Integrative Body-Mind Training § 20-30 min. once/day for 5 days § n = 21 assigned and analyzed	PMR § 20-30 min. once/day for 5 days § n = 22 assigned and analyzed	None	E	Stroop Color-Word Test	Response inhibition: § Stroop interference RT and accuracy (color, word, color-word)	IBMT group showed significantly faster RTs than the control group and less RT interference. There were no group differences in Stroop accuracy.
13	Josefsson, Lindwall, & Broberg	2014	✓	✓				Healthy community adults § N = 126 recruited § N = 104 analyzed	Mindfulness meditation § 45 min. twice/week for 4 weeks § n = 46 assigned § n = 38 analyzed	1) Relaxation training § 45 min. twice/week for 4 weeks § n = 40 assigned § n = 35 analyzed --------------- 2) Wait-list § n = 40 assigned § n = 31 analyzed	None	E	Stroop Color-Word Test	Response inhibition: § Interference RT (incongruent - neutral and incongruent - congruent) § Error rate during incongruent block § Average RT during incongruent block	NS
14	MacCoon, MacLean, Davidson, Saron, & Lutz	2014	✓	✓	✓	✓	✓	Healthy community adults § N = 80 recruited § N =54 analyzed for CPT. § Mean age = 46.5	MBSR § 2.5 hr./week for 8 weeks plus 7-hr. retreat § n = 31 assigned § n = 29 analyzed § Mean age = 45	Health enhancement program § 2.5 hr./week for 8 weeks plus 7-hr. retreat § n = 31 assigned § n = 25 analyzed § Mean age = 48	45 min./day	A	CPT	Discrimination: § Target height discrimination Vigilance: § A' = hits – false alarms § Slope of A'	NS (though trending results for target height discrimination)
15	Jensen et al.	2015	✓			✓	✓	Stressed community adults § N = 72 recruited § N = 68 analyzed § Mean age = 42	1) Open and Calm individual meditation course § 1.5 hr./week for 9 weeks § n = 24 assigned § n = 21 analyzed § Mean age = 42.5 --------------- 2) Open and Calm group meditation course § 2.5 hr./week group, plus two 1.5-hr. optional individual sessions § n = 24 assigned § n = 24 analyzed § Mean age = 41.7	Treatment as usual § n = 24 assigned § n = 23 analyzed § Mean age = 42.6	10-20 min. once or twice/day (audiotape) mini-meditations and frequent 1-2 min.	A	TVA	§ Threshold of conscious perception (t_0)	The Open and Calm group improved more on t_0 than controls adjusting for baseline performance. Greater t0 was associated with increased intervention compliance.
16	Johns et al.	2016	✓	✓	✓	✓	✓	Breast and colorectal cancer survivors with clinically significant fatigue § N = 71 recruited § N = 68 analyzed § Mean age = 57	MBSR § 2 hr./week for 8 weeks § n = 35 assigned § n = 33 analyzed § Mean age = 56.9	Fatigue education and support group § 2 hr./week for 8 weeks § n = 36 assigned § n = 35 analyzed § Mean age = 56.4	20 min./day	E	Stroop Color-Word Test	Response inhibition: § Accuracy rate § Average block RT	No change in RT, but MBSR group showed higher accuracy on the incongruent relative to congruent trials.

17	Menezes & Bizarro	2015	✓			✓		Students at a Brazilian university § N = 46 recruited § N = 33 analyzed § Mean age = 23.9	Focused meditation § 90 min./day for 5 days § n = 23 assigned § n = 14 analyzed § Mean age = 23.9	Wait-list § n = 23 assigned § n = 19 analyzed § Mean age = 24.9	None	A	Concentrated Attention Task	Concentrated attention: § Number of correct responses § Number of errors § Omission errors	Meditation group showed increased correct responses relative to controls.
18	Schonert-Reichl et al.	2015	✓			✓		4th and 5th grade classrooms § N = 100 recruited § N = 99 analyzed § Mean age = 10.2	MindUP program § 40-50 min. 12 times over 4 months § n = 49 assigned § n = 48 analyzed § Mean age = 10.16	Social responsibility program § n = 51 assigned and analyzed § Mean age = 10.31	None	E	Flanker Task	§ Average RT on flanker incongruent trials, switch trials and reverse trials § Average RT and % accuracy on switch and reverse trials	MindUP program showed faster RT on Flanker incongruent, switch, and reverse trials compared to participants in control group.
19	Bhayee et al.	2016	✓	✓	✓	✓	✓	Stressed community dwelling adults § N = 43 recruited § N = 26 analyzed § Mean age = 32.65	N-tsMT § 10 min. once at baseline and once at follow- up (audiotape). § n = 20 assigned § n = 13 analyzed § Mean age = 33.3	Khan Academy math training § 15 min. once at baseline and once at follow- up (audiotape) § n = 23 assigned § n = 13 analyzed § Mean age = 32.0	10 min./day (audiotape) N-tsMT: § Meditation (audiotape) Math: § Algebra practice problems	E	Stroop Color-Word Task	Response inhibition: § Mean RT § Trial interference (incongruent RT – congruent RT)	The mindfulness group showed more improvement in Stroop RT than controls. The mindfulness group initially exhibited greater self-reported effort during practice than controls, but these became equivalent by the end of training.
												A	d2 Test of Attention	§ Commission errors § Omission	NS
20	Kiani, Hadianfard,& Mitchell	2016	✓			✓	✓	Female adolescents with elevated ADHD symptoms § N = 30 recruited. § N = 30 analyzed § Mean age = 13.30	Mindfulness training § 1.5 hr./week for 8 weeks § n = 15 assigned § n = 15 analyzed § Mean age = 13.17	Wait-list. § n = 15 assigned § n = 15 analyzed § Mean age = 13.42	Time not specified	A	CPT	Sustained attention: § Number correct § Omission errors Response inhibition: § Commission errors	NS
												E	Stroop Color-Word Test	Response inhibition: § Color-word interference	Mindfulness group exhibited better inhibition post-training than wait-list.
21	Becerra, Dandrade, & Harms	2017	✓			✓		Students at an Australian university § N = 62 recruited § N = 46 analyzed § Mean age = 33.9	Mindfulness training § Once every 2 weeks for 8 weeks § n = 31 assigned § n = 23 analyzed	Wait-list § n = 31 assigned § n = 23 analyzed	24 min./day (audiotape)	A O E	ANT	Alerting, Orienting, Conflict § Mean RT	Mindfulness training group showed improved orienting and executive attention (conflict), but not alerting.
22	Course- Choi, Saville, & Derakshan	2017	✓	✓		✓		Adults with high worry § N = 86 recruited § N = 60 analyzed § Mean age = 28.67	Mindfulness training § 21 min. once at baseline (audiotape); at home daily for 1 week § n = 15 assigned and analyzed § Mean age = 30.67	1) Adaptive N-back working memory training § At home daily for 1 week § n = 15 assigned and analyzed § Mean age = 27.93 ---------------- 2) Combined mindfulness and adaptive working memory training § At home daily for 1 week § n = 15 assigned and analyzed § Mean age = 28.73 ---------------- 3) Control 1-back training § n = 15 assigned and analyzed § Mean age = 27.33	Mindfulness training: § 21 min./day § Adaptive duration (online) Combined training: § Adaptive duration (online audiotape) 1-back training: § Not specified	O	Anti-saccade and pro-saccade tasks	§ Mean latency of correct anti-saccades. § Error rate (percent incorrect anti-saccades)	NS

23	Felver, Tipsord, Morris, Racer, & Dishion	2017	✓			✓		School-age children § N = 47 recruited and analyzed § Mean age = 11.08	MFSR § 90 min. once/week for 8 weeks § n = 24 parent – child dyads assigned (48 people) § n = 24 children analyzed § Mean age =	Wait-list § n = 23 parent – child dyads assigned (46 people) § n = 23 children analyzed § Mean age = 11.08	15-20 min./day	A O E	ANT	Alerting, Orienting, Conflict § Mean RT	Mindfulness training improved conflict and orienting scores, but not alerting scores.
24	Jansen, Dahmen-Zimmer, Kudielka, & Schulz	2017	✓	✓				Older adults § N = 102 recruited § N = 55 analyzed § Mean age = 63.5	MBSR § 60 min. twice/week for 8 weeks § n = 15 analyzed § Mean age = 63.29	1) Karate § 60 min. twice/week for 8 weeks § n = 23 analyzed § Mean age = 62.57 --------------- 2) Wait-list § n = 17 analyzed § Mean age = 65.24	None	E	Stroop Color-Word Test	Response inhibition: § Accuracy interference	NS
25	Malinowski, Moore, Mead, & Gruber	2017	✓	✓				Older adults § N = 56 recruited § N = 44 analyzed § Mean age = 64.5	Mindfulness training § 90 min. four times over 8 weeks § n = 22 analyzed	Brain training § 90 min. four times over 8 weeks § n = 22 analyzed	10 min./day at least 5 days/week	E	Emotional-Counting Stroop Test	Response inhibition: § Mean RT § Hit rate	Mindfulness group, but not brain training, exhibited improved RTs.
26	Mitchell et al.	2017	✓				✓	Adults with ADHD § N = 22 recruited § N = 20 analyzed § Mean age = 38.39	Mindful awareness practices for ADHD § 2.5 hr./week for 8 weeks § n = 11 assigned and analyzed § Mean age = 40.55	Wait-list § n = 11 assigned § n = 9 analyzed § Mean age = 36.22	Time not specified	A O E	ANT	Alerting, Orienting, Conflict	NS
												A	Conners CPT	Omission, commission, RT, RT SE, variability, detectability, response style (beta), perseverations	NS
27	Oken et al.	2017	✓	✓	✓	✓		Older adults § N = 134 recruited § N = 128 analyzed § Mean age = 60.2	Mindfulness meditation training § 60-90 min. once/week for 6 weeks § n = 66 assigned § n = 60 analyzed § Mean age = 60.2	Wait-list § n = 68 assigned and analyzed § Mean age = 59.4	30-45 min./day (audiotape)	E	Stroop Color-Word Test	Response inhibition: § Accuracy on incongruent Condition § Accuracy interference (color-word)	NS
												E	Flanker Task	RT on incongruent trials	NS
												A	Choice RT task	RT	NS
28	Rahl, Lindsay, Pacilio, Brown, & Creswell	2017	✓	✓	✓			Healthy adults § N = 147 recruited § N = 142 analyzed § Mean age = 21	1) Attention monitoring mindfulness training § 20 min. once/day for 4 days § n = 41 analyzed --------------- 2) Attention monitoring & acceptance mindfulness training § 20 min. once/day for 4 days § n = 41 analyzed	1) Relaxation training § 20 min. once/day for 4 days § n = 38 analyzed --------------- 2) Reading group § 20 min. once/day for 4 days § n = 22 analyzed	None	A	SART	Sustained attention: § Discrimination (hit rate – error rate)	The attention monitoring & acceptance group showed the greatest discrimination compared to other conditions.

29	Rooks, Morrison, Goolsarran, Rogers, & Jha	2017	✓	✓				College football players during high-demand pre-season training § N = 100 § Mean age = 19.81	Mindfulness training § 45 min. group training once/week for 4 weeks § 12 min. proctored guided audio training four times/week § n = 56 assigned § n = 49 analyzed	Relaxation training § 45 min. group training once/week for 4 weeks § 12 min. proctored guided audio training four times/week § n = 44 assigned § n = 32 analyzed	12 min./day audio recordings	A	SART	§ *A'* = hits – false alarms § ICV	Both *A'* and ICV declined during high-demand pre-season training, with no significant impact of intervention group. However, greater engagement in mindfulness training, but not relaxation training, predicted greater protection from decline on both SART measures.
30	Li, Liu, Zhang, Liu, & Wei	2018	✓			✓		Healthy adults § N = 34 recruited § N = 30 analyzed	MBCT with less emphasis on depression-related content § 2.5 hr. once/week for 8 weeks § n = 17 assigned § n = 15 analyzed § Mean age = 30.4	Wait-list § n = 17 assigned § n = 15 analyzed § Mean age = 28.4	30 min./day	A	AX-CPT	Sustained attention: § Error rate § RT § Behavioral Shift Index	NS
31	Quan, Wang, Chu, & Zhou	2018	✓	✓				Chinese undergraduate students § N = 48 recruited § N = 44 analyzed § Mean age = 19.2	MBCT § 100 min. once/day for 7 days § n = 24 assigned § n = 22 analyzed	Relaxation § 100 min. once/day for 7 days § n = 24 assigned § n = 22 analyzed	15 min./day of mindfulness exercises for MBCT group, letting the mind wander for relaxation group	A O E	ANT	Alerting, Orienting, Conflict § Mean accuracy § Mean RT	MBSR group showed greater improvement in orienting and conflict components relative to controls.
32	Giannandrea et al.	2019	✓				✓	Healthy adults § N = 60 recruited § N = 37 analyzed	MBSR § Nine sessions § n = 30 assigned § n = 20 analyzed § Mean age = 36.5	Wait-list § n = 30 assigned § n = 17 analyzed § Mean age = 35.9	Time not specified	A	SART	Commission errors	MBSR group showed greater reduction in SART errors relative to wait-list.
33	Isbel, Lagopoulos, Hermens, & Summers	2019	✓	✓				Healthy older adults aged 60 and older § N = 120 recruited § N = 79 analyzed	Mindfulness- based attention training § 8 weeks, session duration not specified § n = 77 assigned § n = 49 analyzed § Mean age = 71.6	Computer-based attention training § 8 weeks, session duration not specified § n = 43 assigned § n = 30 analyzed § Mean age = 69.5	Daily practice beginning with 20 min./day in week 1 and increasing to 45 min./day in week 8	A	Auditory Oddball Task	§ Total errors § Mean RT § RT_CV	NS
34	Lawler, Esposito, Doyle, & Gunnar	2019	✓	✓		✓	✓	Internationally-adopted children § Age range = 6-10 § N = 106 recruited § N = 96 analyzed	Mindfulness training (MT) § 2 hr./week for 6 weeks § n = 38 assigned § n = 33 analyzed § Mean age = 7.6	1) Executive function training (EFT) § 2 hr./week for 6 weeks § n = 35 assigned § n = 32 analyzed § Mean age = 8.0 ---------------- 2) No intervention (NI) § n = 33 assigned § n = 31 analyzed § Mean age = 8.0	Time not specified	E	Flanker Task	§ Mean accuracy § Mean RT	EFT group showed more improvement on accuracy to incongruent trials relative to MT and NI groups.

Note: * Same study but reported different/follow-up outcomes in the three papers.

Table 1(B)

	Authors	Year	Design 1	Design 2	Design 3	Design 4	Design 5	Sample	Intervention Group(s)	Control Group(s)	Home Practice		Dependent Variables: Task	Dependent Variables: Metric	Main Findings: Group Differences?
35	Brown, Forte, & Dysart	1984						Teachers of Buddhist meditation, staff at retreat center, retreat participants, and control participants § N = 49 recruited and analyzed	*1)* Teachers at the Insight Meditation Society § n = 7 recruited and analyzed § 1-2 hr./day --------------- *2)* Staff at retreat center not actively participating § n = 11 recruited and analyzed § 1-2 hr./day --------------- *3)* Retreat participants § n = 21 recruited and analyzed § 3-month live-in retreat; 16 hr./day	Non-meditators § n = 10 recruited and analyzed	--	A	Visual detection and discrimination	Detection threshold: § Shortest stimulus duration for which 70% correct detection over at least 10 trials Discrimination threshold: § Shortest interval for which 70% correct discrimination of two flashes over at least 10 trials	Control group participants differed from all three meditation groups in detection threshold but not discrimination. The three meditation groups did not differ from one another on detection threshold.
36	Slagter et al.	2007 *				✓		Meditation practitioners and matched novice controls § N = 40 recruited and analyzed § Mean age = 41	3-month live-in Vipassana retreat § 10-12 hr./day § n = 17 assigned and analyzed § Median age = 41	Matched novice controls § 1-hr. meditation class § n = 23 assigned and analyzed § Median age = 41	For controls: § 20 min./day for 1 week prior to the assessment	A	Attentional Blink Task	Attentional blink: § Target 2 accuracy for trials in which target 1 was correctly reported	Retreat participants showed significantly reduced attentional blink (increased accuracy) at post-assessment compared with controls.
	Lutz et al.	2009 *				✓						O	Dichotic Listening Task	§ Mean RT § SD of RT § Sensitivity index (*d'*)	The retreat group demonstrated improved ability to sustain attention as indicated by reduced RT variability (SD). No differences in overall RT or sensitivity.
37	van Leeuwen, Singer, Melloni	2012						Meditation practitioners and matched novice controls § N = 12 recruited and analyzed § Mean age = 50	4-day open monitoring retreat § n = 6 assigned and analyzed § Mean age = 50	Matched novice controls § n = 6 assigned and analyzed § Mean age = 50	Not quantified	O	Global to Local Task	§ Average RT for correct responses	Meditators demonstrated faster RTs, and also reduced local precedence.
38	Zanesco, King, MacLean, & Saron	2013						Meditation practitioners and matched novice controls § N = 55 recruited § N = 50 analyzed § Mean age = 52	1-month live-in Vipassana retreat § 10 hr./day § n = 28 assigned § n = 26 analyzed § Mean age = 50	Wait-list, matched controls § n = 27 assigned § n = 24 analyzed § Mean age = 55	--	A	Response Inhibition Task	§ *A'* = hits – false alarms § RT_CV	The retreat group exhibited increased sensitivity and decreased RT variability compared controls.
39	Kozasa et al.	2018			✓	✓		Experienced and novice meditators § N = 33 recruited § N = 31 analyzed § Mean age = 45	All participants attended a Zen meditation retreat § 12 hr./day for 7 days § Experienced meditators: n = 19 recruited; 18 analyzed § Novice meditators: n = 14 recruited; 13 analyzed		--	E	Stroop Color-Word Task	For congruent, neutral, and incongruent trials: § Accuracy § RT	NS

Note. * Same study but reported different outcomes in the two papers.

Table 1(C)

	Authors	Year	Design					Sample	Intervention Group(s)	Control Group(s)	Home Practice		Dependent Variables		Main Findings: Group Differences?
			1	2	3	4	5						Task	Metric	
40	Jha, Krompinger, & Baime	2007				✓		Graduate students at an American University § N = 51 recruited and analyzed § Mean age = 23	*1)* MBSR § 3 hr. once/week for 8 weeks § n = 17 assigned and analyzed § Mean age = 24 ---------------- *2)* Retreat § 1 month live-in, 10-12 hr./day § n = 17 assigned and analyzed § Mean age = 35	No intervention § n = 17 assigned and analyzed § Mean age = 22	30 min./day	A O E	ANT	Alerting, Orienting, Conflict § Mean accuracy § Mean RT	MBSR participants showed improved orienting RT compared to the control group and retreat group.
41	Zylowska et al.	2008				✓		Adolescents and adults with ADHD § Adolescents: N = 8 recruited; 7 analyzed § Mean age = 15.6 § Adults: N = 24 recruited; 18 analyzed § Mean age = 49	Mindful awareness practices § 2.5 hr. once/week for 8 weeks § n = 32 assigned § n = 25 analyzed	None	Daily (duration not specified)	A O E	ANT	Alerting, Orienting, Conflict § Mean RT	Mindfulness training improved conflict, but not alerting or orienting scores.
												E	Stroop Color-Word Test	Response inhibition: § Accuracy scores for color, word, and color-word conditions	Mindfulness training improved Stroop color and color-word interference, but not word scores.
42	Heeren, Broeck, & Philippot	2009				✓		American adults § N = 44 recruited § N = 36 analyzed § Mean age = 54.5	MBCT § 2.5 hr. once/week for 8 weeks § n = 26 assigned § n=18 analyzed § Mean age = 54	Matched controls § N = 18 assigned and analyzed § Mean age = 55	Not specified; followed MBCT protocol that presumably included home practices	A	GoStop Task	Motor inhibition: § Proportion of inhibited responses/total stop trials	NS
43	Cusens, Duggan, Thorne, & Burch	2010		✓		✓		British adults § N = 32 recruited § N = 30 analyzed § Mean age = 46.7	Breathworks mindfulness training program § 6-10 2.5 hr. sessions once/week § n =12 assigned and analyzed	Treatment as usual § n = 20 assigned § n = 18 analyzed § Mean age = 48.4	30-45 min./day	A	CPT	Sustained attention: § Mean *d'*	NS
44	Rodriguez Vega et al.	2014						Spanish psychiatry and clinical psychology residents § N = 103 recruited § N = 101 analyzed	MBSR § 2.5 hr. once/week for 8 weeks plus 7-hr. retreat § n = 60 assigned § n = 58 analyzed § Mean age = 30	Wait-list § n = 43 assigned and analyzed § Mean age = 28	Not specified; followed MBSR protocol that presumably included home practices	A	CPT	Sustained attention: § Percent omissions § Percent commissions § Mean RT § Mean *d'* § Beta RT consistency: § SE of predicted RT by sub-block § SE of predicted RT by ISI	NS

												E	Stroop Color-Word Test	Response inhibition: § Word & color RT § Congruent, incongruent, neutral RT § Errors § Perseverations	MBSR group had reduced word, congruent, and neutral RT, as well as fewer errors and perseverations compared to controls.
45	Morrison, Goolsarran, Rogers, & Jha	2014				✓	✓	American undergraduate students § N = 58 recruited § N = 43 analyzed § N = 42 analyzed for SART § Mean age = 18	Mindfulness training § 20 min. once/week for 7 weeks § n = 38 assigned § n = 25 analyzed § n = 24 analyzed for SART after removal of outlier	Wait-list § n = 20 assigned § n = 18 analyzed	20 min. twice/week proctored in-lab (audiotape)	A	SART	Sustained attention: § Mean accuracy § Mean target accuracy § Mean non-target accuracy § Mean RT on correct non-target responses	Group X time effects on accuracy driven by decreased non-target performance in controls. Mindfulness decreased RT variability compared to controls.
46	Lenze et al.	2014						Older adults with symptoms of anxiety, depression, and cognitive dysfunction § N = 34 recruited § N = 32 completed MBSR § N = 29 analyzed for cognitive assessments § Mean age = 70.8	*1)* 8-week MBSR § 2.5 hr. once/week for 8 weeks plus one day retreat § n = 16 assigned § n = 15 completed training § Mean age = 70.9 -------------- *2)* 12-week MBSR § 2.5 hr. once/week for 12 weeks plus one 2.5 hour day retreat § n = 18 assigned § n = 17 completed training § Mean age = 70.7	None	Not specified; followed MBSR protocol that presumably included home practices	E	Computerized Color- Word Interference Test	§ Color-word interference: RT	MBSR reduced interference.
47	Tabak & Granholm	2014						Veterans with psychotic disorders § N = 10 recruited § N = 7 analyzed for cognitive assessments § Mean age = 45.1	Mindfulness training § 60 min. once/week for 6 weeks § n = 7 analyzed	None	5-15 min./day	A	MATRICS Consensus Cognitive Battery	§ Attention/ vigilance	NS
48	Meland et al.	2015						Military personnel preparing for redeployment § N = 48 recruited § N = 40 analyzed § Mean age = 37.5	MBSR § 10-hr. introductory course plus 3 hr. once/week § n = 31 assigned § n = 25 analyzed § Mean age = 35	Wait-list § n = 17 assigned § n = 15 analyzed § Mean age = 40	20 min. twice/week (personal sessions)	A	SART	Sustained attention: § Errors of commission § Mean RT	Mindfulness group showed improved SART RT compared to wait-list controls.
												O	Attentional Capture Task	Discrimination: § Sensitivity (*d'*) § Mean RT	NS
49	Sanger & Dorjee	2016						Healthy adolescents § N = 47 recruited § N = 45 analyzed after removal of outliers	.b Foundations Programme § 50 min. once/week for 8 weeks § n = 22 assigned § n = 20 analyzed § Mean age = 16.6	Wait-list § n = 25 assigned and analyzed § Mean age = 17.1	None	A	Oddball Task	Attention: § RT, accuracy, omissions, false-alarms (pre-target, post-target)	NS

50	Spadaro & Hunker	2016						Nursing students § N = 26 recruited and completed intervention § N = 23 analyzed	Online adapted MBSR § 8 weeks § n = 26 assigned and analyzed	None	Encouraged to practice once/week	A O E	ANT	Alerting, Orienting, Conflict § Mean RT § Mean accuracy	NS
51	Huguet, Ruiz, Haro, & Alda	2017			✓			Children with ADHD § N= 6 recruited § N= 5 analyzed	Mindfulness meditation training § 75 min. once/week for 8 weeks § Mean age = 9.2	None	Time not specified	E	Stroop Color-Word Card Test	Color-word accuracy	Significant improvement pre-post mindfulness training.
												A	CPT-3	Inattentiveness, sustained attention, vigilance, impulsivity scales	NS
52	Jha, Morrison, Parker, & Stanley	2017			✓			High-stress predeployment American military personnel § N = 55 recruited § N = 45 analyzed § Mean age = 27.5	MMFT § 2 hr. once/week for 8 weeks plus a full day retreat § n = 31 assigned § n = 28 analyzed § Mean age = 30	Military control group § n = 24 assigned § n = 17 analyzed § Mean age = 25	30 min./day	A	SART	Sustained attention: § Mean RT § Mean accuracy § ICV = SD RT/Mean RT Sensitivity: § *A'* = hits – false alarms	Those with high mindfulness practice times exhibited greater sensitivity and reduced self-reported mind-wandering than those with low practice time. Whereas sensitivity declined from T1 to T2 for controls and low practice individuals, those with high practice maintained performance.
53	Marshall, Laures-Gore, & Love	2017		✓				Adults with aphasia § N = 10 recruited § N = 8 analyzed § Mean age = 56.38	Aphasia Mindfulness Meditation Program § 30 min. for 5 days § n = 5 analyzed	Instructor-led mind-wandering in group setting § n = 3 analyzed	Daily home practice beginning with 10 minutes and increasing to 30 minutes	A	Conners CPT	Sustained attention: § Omissions § Commissions § Hit RT § Hit SE § Detectability § Perseverations § Hit RT block change § Hit SE block change	NS
												A O E	CRSD-ANT	Alerting, orienting, executive control RT measures	NS
54	Ridderinkhof, de Bruin, van den Driesschen, & Bögels	2018			✓			Individuals with Autism Spectrum Disorder and their parents § N = 49 recruited	MYmind § 1.5 hr. once/week for 9 weeks plus booster session 9 weeks post-training § n = 49 assigned § n = 42 pretests analyzed § n = 39 posttests analyzed § n = 36 two-month follow ups analyzed § Mean age = 12.90	Age, gender, and education-matched typically developing children who did not participate in an intervention § n = 51 assigned and analyzed § Mean age = 12.98	Not specified	A O E	Child version of ANT	Alerting, orienting, executive control: § Mean accuracy § Mean RT	NS

55	Tarrasch	2018				✓		Third, fourth, and fifth grade students § N = 101 recruited § N = 93 analyzed CPT § N = 90 analyzed Visual Search	MBSR § 45 min. once/week for 10 weeks § n = 58 assigned § n = 51 complete CPT § n = 48 complete Visual Search § Mean age = 10.1	Wait-list § n = 43 assigned § n = 42 complete CPT § n = 42 complete Visual Search § Mean age = 10.17	Time not specified	A	CPT	Sustained attention: § Percent omissions § Percent commissions § Standard deviation of response time	MBSR groups showed fewer commission errors relative to controls.
												A	Conjunctive Visual Search Task	Selective attention: § Mean accuracy	MBSR groups showed improved accuracy for smaller displays relative to controls. For larger displays, improvements were observed in both groups.
56	Van der Lubbe, De Kleine, Schreurs, & Bohlmeijer	2018				✓		Healthy students § N = 34 recruited § N = 28 analyzed § Mean age = 23.8	Pre-Post Group: § MBSR without full-day retreat § Assessments completed pre and post MBSR training § n = 15 analyzed	Post-Post2 Group: § MBSR without full-day retreat § Assessments completed post training and then 8 weeks later § n = 13 analyzed	45 min./day on 5 days/week	A	Unspeeded Go/No-Go Task	Transient and sustained spatial attention: § *d'* Response bias: § lnβ	NS
57	Wong, Teng, Chee, Doshi, & Lim	2018				✓		Nurses § N = 46 recruited § N = 36 analyzed	MBSR without full-day retreat § 1.5 hr. once/week for 8 weeks § n = 36 assigned and analyzed § Mean age = 30.3	None	Encouraged to practice at least 15 min./day	A	Psychomotor Vigilance Task	Sustained attention: § Median response speed (1/RT) § Lapses (RT > Median + 2SD of the RT)	At post-test, participants exhibited slower response speed and more lapses. However, higher attendance was associated with better performance on response speed and lapses.

Notes. NS = no significant difference.
Interventions: ACT: Attentional Control Training; IBMT: Integrative Body-Mind Training; MBCT: Mindfulness-Based Cognitive Therapy; MBSR: Mindfulness-Based Stress Reduction; MMFT: Mindfulness-Based Mind Fitness Training; MFSR: Mindful Family Stress Reduction; NMSR: Non-Mindfulness Stress Reduction; N-tsMT: Neurofeedback-Assisted, Technology-Supported Mindfulness Training; PMR: Progressive Muscle Relaxation.
Tasks: ANT: Attention Network Task; CEFT: Children's Embedded Figures Test; CombiTVA: Combination Theory of Visual Attention Task; CPT: Continuous Performance Task; CRSD-ANT: Centre for Research on Safe Driving – Attention Network Test; DART: Dual Attention to Response Task; SART: Sustained Attention to Response Task; STAN: Spatial and Temporal Attention Network; TEA: Test of Everyday Attention.
Metrics: ICV: intraindividual coefficient of variation for reaction time; RT: Reaction Time; RT_CV: Reaction Time Coefficient of Variability

studies examining attentional performance before and after an intensive multi-day mindfulness retreat (see Table 1 B for study details), and 18 non-randomized short-term training studies that did not employ randomization of participants to groups (see Table 1 C for study details). There were two studies that reported results in separate papers, and for the purpose of this review, results from the same study were integrated and jointly represented in the tables and figures.

Mindfulness and Attention: a Review of the Current Literature

According to the classical taxonomy proposed by Posner and Petersen (Posner 1980; Posner and Petersen 1990), the attentional system of the brain is classified into three distinct networks that correspond with the independent processes of alerting, orienting, and the executive control of attention. The alerting component, relying on a right-lateralized network of regions including the thalamus and the frontal and parietal cortices (Sturm and Willmes 2001), is involved in the maintenance of an aroused state. Phasic alertness captures moment-to-moment fluctuations in this state of internal readiness, whereas tonic alertness captures the sustained vigilance of an aroused state (Petersen and Posner 2012). Orienting of attention, by contrast, is concerned with prioritizing the sensory representations that capture our attention, either through top-down, goal-driven stimuli or through bottom-up, salient stimuli. The orienting network is further partitioned into a top-down, dorsal attention stream, comprised of the frontal eye fields and the intraparietal sulci, and a bottom-up, ventral stream, comprised of the right-lateralized temporal parietal junction and the ventral frontal cortices (Corbetta and Shulman 2002). Measures assessing orienting often involve tasks of spatial attention in which attention is directed to a spatial location either through goal-driven activity or unexpected salience of the

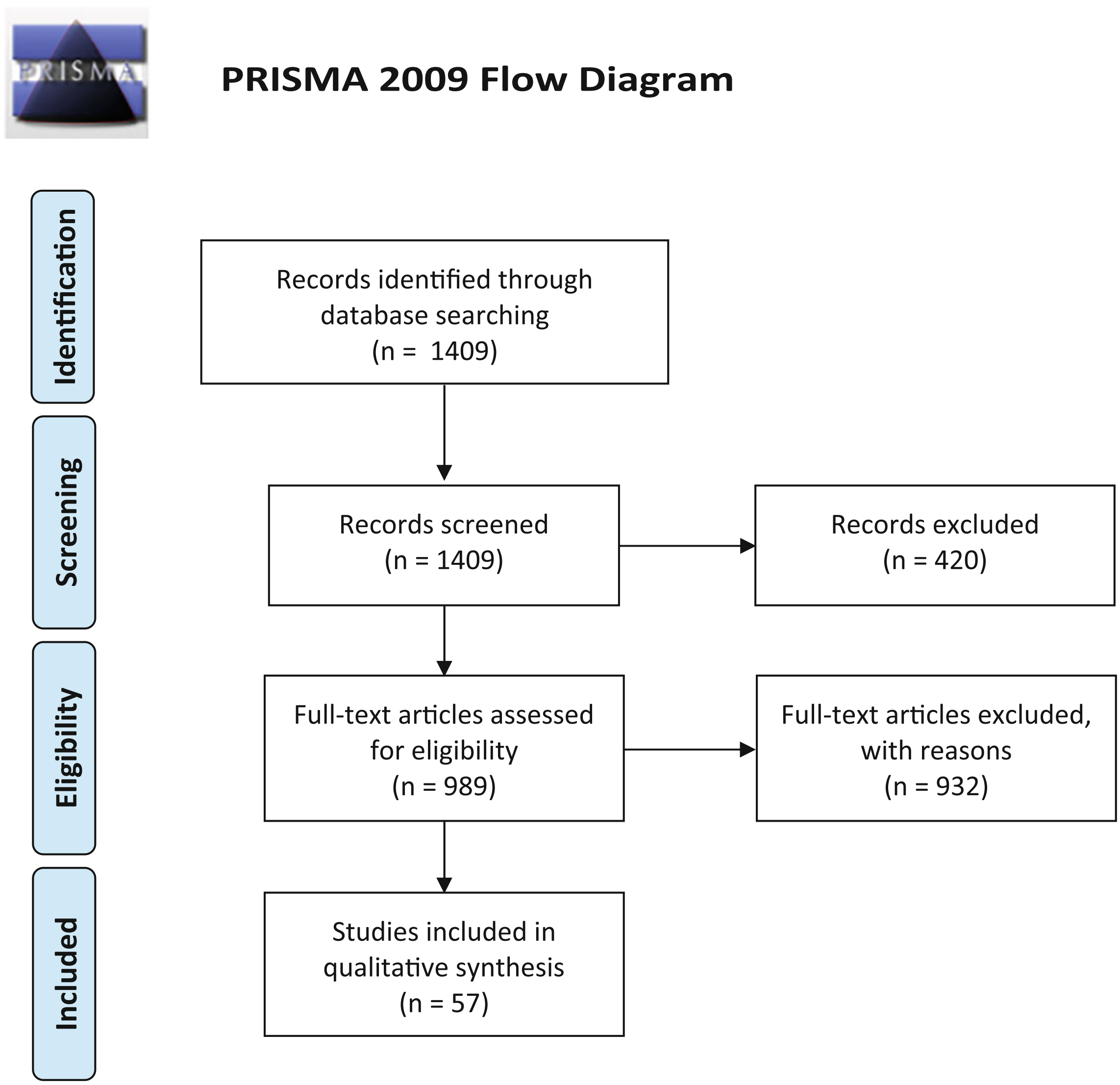

Fig. 1 Presents the search results using the PRISMA flowchart

stimuli. The third and final component of attention, conflict monitoring, is largely reliant on the frontoparietal and cingulo-opercular networks (Dosenbach et al. 2008) and involves detecting and resolving competition between dominant and non-dominant responses (Petersen and Posner 2012).

These three systems are subserved by distinct sets of interconnected nodes distributed throughout the brain. Together, they support processes involved in maintaining an aroused state, selection of endogenously or exogenously driven sensory representations, and finally, the detection of relevant targets. This detection amplifies activity within neural representations of the target stimuli, while simultaneously suppressing or slowing activity of other sensory representations. Although there is evidence that the three components of attention are largely independent, the attention network task, developed by Posner and Petersen (1990), allows for assessment of all three components within a single task (Fan et al. 2005). The ANT is a classic Flanker task requiring participants to respond to the direction of a central arrow while ignoring two flanking arrows on either side of this target arrow. Trials are preceded by various cue conditions serving either an alerting function, by giving a warning signal indicating the upcoming trial, or an orienting function, by spatially directing attention to the location at which the arrows will appear. While alerting is concerned with indicating when the target will appear, orienting provides information about where the target will appear (Petersen and Posner 2012). And finally, the conflict component of the ANT, providing a measure for executive control of attention, involves comparison of incongruent trials, where the target and flanking arrows point in opposite directions, with congruent trials, where all arrows are pointing in the same direction.

In the section below, we review the current state of the mindfulness training literature for the three components of attention. Given that the ANT was designed specifically to capture these three components of attention and has been extensively studied in the mindfulness training literature, we start each section by discussing results from this task, followed by a discussion of other measures tapping the individual components. Additionally, all sections first include a discussion of preliminary results offered by non-randomized retreat and short-term training studies, followed by a presentation of results from more rigorous randomized trials.

Alerting

As noted above, the alerting component of attention captures the internal readiness for incoming stimuli, specifically for high priority targets. This component can be further parcellated into phasic and tonic alertness. Phasic alertness refers to moment-to-moment fluctuations in attention in response to cues and is primarily assessed using visual and auditory discrimination tasks. Tonic alertness refers to maintenance of a vigilant state and is often assessed with tasks of sustained attention. In this section, we review the effects of mindfulness training on both of these sub-components of alertness.

Phasic Alerting In what is now considered to be a seminal study, Jha et al. (2007) employed the ANT to examine changes in the three different components of attention following a 1-month retreat and an 8-week MBSR program. Although this study was a non-randomized trial, it provided evidence for enhanced alerting or a general "attentional readiness" to incoming stimuli following engagement with mindfulness practices in a 1-month retreat. However, short-term training studies, including five non-randomized studies (Jha et al. 2007; Zylowska et al. 2008; Spadaro and Hunker 2016; Marshall et al. 2017; Ridderinkhof et al. 2018) and six RCTs (Tang et al. 2007; Ainsworth et al. 2013; Becerra et al. 2017; Felver et al. 2017; Mitchell et al. 2017; Quan et al. 2017), have found no improvements on the alerting component of the ANT. This pattern of results, with benefits for phasic alerting observed after longer-term retreat training, has also been found in studies employing other metrics.

For example, an early study by Brown et al. (1984) provided the first evidence for improvements in perceptual detection following mindfulness training. Specifically, the authors examined changes in the ability to detect rapidly presented flashes of light and discriminate between successive flashes, which depend on the ability to activate relevant topographic areas in the visual cortex (Chun et al. 2011; Tootell et al. 1998). This study found a decrease in detection thresholds in participants, teachers, and staff members following a 3-month intensive retreat, but such gains were not observed for the control group. Similarly, MacLean et al. (2010) and Sahdra et al. (2011) provided evidence that 3 months of intensive retreat training improved visual discrimination. Notably, improvements in visual detection and discrimination have also been observed in short-term RCTs (Jensen et al. 2012, 2015 Menezes et al. 2013). For example, employing the combiTVA paradigm (Kyllingsbæk 2006), which provides a computationally derived estimate of four attention parameters, Jensen et al. (2012) found that MBSR resulted in reduced visual perception thresholds.

There is also evidence indicating that mindfulness training improves other aspects of phasic alertness. For example, participating in a 3-month mindfulness retreat increased performance on the attentional blink task (Slagter et al. 2007), which captures the temporal limits of attention. In this study, the retreat group exhibited an increased ability to detect the second target in a rapid stream of distractor letters, with neuroimaging evidence from electroencephalography demonstrating that this was accompanied by decreased allocation of neural resources to the first target. There is also evidence, across RCTs, of increased phasic alertness in mindfulness participants, compared with control groups, on tasks of visual search that require detection of a target stimulus in an array of objects (Jensen et al. 2012; Menezes et al. 2013; Menezes and Bizarro 2015).

Taken together, the landscape of studies assessing the impact of mindfulness training on phasic alertness via tasks of perceptual encoding and discrimination provides promising results. Although a handful of RCTs failed to find improvements on some measures of phasic alertness, such as the auditory oddball task (Isbel et al. 2019), choice reaction time (Oken et al. 2017), and visual search tasks (Anderson et al. 2007; Bhayee et al. 2016), many long-term and short-term studies provide evidence of gains in visual detection and discrimination following training. However, it is important to note that the majority of these studies either did not include a comparison group or included wait-listed control groups, limiting the causal attributions that can be assigned to training in mindfulness.

Tonic Alerting Given the emphasis placed on monitoring emerging thoughts, emotions, and sensations in mindfulness training, metrics of sustained attention, or "tonic alerting," are frequently examined outcome variables. Two retreat studies, 12 non-randomized short-term training studies, and 12 RCTs have evaluated the impact of mindfulness on various metrics of sustained attention. Most of these studies have employed variants of the Go/No-Go task or the sustained attention to response task (SART), in which participants are asked to respond to frequently presented distractor stimuli and withhold responses to rare targets (Robertson et al. 1997). These tasks capture both the ability to discriminate hits from false alarms (sensitivity index) as well as decline in this vigilance index over time (slope of the sensitivity index). An additional measure that can be captured in these long-duration tasks is the variability in reaction time to frequently occurring stimuli (reaction time coefficient of variability; RT_CV). This index of response speed variability is largely unaffected by practice effects (Flehmig et al. 2007) and is often considered to be an objective marker of mind wandering, thus reflecting fluctuations in the maintenance of a vigilant state (Cheyne et al. 2009). Similar to studies assessing phasic alerting, the two studies assessing change following long-term engagement in mindfulness practices (MacLean et al. 2010; Zanesco et al. 2013), yielded positive results. Across these studies, there were significant improvements on metrics of sustained attention, both the sensitivity index and RT_CV, at post- compared with pre-training, suggesting increasing ability to sustain attention and reduce mind wandering following participation in mindfulness retreats.

In contrast, short-term studies have yielded conflicting evidence for the benefits of mindfulness training on these metrics of sustained attention. For example, although there is some evidence for decreased RT_CV (Morrison et al. 2014), reduced reaction time (RT; Meland et al. 2015), and fewer errors of commission (Tarrasch 2018) in non-randomized studies following mindfulness training, eight of the other non-randomized mindfulness training studies failed to find benefits. Similarly, of 12 short-term RCTs examining the impact of mindfulness training on sustained attention, only four found improvements on metrics of sustained attention. In one study, a 4-week mindfulness intervention improved discrimination over and above a progressive muscle relaxation group and a wait-listed control group (Semple 2010). However, differential gains were observed only on the sensitivity index, not other measures of vigilance, and this effect was larger for older than younger participants ($max_{age} = 56$ years). It is also possible that these benefits were inflated by the additive effects of training and engagement in mindfulness practices at the post-assessment sessions, particularly given that just one session of mindfulness training has been found to affect cognitive control abilities (Dickenson et al. 2013; Lee and Orsillo 2014). In another study, improved sensitivity was observed following training that combined attention monitoring and acceptance compared to attention monitoring alone, relaxation training, or a reading control group (Rahl et al. 2017). Notably, the third RCT reporting benefits on measures of sustained attention (Jensen et al. 2012) concluded that stress reduction, rather than mindfulness, explained these gains. Specifically, Jensen and colleagues, in addition to including an active control group, a "nonmindfulness" stress reduction group, also manipulated levels of attentional effort in half of the inactive control participants by incentivizing performance at post-training assessment (Jensen et al. 2012). Although training in mindfulness resulted in decreased RT_CV and this was significantly greater than both the inactive control groups, the stress reduction group also showed a similar reduction in RT_CV, suggesting a potentially important role of stress reduction in impacting this objective

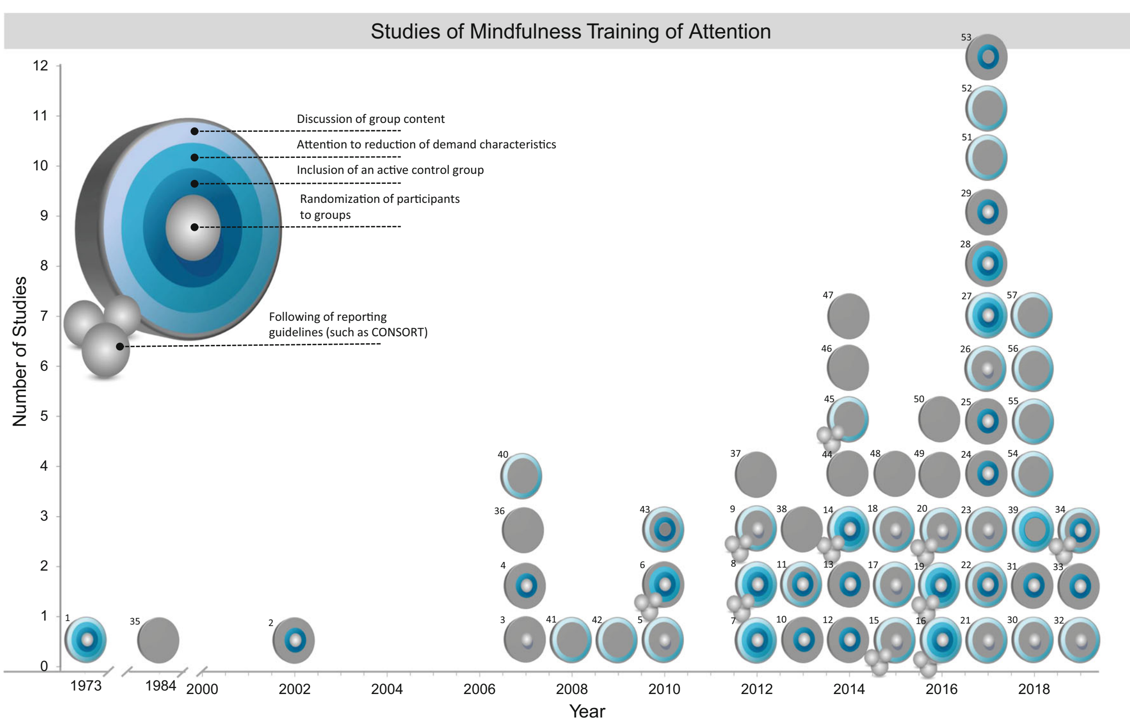

Fig. 2 Study design characteristics of longitudinal studies of mindfulness training. Spheres represent existing longitudinal training studies examining the impact of mindfulness training on facets of attention (labeled with their study numbers as listed in Table 1 A–C). Concentric layers are used to denote the presence of the first four study design issues discussed in the manuscript. The clustered "pearls of wisdom" denote studies that followed CONSORT guidelines

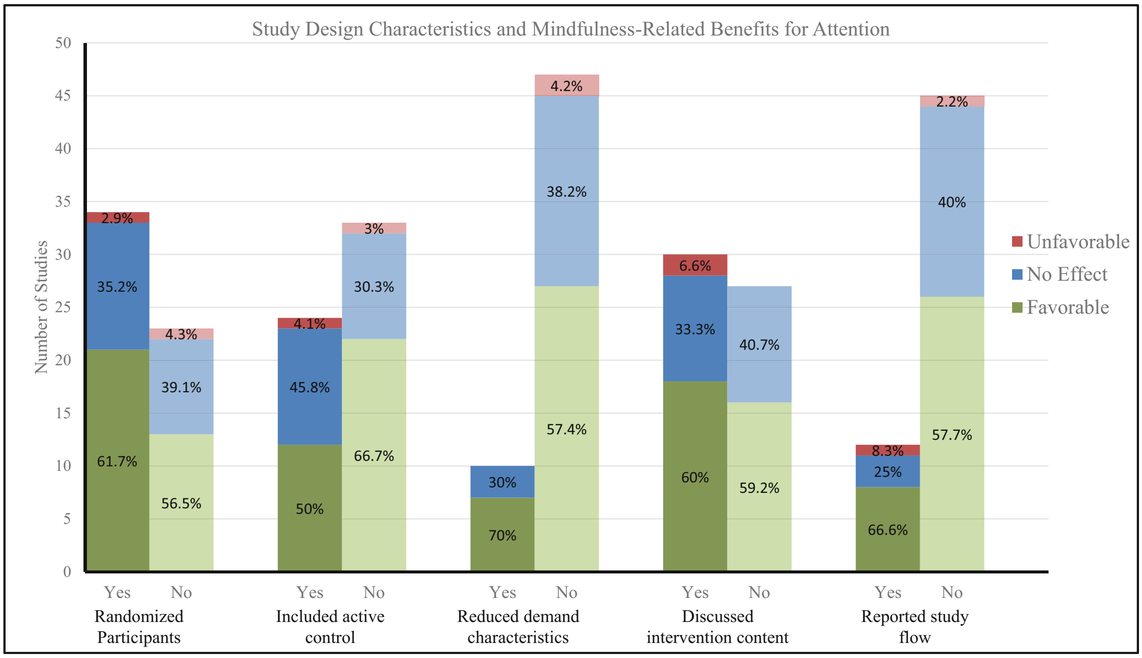

Fig. 3 Results of mindfulness training studies on attention separated by study design characteristic. For each characteristic, separate bars represent studies that did (“**Yes**,” **opaque colors**) and did not (“**No**,” **faded colors**) employ each characteristic. Studies finding benefits of mindfulness for one or more measures of attention are shown in green (“**Favorable**”). For RCTs, this refers to differential improvements in the mindfulness group compared to control groups, but for retreat studies and non-randomized studies, where no control group was employed, this includes pre-post improvements within the mindfulness group or where control participants were included, differential improvements compared to controls. Studies finding no significant effect of mindfulness training on attention or equivalent performance between the mindfulness and the control group at post-training are shown in blue (“**No Effect**”) and those finding a benefit for a control group over mindfulness training are shown in red (“**Unfavorable**”). The percentage of studies with each result are indicated within the bars, calculated separately for studies that did and did not employ each design characteristic

marker of mind wandering. And finally, Giannandrea et al. (2019) reported significant reductions in errors of commission on the SART at post-training for participants in the MBSR group compared with wait-list control participants.

Overall, there is limited evidence suggesting that mindfulness training, especially short-term training, enhances vigilance. One critical direction for future research is to assess the impact of mindfulness training on sustained attention at long-term follow-up periods. With the exception of a few studies that collected follow-up data at 6- and 12-month follow-up, assessments in the majority of short-term studies were conducted immediately after the training period. Although speculative, it could be the case that the beneficial impact of mindfulness training, especially for measures of sustained attention, emerges at a later period in time.

Orienting

Orienting involves the direction of attention towards internal or external stimuli, biasing selection either through internally generated task goals (top-down) or via perceptual capture of attention (bottom-up). In addition to the orienting metric of the ANT, this component has also been examined using tasks of attentional capture in which interference on a discriminability task is evaluated in the presence or absence of a salient task-irrelevant stimulus (Theeuwes and Chen 2005). In comparison to the other two components of attention, studies assessing the impact of mindfulness training on selective capture of attention are limited.

Initial evidence of mindfulness-related improvements on the orienting component of the ANT was provided by Jha et al. (2007), in which MBSR participants, relative to controls, showed facilitation of RT for trials with spatially directed cues compared with trials with a center cue. Benefits on this component of the ANT were also observed in two other RCTs comparing 8-week MBSR training with wait-listed control participants (Becerra et al. 2017; Felver et al. 2017) and one 7-day RCT comparing MBCT with a relaxation control group (Quan et al. 2018). However, no improvements on the orienting component of the ANT were observed in shorter-term studies involving 5 days of 20-min integrative body-mind training (Tang et al. 2007), three, 1-h sessions over an 8-day period of either focused attention or open monitoring practices (Ainsworth et al. 2013), or an 8-week MBSR program for adults with ADHD (Mitchell et al. 2017). Further, four additional non-randomized studies found no significant benefit for mindfulness training on this component of the ANT (Zylowska et al. 2008; Spadaro and Hunker 2016; Marshall et al. 2017; Ridderinkhof et al. 2018).

Several studies employing different measures of orienting, such as the dichotic listening task, the attentional capture task, and the anti-saccade task, have also not reported mindfulness-related gains. For example, Lutz et al. (2009) used the dichotic listening task to examine changes in attentional functioning following a 3-month intensive retreat. Although practitioners showed reduced variability in reaction time at post-training compared with novices, there were no differences between the two groups on target detection rates. Similarly, Meland et al. (2015), employing a non-randomized design, examined changes in an attentional capture task in military personnel preparing for deployment and found no differences between the two groups on this bottom-up task of perceptual attention. And finally, evidence from RCTs also provides weak support for mindfulness training impacting the orienting component of attention. For example, in the Jensen et al. (2012) study discussed above, the authors also examined the impact of MBSR on temporal attention and spatial attention, measures of perceptual selection to time points and locations that are prioritized by either exogenous or endogenous cueing. Their results provided evidence for greater improvements in the spatial attention measure in the incentivized control participants compared with the MBSR participants, highlighting the necessity of matching groups based on attentional effort. In the same study, Jensen et al. (2012) included a metric of top-down selectivity and also found that incentivized control participants and active control participants showed greater gains on this measure compared with MBSR participants. Similarly, one RCT found no differential impact of mindfulness training compared to N-back training or combined training on anti-saccade task performance, which required participants to inhibit a reflexive saccade towards a peripheral stimulus and instead quickly execute a voluntary saccade in the opposite direction (Course-Choi et al. 2017).

Thus, there is weak support in the literature for mindfulness-related benefits for the orienting component of attention. This is driven both by a lack of observed effects and a limited number of studies assessing either top-down or bottom-up attentional orienting.

Executive Control of Attention

The executive control component of attention helps resolve conflict among competing information by amplifying activity in target-relevant sensory representations and slowing detection in target-irrelevant representations. Within the mindfulness literature, the conflict component of the ANT and the Stroop task are two frequently employed measures of conflict monitoring.

Among non-randomized trials, only one retreat study has examined changes in the conflict component of the ANT (Jha et al. 2007). Although participants with prior meditation experience performed better on the conflict component of the ANT than controls at baseline, there were no significant improvements on this component following engagement in either the 1-month retreat or the 8-week MBSR program. Additionally, several other non-randomized short-term studies have failed to show mindfulness-related benefits for the conflict component of the ANT (Spadaro and Hunker 2016; Marshall et al. 2017; Ridderinkhof et al. 2018). Despite these studies suggesting a lack of improvement in the executive control of attention following mindfulness training, five RCTs comparing mindfulness training with either wait-listed or active control groups have found support for improvements on this component of the ANT (Ainsworth et al. 2013; Becerra et al. 2017; Felver et al. 2017; Tang et al. 2007, Quan et al. 2018; though see Mitchell et al. 2017 for non-significant results on this component of the ANT following mindfulness training for adults with ADHD).

For example, Becerra et al. (2017) examined the impact of an 8-week MBSR program on the three components of the ANT in undergraduate students in Australia. Comparing performance against a wait-list control group, they provided evidence for improvements on the conflict score. Similarly, Felver et al. (2017) also showed benefits of a mindfulness intervention, compared with a wait-list control group, for attentional performance in school-age children. Although encouraging, drawing causal conclusions from these studies is challenging given a lack of control over non-specific factors and demand characteristics. However, two additional RCTs, albeit of shorter duration, employed active control comparisons and provided evidence for improvements on the conflict component of the ANT. Tang et al. (2007) engaged undergraduate students in just 5 days of 20-min practices in integrated body-mind training and found improved conflict monitoring. Similarly, Ainsworth et al. (2013) found improvements after just three, 1-h sessions over an 8-day period of either focused attention or open monitoring practices. Thus, the positive results of these RCTs offer promise that mindfulness training promotes conflict monitoring, especially in the context of resolving selective interference during the Flanker-like ANT.

In contrast, the effects of mindfulness training on performance on the Stroop task are more equivocal, especially when comparing non-randomized to randomized controlled trials. The Stroop task, also conceptualized as a measure requiring the executive control of attention, involves suppression of reflexive word reading in favor of naming the color of ink in which the word is printed (Stroop 1935). Depending upon the modality of test administration (paper-or-pencil vs.

computerized), several dependent variables, including RT, errors on incongruent trials, or RT and accuracy interference, can be computed and examined for training-related change.

With the exception of one retreat study (Kozasa et al. 2018), non-randomized studies of mindfulness training have consistently reported improvements on the Stroop task. In these studies, 8 weeks of training resulted in reduced interference of Stroop color-word accuracy in adults and adolescents with ADHD (Zylowska et al. 2008), children with ADHD (Huguet et al. 2017), and older adults with clinically significant anxiety (Lenze et al. 2014), as well as reduced total errors in medical residents (Rodriguez Vega et al. 2014). In contrast, several well-designed RCTs have failed to provide support for mindfulness-specific benefits on various Stroop measures, including RT (Jensen et al. 2012; Josefsson et al. 2014; Moore et al. 2012), error rate (Anderson et al. 2007; Josefsson et al. 2014), and interference (Semple 2010; Josefsson et al. 2014; Jansen et al. 2016; Oken et al. 2017). For example, one RCT comparing 8 weeks of MBSR to a wait-list control group found no improvements on Stroop errors or RT despite having participants engage in meditative practices immediately prior to the assessment (Anderson et al. 2007). However, the authors acknowledged that the healthy sample and ceiling performance likely contributed to the lack of improvements. Similarly, other studies, employing either wait-list control groups (Moore et al. 2012; Josefsson et al. 2014) or active control groups (Jensen et al. 2012; Jansen et al. 2016; Oken et al. 2017), have also failed to find differential improvements on the Stroop task. Notably, Jensen et al. (2012) demonstrated the role of participant effort/motivation in explaining variance in cognitive gains. As described above, this study compared 8-week MBSR to an active control stress reduction group, a no-incentive wait-list control group, and an incentivized wait-list control group. Interestingly, although the mindfulness group improved in Stroop accuracy compared to the non-incentivized control participants, these improvements were not greater than those observed in the incentivized control participants, highlighting the role of participant effort on task outcomes. In fact, there is much discussion in the broader cognitive training literature regarding the role of participant expectancy in performance on measures of attentional control (Boot et al. 2011, 2013), and these results lend credence to such considerations in the mindfulness literature.

However, beneficial effects of mindfulness training for Stroop performance have been observed in several other RCTs, including faster RT (RT; Bhayee et al. 2016; Fan et al. 2014; Malinowski et al. 2017) and lower accuracy and RT interference (Allen et al. 2012; Fan et al. 2014; Johns et al. 2016; Kiani et al. 2016). Importantly, several of these studies did in fact address or control for expectancy effects. For example, one particularly well-designed RCT compared a 6-week mindfulness intervention to a group-based reading and listening group that was carefully matched for non-specific factors (Allen et al. 2012). Compared to this active control group, mindfulness training resulted in decreased RT interference on an affective Stroop task. One of the strengths of this study was the reduction of demand characteristics and expectancy bias through non-specific advertisements indicating that participants would be randomized to one of two wellness courses. Notably, all of these RCTs that found benefit (with the exception of Kiani et al. 2016) limited the influence of non-specific factors by comparing mindfulness training to active control interventions. These included psychoeducation and support (Johns et al. 2016), reading groups (Allen et al. 2012), brain training (Malinowski et al. 2017), math training (Bhayee et al. 2016), and progressive muscle relaxation (Fan et al. 2014). Thus, these studies provide confidence that the observed gains in the executive control of attention can be attributed to engagement with mindfulness practices rather than non-specific factors including, but not limited to, social support, engagement with stimulating materials, or facilitation of an intervention by experts.

Collectively, there is promising support for improvements in conflict monitoring, both when assessed via the Flanker task or the Stroop task, across several rigorous RCTs. Interestingly, with the exception of Kozasa et al. (2018), which was a 7-day intensive retreat study, the majority of studies assessing performance on the Stroop task were short-term training studies, providing encouraging support for the malleability of this component after short-term training. In at least one such study (Johns et al. 2016), benefits on the Stroop task were maintained at 6-month follow-up as well. Thus, across the three components of attention, benefits on conflict monitoring are well-supported through even short-term engagement with mindfulness practices.

Summary

Taken together, the literature examining attentional gains following mindfulness training, although offering promising support for some components of attention, is mired with conflicting evidence. Currently, there is a larger literature examining alerting and conflict monitoring rather than orienting, with the most promising support for conflict monitoring. Mindfulness-related benefits for this component have been observed in tightly controlled RCTs across the continuum of conflict monitoring tasks. This is especially noteworthy, as many of these RCTs reporting benefits for both the conflict component of the ANT and the Stroop task, included active control groups, and addressed issues related to expectancy effects. This suggests that the active ingredients of mindfulness training do have the potential to promote at least this component of attention. However, positive findings are by no means consistent, and so the field remains tasked with clarifying the features of training or particular dosages required for significant effects. This will require researchers to conduct rigorous RCTs that assess maintenance over an extended post-training period.

One potential contributor to the discrepant findings across studies is variation in task characteristics. For example, the modality of administration may impact the quality and quantity of outcome measures. Whereas the paper-and-pencil measures of most tasks are limited to assessment of errors, computerized assessment allows for an assessment of more fine-grained accuracy and RT variables with increased precision. Whereas some tasks such as the ANT are almost always computer-based, there is significant heterogeneity across studies in the characteristics of other tasks, including duration, number of trials, and established psychometric properties. These variations in task design, or even simple differences, such as the ordering of tasks within a session, should be taken into consideration as they are likely potent sources of variance in observed outcomes. In addition to these differences in task characteristics, there are a number of key study design issues that likely impact the observed results and are critical for clarifying the true impact of mindfulness training. One of the primary goals of this review is to highlight the necessity of rigorous RCTs in this literature and provide suggestions for future research. Thus, in the next section, we outline five criteria that we believe will help strengthen the design of future longitudinal studies in this field.

Study Design Considerations

We examined the longitudinal training studies reviewed above through the lens of five study design issues that are emphasized in the broader training literature as essential elements for establishing confidence in results (Boot and Simons 2012; Boot et al. 2013; Stothart et al. 2014). These criteria included (1) randomization of participants to groups, (2) inclusion of an active control group, (3) explicit attention to reduction of demand characteristics, (4) detailed discussion of content of the intervention and control groups, and (5) following of study reporting guidelines (such as CONSORT). Figure 2 is a graphical representation of the degree to which each longitudinal study satisfies these criteria, with the concentric spheres representing the first four criteria and the clustered "pearls of wisdom" representing explicit compliance with CONSORT guidelines. The number of studies employing each criterion varies considerably, with less than half of the studies including an active control group, reducing demand characteristics, or reporting on CONSORT guidelines (Fig. 3). Attention to such study design issues, we believe, will allow for reliable and valid causal claims regarding the benefits of mindfulness training for facets of attentional control.

1) Randomization of Participants to Groups Of the 57 studies identified and reviewed above, 34 randomized participants to the treatment group or the control group, an important step in establishing the causal influence of mindfulness practices in improving attentional control. As is well known, randomization of participants is essential for attributing changes in the outcome variables to treatment. Randomization also limits self-selection biases that may predispose the group, compared to the broader population, to benefit from the intervention. An important additional component to randomization is blinding experimenters who conduct pre–post-assessment sessions to participant group membership. The studies that did not employ randomization by design were either non-randomized trials of short-term training in mindfulness (18 studies) or retreat studies that examined the effect of either long-term or short-term intensive meditation practice on attention (5 studies). Non-randomized studies, assessing changes in the outcome variable pre- and post-intervention, are pragmatic and efficient ways of examining programs that are already being implemented in community settings and can provide valuable pilot data. For example, the non-randomized study conducted by Jha et al. (2007) suggested improvements in different components of the ANT following an 8-week program vs. a 1-month retreat. This type of study design can also be critical for assessing the feasibility and acceptability of an intervention in unique populations with differential sets of strengths, limitations, and needs. For example, Lenze et al. (2014) recently provided feasibility data for 8-week and 12-week MBSR programs for older adults (ages 65 and older), noting the necessity of modifying yoga poses and shortening retreat days for the aging cohort. However, there is an immediate need to expand upon these initial non-randomized studies to conduct trials that randomize participants to the training and control groups so that changes in outcome variables can be attributed to the mindfulness training.

Retreat studies are plagued by similar criticisms. Only one retreat study (reporting results in MacLean et al. 2010; Sahdra et al. 2011; Zanesco et al. 2018) randomized participants, in this case to either a 3-month intense retreat or a wait-list control condition. However, even in this study, pre-intervention assessments were conducted after randomization, creating the possibility of differential expectations influencing the obtained results. Inherent to these programs, which involve longer training periods and substantial daily commitments, is a pragmatic obstacle to randomization of participants. Individuals who are interested in such long-term training studies are willing or able to invest considerable resources to participate in such intense retreats. As such, a wait-list control condition that further delays participation might not be an appealing or realistic alternative. Thus, an ideal method for future research evaluating the effects of such retreat programs on attentional control might involve comparison of long-term meditation retreats with an active control condition that is designed to match the retreat condition for intensity and duration of training.

2) Inclusion of an Active Control Group Of the 34 studies that randomized participants, 22 included an active control group; additionally two non-randomized trials included an active control group. A contentious issue within this literature regarding the design of active control groups is the dissociation of "active" ingredients of mindfulness from non-specific factors that may also be contributing to the success of such training programs. Across studies, there is good agreement on a few of these non-specific factors. For example, given that mindfulness training is typically offered in a group format, social support is one non-specific factor that could influence attention (Bassuk et al. 1999). Inclusion of an active control group that offers training in a group format can be a valid control for this important determinant of cognitive functioning. Similarly, interacting with a group leader with expertise on the content of the intervention could also have an impact on the expectations of benefit. The majority of studies that had a facilitator for the training group also employed a facilitator for the control group who was matched with respect to expertise.

The training studies that employed active control groups did, however, differ on some critical non-specific factors that could have implications for observed effects. The three control groups that have been regularly used in the literature include relaxation controls, nutrition education groups, and book reading groups. Despite some variations in relaxation control groups, most have been designed to control for the stress-reducing effects of physical relaxation on attention. Although mindfulness programs are designed to cultivate alertness, the practice of paying attention to some specific anchor in a non-judgmental manner often results in a state of relaxation (Baer 2003; Dunn et al. 1999). Thus, a relaxation control group, designed to invoke a physical state of restfulness, can control for the stress-reducing aspects of relaxation on attentional control. However, it is often not clear the extent to which these relaxation control groups involve collaborative discussions, which allow participants to engage with the intervention content with similarly experienced peers and discuss methods for incorporating these practices into their daily lives. Such discussions often act as a critical source of social support in group settings and are an important ingredient likely influencing attentional control. As such, nutrition education control groups and book reading groups that facilitate such social engagement offer a tighter control for the non-specific factor of social support. Interestingly, Fig. 3 shows that the percentage of studies observing benefits for mindfulness over control groups drops from 64% in studies with inactive control groups to 54% in those including an active control group. This pattern highlights the need for effective, active control groups, to most accurately capture mindfulness-specific benefits.

3) Explicit Attention to Reduction of Demand Characteristics When designing active control groups, it is also important to pay explicit attention to reduction of demand characteristics that may predispose participants in the experimental group to perform better on tasks of attention (Boot et al. 2011, 2013). That is, even though active control groups may account for the effects of some non-specific factors, such as social support and physical relaxation, it is likely that participants in the two groups have differential expectations of improvements as a function of the intervention. These differential expectations could be the result of their prior exposure to the assigned training, recruitment efforts, or experimenter bias during assessment sessions, and may collectively have a significant impact on training outcomes. In fact, one study directly assessed the impact of motivation on improvements in cognitive outcomes by randomizing participants in the wait-list control group to an incentive or a no-incentive group, where the incentive group was given a monetary enticement to improve their performance at post-test (Jensen et al. 2012). Although increased attentional effort in the incentive group did not fully account for all positive results of MBSR, some of the improvements observed in the MBSR group were also observed in the incentivized control group, thus providing critical evidence for the role of effort and motivation in observed effects. Unfortunately, only 10 out of 57 studies explicitly reported attempts to equate demand characteristics across groups (Fig. 3). Although this does not necessarily mean that efforts were not made, this trend suggests that there is room for growth in this domain.

Several strategies have been utilized in the broader training literature to successfully reduce the differential expectation of benefits between training and control groups (Boot et al. 2013). First, recruitment plays a critical role in the creation of such differential expectations and thus, close attention needs to be paid to recruitment strategies. The content of recruitment advertisements should be explicitly stated in published manuscripts to provide information regarding the potential motivations of participants who volunteered for the study. Indeed, the majority of training studies with active control groups have paid explicit attention to reducing demand characteristics by using advertising materials that promote common aspects of both groups and that emphasize the potential for both groups to enhance cognitive functioning. It is less common, however, for studies to explicitly assess these expectations pre- and post-intervention despite recent commentary in the training literature on the importance of systematically assessing expectancy effects (Boot et al. 2013). An early study of two forms of meditation training, Langer meditation and Transcendental meditation, by Alexander et al. (1989) methodically assessed for these differential expectancy effects in their various training groups 2 weeks into the training program. Critically, there were no significant differences in expectation of benefits between the groups, successfully providing quantitative data on the matching of placebo effects across the groups. Thus, although mindfulness training studies have been careful in the design of recruitment strategies, and many address matching of demand characteristics, it is equally important to collect data on such pre- and post-training expectations in order to examine their associations with changes in outcomes.

4) Detailed Discussion of Content of Intervention and Control Groups Thirty-two of the 57 included studies discussed the content of the mindfulness-based and active control interventions employed (Fig. 3); however, there is a great deal of variability in the level of detail provided. In addition to more standardized protocols, such as MBSR and MBCT, many studies have employed adapted protocols varying in duration, frequency, and content, with little information on the types of practices participants engaged in. Standardized MBSR and MBCT protocols typically involve two different types of meditative practices. First, focused attention (FA) meditation involves the maintenance of selective attention on a chosen object. This regulatory process involves monitoring, or being vigilant of distractions without compromising the intended focus; disengaging from the distractors without further processing; and promptly redirecting attention to the chosen object (Lutz et al. 2008). Lutz et al. (2008) suggest that as one's practice progresses, there is a trait-level change whereby one's ability to maintain such focus without the use of regulative skills increases. Second, open monitoring (OM) meditation is achieved by moving from the use of regulative skills to attending to transient occurrences without directed focus on one object. This process involves the development of reflexive awareness of the detailed features of each experience. The types of training that have been provided in the reviewed studies range from focused attention practices and open monitoring practices, to a combination of these components with other elements. Importantly, given that there is preliminary evidence from studies of expert meditators suggesting unique cognitive advantages on the Stroop task, counting task, and the continuous performance test in practitioners of OM, FA, and loving-kindness meditation (Josefsson and Broberg 2011; Lee et al. 2012; Valentine and Sweet 1999), it is critical that future studies provide details regarding the contents of their unique protocols in order to clarify the degree to which there are meaningful differences that might impact results on attentional control measures. This is applicable both for the mindfulness groups as well as any control groups in order to establish the non-specific elements that are being controlled for in the study.

Relatedly, engagement with mindfulness training, quantified as number of hours spent engaging in meditative practices, number of formal meditative sessions attended, or even overall motivation to engage with the practices, is an important metric that needs to be systematically evaluated in this literature. Existing investigations of the dose-response relationship between practice metrics and attentional outcomes are mixed, with studies reporting either no relationship between engagement and attentional outcomes (Jensen et al. 2012) or a strong impact of engagement with mindfulness practices in predicting attentional outcomes (Rooks et al. 2017). Future studies, especially those delivering practices via online interfaces, such as mobile applications, are encouraged to quantify the extent to which training engagement explains meaningful variance on attentional scores.

5) Following of Study Reporting Guidelines (Such as CONSORT) Finally, there has been increasing emphasis placed on following a standard pipeline for reporting results that can be instrumental in guiding future research. The CONSORT guidelines (CONsolidated Standards of Reporting Trials) provide an evidence-based framework for researchers to report results of RCTs (Moher et al. 2001). Although only 12 studies followed such guidelines, a larger percentage of studies reporting on CONSORT guidelines found mindfulness-related benefits (67%) than those that did not (58%, Fig. 3). We strongly encourage future RCTs in this literature to follow these or similar guidelines as systematic and thorough reporting of RCT results can help clarify the nuances of the study's design and results as well as aid in future research design. Studies that report the results of their RCT while following CONSORT or similar reporting guidelines are denoted by the "pearls of wisdom," represented as the clustered spheres, in Fig. 2.

Overall, the mindfulness training literature boasts a handful of rigorous RCTs that have paid attention to the various study design issues highlighted above. Setting aside the CONSORT criterion that has only recently been emphasized in the literature, six studies meet all of the remaining four criteria (see column 4 in Table 1 A).

Summary and Final Thoughts

There is a great interest in both the scientific community and the broader public in the use of mindfulness meditation as a cognitive rehabilitation tool, particularly to enhance components of attention. Given the widespread prevalence of off-task thoughts in our everyday lives, and the functional consequences of mind wandering for happiness, cognitive functioning, and overall quality of life (Killingsworth and Gilbert 2010; Smallwood and Schooler 2015; Fountain-Zaragoza et al. 2016), mindfulness training presents a promising tool with which to alert, orient, and guide on-task behavior through improved attention. Further, from a cognitive science perspective, attention underlies multiple perceptual and cognitive systems, and deficiencies in such attentional processes heavily impact individuals with neurological and psychiatric diagnoses. As such, mindfulness training is increasingly being employed to enhance cognitive function in a variety of populations with the promise of improving cognition and overall quality of life.

Given the extensive interest in this training technique, it is our collective responsibility to ensure the methodological rigor of studies either supporting or refuting claims of mindfulness' benefits. This review highlights several key methodological issues currently plaguing this literature—problems that need to be addressed for us to have confidence in the efficacy of mindfulness meditation training. In this review of training studies, we stress the critical need for going beyond random assignment to the inclusion of active control groups, as well as explicit attention to reduction of demand characteristics. Given the well-known and powerful effects of placebos on not only self-report data, but also behavioral and neuroimaging data, it is likely that these effects explain some of the variance in improved attention following mindfulness training, particularly in non-randomized and retreat studies. Thus, explicit attention to either the reduction of those placebo effects, or at the very least, a disentanglement from treatment effects, will improve our understanding of the mechanisms through which mindfulness interventions are having an impact. Additionally, further clarification of the nature of interventions and the fidelity with which they are implemented is needed. Variants of traditional mindfulness-based approaches are not problematic; in fact, tailoring these interventions to some extent in order to accommodate needs, challenges, and priorities of different clinical populations will be necessary. What is needed, however, is more extensive documentation of the content of the training programs and how they may or may not differ from more traditional, manualized approaches.

Finally, it is important to consider whether the variables selected in existing studies fully capture the effects of mindfulness-based interventions on attention. Taken from the well-established fields of neuropsychology and cognitive/vision sciences, these computerized or paper-and-pencil tasks are designed to capture basic attentional processes in isolation, which is a necessary step in the scientific investigation of mindfulness's effects. However, given that attention does not function in isolation in our daily lives, the field would further benefit from the use of more integrative research strategies to investigate attention in relevant contexts and as one component of a complex causal pathway. Thus, future studies might employ more idiographic or naturalistic outcome measures and explore the effects of mindfulness training on multiple, interrelated components such as attention, emotion regulation, social support, and inflammation. Further, consideration of individual difference variables, such as baseline cognitive resources, age, personality, motivation, or clinical features, will further elucidate who benefits from mindfulness training and in what ways. Active consideration of these key methodological issues, along with theoretically-motivated outcome variables, will significantly advance the field.

Mindfulness meditation continues to be a promising tool for enhancing cognitive vitality with some methodologically rigorous studies providing support for its impact on select components of attention. However, there is also evidence that refutes such claims. Thus, going forward, it is of paramount importance that evidence be based on sound, rigorous studies that address alternative interpretations in order to avoid making unsubstantiated claims. We must conduct systematic, incremental research that will allow us to examine whether this technique is effective, to understand the mechanisms through which it is effective, and finally, to identify for whom the effects are most potent.

Compliance with Ethical Standards

Conflict of Interest The authors declare that there is no conflict of interest.

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