Mindfulness (2020) 11:1500–1510
https://doi.org/10.1007/s12671-020-01364-z

ORIGINAL PAPER

Mindfulness Improves Attention Resource Allocation During Response Inhibition in Older Adults

Ben Isbel[1] · **Jim Lagopoulos**[1] · **Daniel Hermens**[1] · **Kayla Stefanidis**[1] · **Mathew J. Summers**[1]

Abstract

Objectives A core process trained during mindfulness is inhibitory control. A decline in inhibitory control is thought to underlie age-related cognitive declines. Electroencephalographic event-related potentials (ERPs) index both the speed and allocation of attentional resources, making them useful in assessing cognition in ageing. While mindfulness has been shown to improve attentional control, studies examining ageing cohorts are lacking. Here, we examine ERP changes during an inhibitory control task in older adults to assess the ability of mindfulness to enhance cognition in ageing.

Methods A longitudinal RCT was conducted to examine the effect of an 8-week mindfulness training (MT) intervention on the N2 and P3 ERP components during the Sustained Attention to Response Task (SART) in healthy older adults aged over 60 years ($n = 48$). An active control computer-based attention training (CT) program ($n = 27$) designed to activate similar attentional components to mindfulness was used to determine if outcomes resulted from attention training or mindfulness-specific factors.

Results While both the MT and CT groups displayed improved SART performance following the interventions (as indexed by errors of commission and reaction time coefficient of variation), only the MT group showed significant reductions in frontal P3 latency during response inhibition.

Conclusions The results suggest that mindfulness may enhance the speed and efficiency of attentional processes, thus providing protective benefits against age-related cognitive decline.

Keywords Mindfulness · Attention · Inhibitory control · Event-related potential · Cognitive training · Ageing · EEG · Sustained attention to response task

The ability to sustain attention by inhibiting competing distracting processes represents a core attentional function that underpins complex cognitive operations (Sarter et al. 2001). Sustained attention refers to the ability to endogenously and purposely maintain an object in awareness using top-down executive control to inhibit competing distracting processes (Sturm and Willmes 2001). This type of inhibition forms a common executive function underlying other forms of attentional control, such as updating and shifting, and thus represents a core process upon which much of controlled cognitive processing is based (Miyake and Friedman 2012). Since these processes are central to higher cognitive operations, deficits in inhibitory control and sustained attention are amongst the most pervasive of cognitive impairments, leading to a reduced ability to control attention together with a deterioration in working memory and learning capacity.

Attentional processes are known to slow and become increasingly susceptible to interference with increasing age (Hedden and Gabrieli 2004). A reduction in inhibitory control during controlled cognitive processing is thought to lead to age-related decline in attentional performance (Andrés et al. 2008). Deterioration of inhibitory control with increasing age in this way leads to an increased susceptibility of attentional processes to interference along with concomitant declines in performance across a range of cognitive domains. This form of age-related cognitive decline (ARCD) has been shown to be reversible with cognitive training (Gajewski and Falkenstein 2012; Kelly et al. 2014). Mindfulness has recently

---

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s12671-020-01364-z) contains supplementary material, which is available to authorized users.

✉ Ben Isbel
bisbel@usc.edu.au

[1] Sunshine Coast Mind and Neuroscience – Thompson Institute, University of the Sunshine Coast, Locked Bag 4 (ML59), Maroochydore DC, QLD 4558, Australia

emerged as a training technique shown to enhance attentional control (Van den Hurk et al. 2009) and may provide protective benefits for older adults against ARCD through enhancing sustained attention and inhibitory control, thereby leading to improved operation of higher cognitive processes.

Mindfulness involves the training of attentional processes in conjunction with equanimity, which is an unbiased and non-reactive orientation toward the contents of experience (Kabat-Zinn 1990). The attentional component in mindfulness sustains attention toward the breath while exerting inhibitory control over distracting processes across sensory modalities which may interfere with this primary task. This style of attention training requires the continuous activation of attentional control processes, and thus repeatedly activates the neural networks associated with these functions (Tang et al. 2015). Equanimity in mindfulness training functions to reduce cognitive and emotional elaboration upon the contents of experience, further assisting the development of sustained attention through reduced reactivity toward affective stimuli (Isbel and Summers 2017). For a detailed description of the cognitive processes activated during mindfulness practice, see Isbel and Summers (2017). Accordingly, mindfulness training has been shown to improve sustained attention (Jha et al. 2015; MacLean et al. 2010) and inhibitory control (Sahdra et al. 2011; Zanesco et al. 2013) in adults aged less than 60 years. Given the importance of inhibitory control in ARCD and dementia, it is perhaps surprising that there currently exists very little evidence examining these mindfulness-related training outcomes in adults aged greater than 60 years. Encouragingly, one study has demonstrated that short-term mindfulness training is capable of improving performance on an inhibitory control task in a group of community dwelling healthy older adults (Malinowski et al. 2017). It should be noted that computer-based cognitive training interventions utilising attentional tasks have also been shown to improve attentional performance in older adults (Kelly et al. 2014), and thus, a comparative examination of the benefits of mindfulness and cognitive training interventions to enhance attention in ageing may help inform the development of interventions targeted toward improving cognition in ageing.

Electroencephalographic event-related potentials (ERPs) offer sensitive temporal measures of attentional processing. ERPs are waveforms representing the summed post-synaptic potentials of spatially aligned cortical pyramidal cells which are simultaneously activated in response to a stimulus (Luck and Kappenman 2011). This activity is reflected as an ERP consisting of a succession of positive and negative voltage fluctuations known as components which reflect underlying neural processes. Short latency components reflect predominantly pre-attentional neural responses and are known as exogenous ERP components. Longer latency components reflect attentional processing of information, and thus are known as endogenous components.

Two endogenous components of interest in the study of cognition are the N2 and P3 components, which provide high temporal resolution of brain resource allocation in response to a cognitive task. During a go/no-go task such as the Sustained Attention to Response task (SART; Robertson et al. 1997), N2 and P3 ERP components have consistently been evoked when response inhibition is required. During tasks of sustained attention that involve either stimulus or response conflict, an N2 response thought to reflect processes involved in conflict monitoring and inhibitory control is elicited, with this response appearing to be generated in the anterior cingulate cortex (Donkers and van Boxtel 2004; Gajewski et al. 2018; van Veen and Cameron 2002). Increases in N2 amplitudes during tasks requiring inhibitory control have been reported after mindfulness training, indicating an enhanced ability to activate neural resources to meet task demands after mindfulness training (Malinowski et al. 2017). Furthermore, the P3 component has generally been thought to index firstly a frontally oriented response related to stimulus evaluation, followed by a temporoparietal response related to context updating and memory storage (Gaeta et al. 2003; Polich 2007). While there is evidence suggesting that this parietal P3 component may represent the completion of a stimulus-response event (Verleger et al. 2005), it is assumed that both the N2 and P3 components index underlying neural processes involved in information processing. Increases in P3 amplitude during attentional tasks have been reported following mindfulness training, suggesting that mindfulness may enhance practitioner's ability to mobilise attentional resources during tasks of attention (Delgado-Pastor et al. 2013).

Age-related changes within these neural networks of attention are reflected in prolonged latencies of both the N2 and P3 components with increasing age, suggesting a slowing of attentional processes (Anderer et al. 1996). This age-related slowing of attention is accompanied by increased variability of attentional performance due to greater susceptibility to interference as a result of declining inhibitory control performance. This decline in inhibitory control performance is observed as greater reaction time variability during tasks of sustained attention with increasing age (Staub et al. 2014). While studies reporting the attentional benefits of mindfulness upon these cognitive processes in younger cohorts continue to grow, there is little evidence of its effectiveness to improve attention in ageing.

In order to investigate the efficacy of mindfulness to enhance attention in normal ageing, we conducted an RCT with an active control to assess ERP outcomes resulting from an 8-week mindfulness intervention (MT) in a group of healthy older adults. The SART, a widely used measure of sustained attention and inhibition, was used to elicit ERPs and assess the effectiveness of the interventions in improving attentional control. An active control computer-based training program (CT) designed to activate similar attentional processes to mindfulness was utilised to determine if the reported benefits of mindfulness to attention resulted from its attention-training component or from an attentional style of training unique to mindfulness, where attentional deployment is coupled with equanimity. Performance on the SART was expected to improve in both groups, since both engaged in attention training. However, in line with previous findings, we hypothesised that the MT group would show increases in N2 and P3 amplitude and decreases in N2 and P3 latency after training due to enhanced attention resource mobilisation resulting from this practice. No change in N2 or P3 amplitude or latency was predicted for the active control CT group.

Methods

Participants

Healthy older adults (≥ 60 years age; *n* = 120) recruited from the general community were randomly assigned to two interventions which were described as attention training programs, thus blinding participants to experimental and control conditions. Prior to acceptance into the study, all participants were screened for conditions known to adversely impact cognitive performance (including current diagnosis of mild cognitive impairment, dementia or other psychiatric disorder (e.g., depression, anxiety), prior head injury requiring hospitalization, cerebrovascular complication (e.g., stroke, aneurysm, transient ischaemic attack), neurological disorder (e.g., cerebral palsy or spina bifida), current use of medications affecting CNS function (e.g., anti-depressants), multiple sclerosis, epilepsy, chronic obstructive pulmonary disease and heart disease). In addition, participants with prior exposure to either mindfulness or computerised brain training, or who had a current regular practice of other mind-body techniques such as yoga or tai-chi, were excluded from the study. After participant attrition, artefact-free data from 75 participants (MT: *n* = 48; CT: *n* = 27) was available for final analysis (see Fig. 1 for flowchart of participant retention). Participant demographic information for the reported data is presented in Table 1.

Procedures

Participants were assessed on the SART with concurrent EEG data collection at both pre- (T1) and post-intervention (T2). Symptoms of anxiety and depression (using the Hospital Anxiety and Depression Scale; Zigmond and Snaith 1983) were reported before each session as they are known to adversely impact EEG measures. No participant reported elevated symptoms of anxiety or depression. The Wechsler Test of Adult Reading (WTAR) was performed only at T1 in order to provide an estimate of each participant's intelligence quotient. Participants were fitted with the EEG equipment, after which they completed the SART. Task instructions were presented on a monitor screen placed 65 cm from the participant. Stimuli were presented using E-Prime 2.0.10 software (Psychology Software Tools, Pittsburgh, PA, USA).

Participants were blinded to experimental and control conditions during the study by presenting the interventions to participants as attention training programs differing only in delivery format. The two intervention programs were structurally equivalent, consisting of weekly teacher-guided group training sessions for 8 weeks (conducted by BI), along with a home practice requirement of 20 min/day in week 1 increasing to 45 min/day in week 8 (see Supplementary Material 1 for weekly structure of the programs). Daily home practice was recorded, and ten participants were excluded from analysis for not meeting the minimum training requirement for the program (MT: *n* = 8; CT: *n* = 2), set a priori at a level of 75% attendance to program requirements.

Mindfulness-Based Attention Training Program

A standardised mindfulness technique developed to facilitate the accurate investigation of the cognitive processes activated during mindfulness and designed for use in longitudinal RCTs was used in the MT program (Isbel and Summers 2017). This technique trains mindfulness in relation to the sensations accompanying the breath through the development of two primary components: (1) an attentional component involving the activation of sustained attention, selective attention, inhibitory control and working memory, together with (2) equanimity, which is an unbiased and non-reactive orientation toward the contents of experience. During this practice, participants are required to inhibit distracting processes as well as cognitive and emotional reactivity in order to sustain attention selectively upon the breath in an equanimous manner. When attention wanders from this primary task, participants are instructed to inhibit and disengage from distracting processes and redirect attention back to the primary task. A primary attentional process trained in this practice is therefore executive inhibitory control, through which sustained attention and equanimity are gradually developed. Importantly, the standardised mindfulness technique used here does not contain secondary intervention components such as relaxation, psycho-education or yoga which are commonly found in therapeutic mindfulness-based interventions (MBIs), and thus permits the drawing of clearer inferences regarding the mechanisms underlying observed outcomes.

Computer-Based Attention Training Program

A computerised game format was used to deliver exercises designed to activate similar attentional processes to those activated in mindfulness practice, thus providing an accurate active comparison condition rather than a sham control or an active control condition bearing no resemblance to

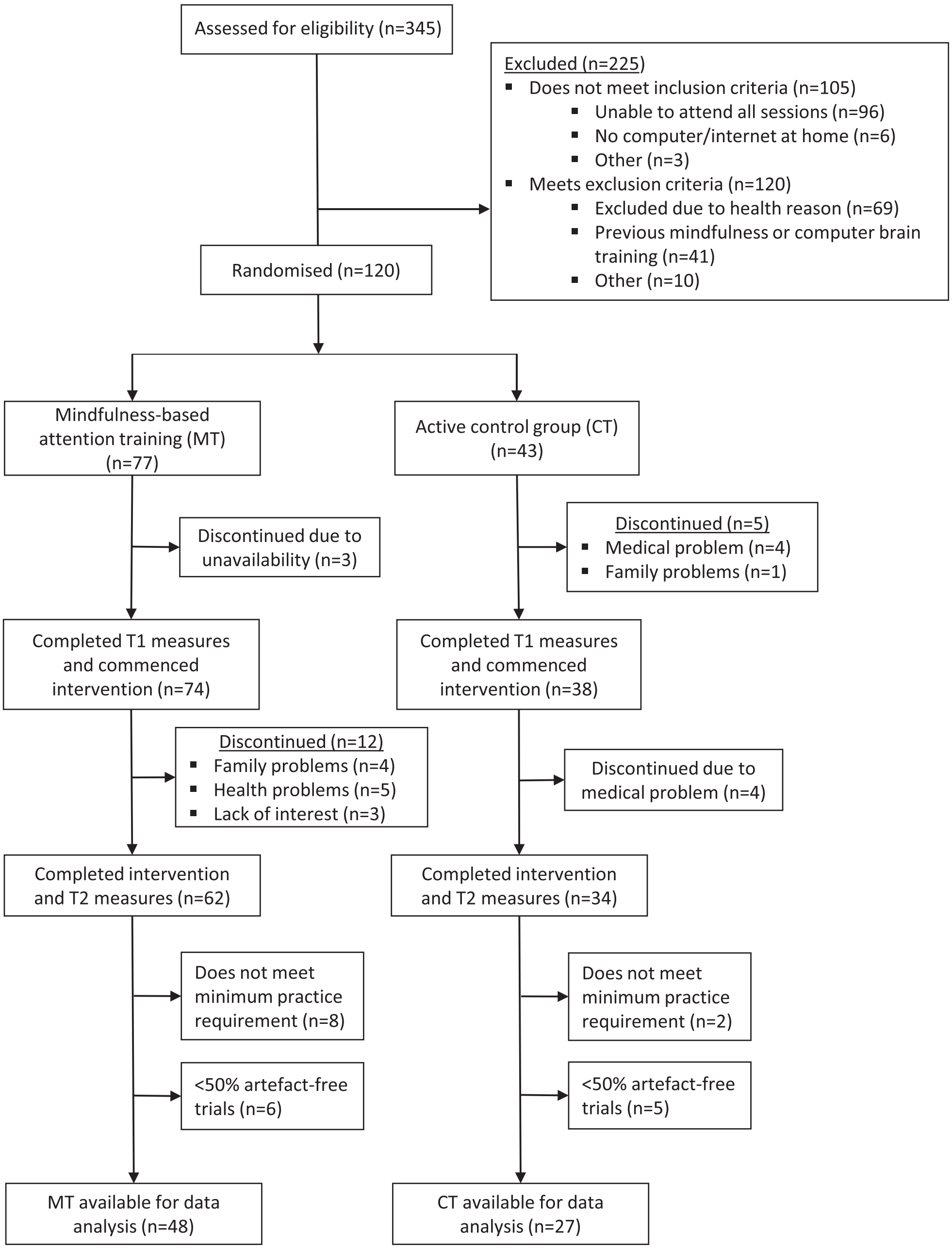

Fig. 1 CONSORT flowchart of participant retention through study

mindfulness practice. Each game emphasised a specific aspect of attention, such as sustained attention, selective attention, inhibitory control or working memory to replicate the attention training occurring in the MT program. Difficulty increased on some tasks with successful performance to replicate the changing nature of attentional demands that occurs in mindfulness practice with increasing proficiency. Furthermore, participants were required to play an assigned game continuously each day during their home training sessions rather than switching between games in order to replicate the continuous application to a single task that occurs in mindfulness training. Tasks activating sustained attention, selective attention, inhibitory control and working memory were used by presenting modified versions of the Eriksen flanker task (Eriksen and Eriksen 1974), a visual search task (Treisman and Gormican 1988), task switching task (Kiesel et al. 2010), Stroop task (Stroop 1935), divided attention task (Treisman 1982), a Corsi block task (Milner 1971) and a card matching working memory task. Tasks were changed weekly.

Measures

Wechsler Test of Adult Reading

The Wechsler Test of Adult Reading is a widely used word reading list used to estimate full-scale intelligence quotient

Table 1 Participant demographic information and pre-intervention scores on Sustained Attention to Response Task

		Mindfulness-based training group	Active control group	Statistical values
Gender	(% female)	55%	75%	$X^2(1, N = 71) = 3.00$, $p = .08$
Age	*M* (*SD*)	71 (4.5)	70 (5.9)	$t_{(73)} = 1.61$, $p = .11$
	Range	60–83	60–86	
Predicted FSIQ	*M* (*SD*)	112.6 (7.0)	112.5 (5.7)	$t_{(73)} = 0.10$, $p = .92$
Errors of commission (%)	*M* (*SD*)	16.4 (9.9)	21.3 (12.3)	$t_{(73)} = -1.887$, $p = .06$
RT (ms)	*M* (*SD*)	500.8 (56.7)	480.0 (53.3)	$t_{(73)} = 1.557$, $p = .12$
RT CV	*M* (*SD*)	0.228 (0.05)	0.218 (0.04)	$t_{(73)} = 0.843$, $p = .40$

FSIQ full-scale IQ (as estimated by the Wechsler test of adult reading), *RT* reaction time, *RT CV* reaction time coefficient of variation

(FSIQ) in adults. The WTAR co-normed against the Wechsler Adult Intelligence Scale, 3rd edition, is a reliable and valid estimate of intellectual capacity and was used to assess pre-intervention between-group differences in estimated FSIQ.

Sustained Attention to Response Task

The SART consisted of a serial presentation of digits (1–9) to which participants respond via keypress to go stimuli (digits 1–2, and 4–9) while withholding a response to no-go stimuli (digit 3). For each block of nine trials, a single digit (1–9) was randomly chosen without replacement. An experimental block consisting of 540 trials (60 blocks of 9 trials) containing 60 no-go stimuli (11% of total trials) was presented using digits in black font of randomly allocated sizes (100, 120, 140, 160 or 180 points) in the centre of a grey background for 200 ms. After stimulus offset, a yellow fixation cross was presented in the middle of the grey background for a variable inter-stimulus interval between 1000 and 2000 ms. Participants were instructed to respond as quickly and accurately as possible during the task. Participants completed a practice block with performance feedback prior to task commencement to ensure the task was correctly understood.

Performance measures for the SART included errors of commission (percentage of errors on no-go), reaction time (RT), and reaction time coefficient of variation (RT CV). Errors of commission index failures of inhibitory control while variability in RT indexes sustained attention, wherein greater fluctuations in sustained attention are observed as increasing variability (CV) of responding (RT) to stimuli (Mrazek et al. 2012; Robertson et al. 1997). Response variability during a sustained attention task is inversely related to successful inhibitory control activation, where greater variability is associated with attentional lapses due to mind wandering and a loss of executive goal maintenance (Bellgrove et al. 2004; Unsworth et al. 2010).

EEG Measures

EEG was acquired using a Biosemi ActiveTwo system with Ag/AgCl electrodes (Biosemi, Amsterdam, Netherlands) with vertical and horizontal EOG electrodes to monitor eye movements. Data was sampled at 1024 Hz with additional offline processing conducted using BrainVision Analyzer2 (Brain Products, GmbH, Gilching, Germany).

EEG data from F3, Fz, F4, C3, Cz, C4, P3, Pz and P4 sites were used for ERP analysis. Data was referenced offline to average mastoid, and then filtered using a zero phase-shift Butterworth filter (0.1-30 Hz, 12 dB/octave) with a 50-Hz notch filter. Ocular artefacts were corrected using the technique of Gratton et al. (1983) and correct no-go trials segmented − 200 ms before to 800 ms after stimulus onset. Trials containing voltages exceeding an absolute change of 50 µV/ms or an absolute min-max difference of 100 µV/200 ms were rejected from analysis. Remaining trials were baseline corrected and averaged. An a priori decision to reject participants with fewer than 50% artefact-free trials resulted in 11 participants being excluded due to insufficient artefact-free data (MT: $n = 6$; CT: $n = 5$). Common artefacts included excessive eyeblink activity, slow voltage drift due to skin potentials changes, head or facial muscle activity and excessive eye movement leading to neural EEG signal interference. There were no significant differences in the number of artefact-free trials to no-go stimuli between the groups at both pre [MT: $M = 46.6$ ($SD = 7.3$); CT: $M = 45.5$ ($SD = 7.7$)] and post-intervention [MT: $M = 48.0$ ($SD = 6.8$); CT: $M = 48.0$ ($SD = 6.0$)].

Latency windows for N2 and P3 components were determined using grand average ERP waveforms at T1. Peak amplitude and latency for N2 (180-380ms) and P3 (380-580ms) were determined for each electrode using an automated peak detection tool, with all peaks visually inspected and confirmed manually. ERP component amplitude was calculated using peak-to-peak measures to control for positive or negative drift across multiple components, where N2 amplitude was calculated as the change in voltage from P2 to N2 peaks, and P3 amplitude as the change in voltage from N2 to P3 peaks. In order to control for the possibility of bias due to author involvement in the data analysis procedure, an experienced ERP researcher unconnected to the present study (KS) and blinded to intervention group reviewed all ERP waveforms to confirm individual component peak selection. Where differences arose, a third researcher with extensive expertise in ERP data analysis who was also blinded to group (JL) was consulted for final determination.

Data Analysis

Independent groups *t* tests were performed to examine pre-intervention between-group differences in age, FSIQ, SART measures, and N2 and P3 amplitudes and latencies. Between groups gender balance difference was examined using chi square analysis. Behavioural measures for the SART were analysed using mixed-design ANOVA of total commission errors, RT and RT CV with group (MT, CT) as a between-subjects factor and time (T1, T2) as a within-subjects factors. Significant effects were investigated with follow-up pairwise comparisons. Mixed-design ANOVAs for N2 and P3 latency and amplitude were conducted for each region (frontal, central, parietal) with electrode (3 levels) and time (T1, T2) as within-subjects factors, and group (MT, CT) as a between-subjects factor. Significant effects were investigated with follow-up pairwise comparisons. Where a breach of the assumption of sphericity occurred in any ANOVA, Greenhouse-Geisser corrected *p* values are reported. In order to demonstrate the relationship between electrophysiological markers of brain resource allocation and behavioural performance, partial correlations controlling for group were calculated between N2 and P3 latency and RT. All statistical analysis was performed using SPSS version 24 (SPSS Inc., Chicago, IL, USA).

Results

Pre-Intervention Between-Group Comparisons

There were no significant pre-intervention differences between the MT and CT groups in age, gender balance, FSIQ, errors of commission, reaction time or RT CV (see Table 1). No significant pre-intervention difference in N2 or P3 amplitude or latency was observed between the MT and CT groups (see Table 2).

Sustained Attention to Response Task

Repeated-measures ANOVA revealed a main effect of time for total errors of commission ($F_{(1,73)} = 16.533$, $p < .001$, partial $\eta^2 = 0.185$) and RT CV ($F_{(1,73)} = 26.354$, $p < .001$, partial $\eta^2 = 0.265$). No interaction effects were observed for total errors of commission ($F_{(1,73)} = 1.820$, $p = .182$, partial $\eta^2 = 0.024$) or RT CT ($F_{(1,73)} = 0.002$, $p = .969$, partial $\eta^2 = 0.000$), indicating that both groups demonstrated improved inhibitory control and sustained attention performance during the SART following the interventions.

ERP Data

N2 Results

Mixed ANOVA for N2 amplitude revealed a group × time interaction for central region ($F_{(1,73)} = 3.988$, $p = .050$, partial $\eta^2 = 0.052$) that approached significance, together with a similar group × time × electrode interaction ($F_{(1.72,125.78)} = 3.063$, $p = .058$, partial $\eta^2 = 0.040$). Inspection of mean amplitude values revealed that while the CT group showed increases in N2 amplitude at central sites (C3: $M_{I\text{-}J} = 0.716$, SE = 0.616, $p = .249$; Cz: $M_{I\text{-}J} = 1.457$, SE = 0.638, $p = .025$; C4: $M_{I\text{-}J} = 0.660$, SE = 0.605, $p = .279$), the MT group showed decreases (C3: $M_{I\text{-}J} = -0.533$, SE = 0.462, $p = .252$; Cz: $M_{I\text{-}J} = -0.702$, SE = 0.479, $p = .147$; C4: $M_{I\text{-}J} = -0.165$, SE = 0.454, $p = .717$). A similar non-significant group × time interaction was observed at frontal ($F_{(1,73)} = 2.956$, $p = .090$, partial $\eta^2 = .090$) and parietal ($F_{(1,73)} = 2.516$, $p = .117$, partial $\eta^2 = .033$) regions, where again the CT group showed increases in N2 amplitude while MT group showed reductions (see Fig. 2). No main or interaction effects were observed for N2 latency at either region.

P3 Results

Mixed ANOVA for P3 latency revealed a significant group × time interaction for frontal region ($F_{(1,73)} = 7.111$, $p = .009$, partial $\eta^2 = 0.089$). Follow-up pairwise comparisons revealed significant reductions in P3 latency for the MT group at F3 ($M_{I\text{-}J} = -11.230$, SE = 4.413, $p = .013$), Fz ($M_{I\text{-}J} = -11.779$, SE = 4.261, $p = .007$) and F4 ($M_{I\text{-}J} = -12.165$, SE = 4.399, $p = .007$). No significant change in P3 latency was observed at frontal sites in the CT group. A similar but non-significant interaction was observed at both central ($F_{(1,73)} = 0.996$, $p = .322$, partial $\eta^2 = 0.013$) and parietal regions ($F_{(1,73)} = 1.931$, $p = .169$, partial $\eta^2 = 0.026$), where the MT group displayed reductions in P3 latency not observed in the CT group (see Fig. 3). No main or interaction effects were observed for P3 amplitude at either region.

Correlations

Significant moderate bivariate correlations between P3 latency and RT were observed at all electrodes for each time point (see Table 3), demonstrating that P3 latency times were

Table 2 Pre-intervention difference in ERP component latency and amplitude at midline electrode sites

				Mindfulness-based training group	Active control group	Statistical values
N2	Fz	Latency (ms)	*M* (*SD*)	331.7 (33.7)	318.7 (41.0)	$t_{(73)} = 1.487, p = .14$
		Amplitude (μV)	*M* (*SD*)	− 9.06 (5.7)	− 9.13 (5.6)	$t_{(73)} = 0.053, p = .96$
	Cz	Latency (ms)	*M* (*SD*)	325.2 (35.3)	312.8 (40.7)	$t_{(73)} = 1.380, p = .17$
		Amplitude (μV)	*M* (*SD*)	− 11.75 (6.1)	− 10.91 (5.8)	$t_{(73)} = -0.584, p = .56$
	Pz	Latency (ms)	*M* (*SD*)	319.1 (42.2)	306.2 (49.7)	$t_{(73)} = 1.196, p = .23$
		Amplitude (μV)	*M* (*SD*)	− 7.89 (5.8)	− 6.80 (5.0)	$t_{(73)} = -0.816, p = .42$
P3	Fz	Latency (ms)	*M* (*SD*)	492.6 (49.9)	484.5 (41.9)	$t_{(73)} = 0.714, p = .48$
		Amplitude (μV)	*M* (*SD*)	15.6 (5.1)	16.9 (4.6)	$t_{(73)} = -1.078, p = .28$
	Cz	Latency (ms)	*M* (*SD*)	500.0 (47.8)	495.8 (39.6)	$t_{(73)} = 0.391, p = .70$
		Amplitude (μV)	*M* (*SD*)	20.0 (6.3)	21.5 (5.8)	$t_{(73)} = -1.006, p = .32$
	Pz	Latency (ms)	*M* (*SD*)	496.3 (50.8)	488.8 (35.5)	$t_{(73)} = 0.675, p = .50$
		Amplitude (μV)	*M* (*SD*)	16.9 (6.1)	17.5 (5.5)	$t_{(73)} = -0.403, p = .69$

significantly related to the behavioural reaction time measure during the SART at both pre- and post-intervention. Furthermore, N2 latency was significantly correlated at central sites at post-intervention only (see Table 3), indicating that the cognitive training interventions resulted in a strengthen relationship between N2 latency and reaction time on the SART after training.

Discussion

The present study reports significant reductions in frontal P3 latency during an inhibitory control task after 8 weeks of mindfulness training in healthy older adults, indicating that the speed of attention resource allocation during this task had improved as a result of mindfulness training but not as a result of computer-based cognitive training. In addition, mindfulness training was associated with a non-significant reduction in N2 amplitude at central sites during response inhibition, suggesting a reduced allocation of neural resources to meet task demands.

While both intervention programs were successful at improving inhibitory control and attentional lapses as measured by errors of commission and reaction time variability during the SART, only the MT group displayed reductions in frontal P3 latency. This finding may be due to a differential activation of inhibitory control across the two interventions. In the CT program, inhibitory control during game-based tasks is required to inhibit gross instances of mind wandering which interfere with task performance (Smallwood and Schooler 2015). Cognitive models of mindfulness suggest that during mindfulness practice inhibitory control is required to inhibit

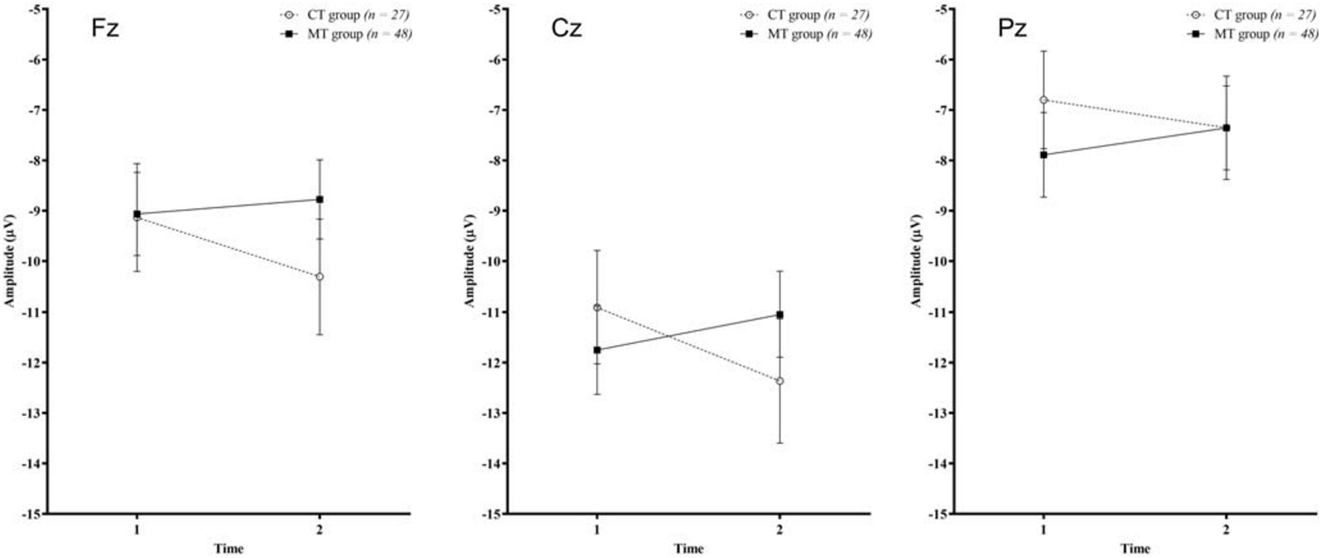

Fig. 2 Mean N2 amplitudes at midline electrode sites at pre- (T1) and post-intervention (T2) for the mindfulness-based attention training group (MT) and the computer-based attention training group (CT). Error bars show standard error of the mean

not only gross mind wandering but also subtle mind wandering together with cognitive and affective responses toward the contents of experience, leading to the development of equanimity (Isbel and Summers 2017). As such, inhibitory control in mindfulness training enacts meta-cognitive regulation of both cognitive and emotional reactivity.

The SART is a cognitive task designed to assess gross mind wandering resulting in a failure to inhibit a prepotent motor response (Seli 2016). Thus, the SART has been designed to specifically assess the type of inhibitory control trained in the CT program rather than the broader type of meta-cognitive inhibitory control central to mindfulness practice. Reductions in frontal P3 latency during response inhibition observed in the MT group and not the CT group further suggest the presence of mechanisms in the MT program absent in the CT program. One such mindfulness-specific factor is equanimity. Equanimity refers to a non-reactive orientation toward the contents of experience and experience itself, involving cognitive and affective impartiality (Desbordes et al. 2015). Meta-cognitive inhibitory control and equanimity are closely linked in mindfulness practice. In order to develop equanimity, one must inhibit automatic prepotent responses to affective stimuli as well as cognitive elaboration upon experience, while equanimity itself is supported by successful inhibitory control across sensory modalities (Isbel and Summers 2017). Thus, while both the CT and MT programs focussed on developing attentional control, it is possible that mindfulness involved a broader application of inhibitory control across both coarse and subtle mind wandering as well as emotional regulation.

Table 3 Partial correlations of reaction time (RT) and N2 and P3 latency controlling for group

	Electrode	T1 RT	T2 RT
N2 latency	F3	0.077	0.195
	Fz	0.065	0.208
	F4	0.068	0.192
	C3	0.123	0.224
	Cz	0.101	0.239*
	C4	0.132	0.268*
	P3	0.040	0.168
	Pz	0.084	0.169
	P4	0.072	0.118
P3 latency	F3	0.314**	0.352**
	Fz	0.309**	0.350**
	F4	0.298**	0.347**
	C3	0.344**	0.305**
	Cz	0.340**	0.365**
	C4	0.307**	0.359**
	P3	0.289*	0.264*
	Pz	0.271*	0.314**
	P4	0.277*	0.339**

df = 72

*Significant at $p = 0.05$; **Significant at $p = 0.01$

The reductions in frontal P3 latency reported here suggest that 8 weeks of mindfulness training may be associated with faster deployment of attentional resources during tasks requiring inhibitory control. Neural networks located in the prefrontal cortex (PFC) are known to play important roles in attention and executive functions, with evidence suggesting that inhibitory control processes are dependent upon networks located in the dorsolateral PFC (Ambrosini and Vallesi 2016; Pessoa 2008; Posner and Petersen 1990). The speed and efficiency of attentional networks are known to decline with age, and these declines are accompanied by longer P3 latencies and an increased dependence upon anterior executive control processes during

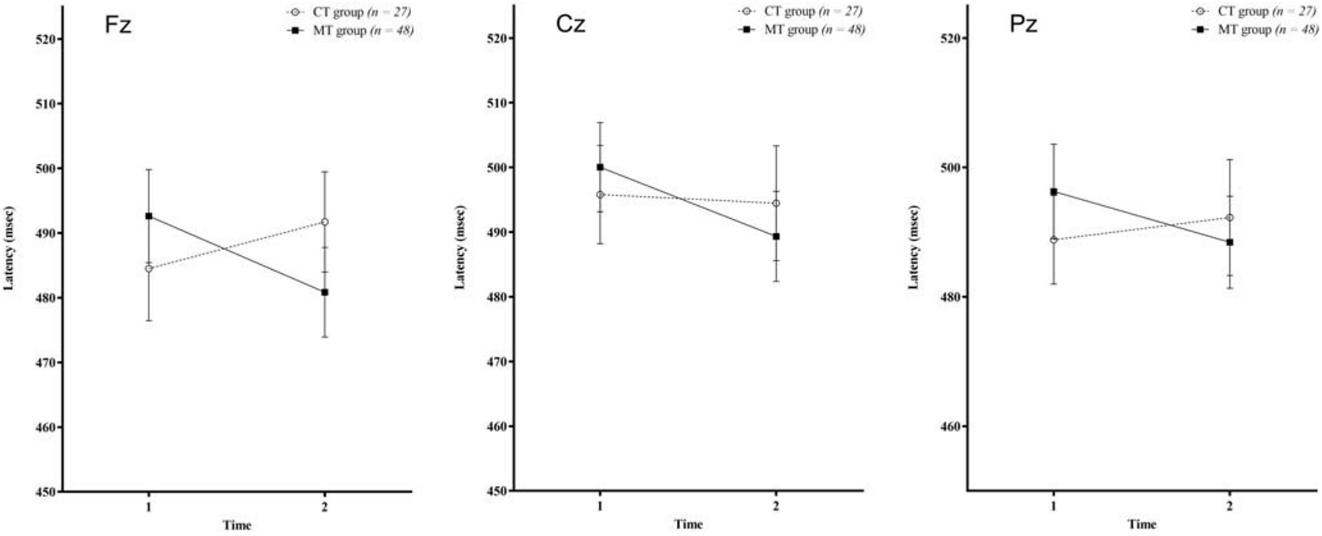

Fig. 3 Mean P3 latency at midline electrode sites at pre- (T1) and post-intervention (T2) for the mindfulness-based attention training group (MT) and the computer-based attention training group (CT). Error bars show standard error of the mean

attentional tasks, observed as a greater activation of anterior inhibitory control networks (Bellgrove et al. 2004; Staub et al. 2014; West 2004). Increasing reliance upon top-down inhibitory control with age reflects an increasing need to regulate attention in the face of increasing susceptibility to interference (Adam et al. 2015; Weissman et al. 2006). This vulnerability of attention to interference with age is observed as an increased variability of attentional deployment during attentional tasks, as indexed by reaction time coefficient of variation (RT CV; Andrés et al. 2008; Weeks and Hasher 2015).

Mindfulness has been hypothesised to train attentional control processes through the repeated activation of anterior neural networks associated with executive functions (Tang et al. 2015). Accordingly, it is notable that while both the CT and MT programs were successful at improving the stability of attentional deployment (as indexed by RT CV), reductions in frontal P3 latency were observed only in the MT group. These findings suggest that while both interventions were capable of improving participants' ability to regulate attentional deployment, only the MT program was capable of increasing the speed of attentional processes, which are known to slow with ageing. Furthermore, these findings lend support to the hypothesised primacy of anterior executive attentional processes in mindfulness training and suggest that these networks were preferentially targeted by the MT program.

Faster attention resource allocation during an attentional blink task has previously been reported following 3 months of intensive mindfulness training (Slagter et al. 2007). The attentional blink task requires the serial identification of two numbers presented amongst a stream of rapidly appearing letters and is designed to determine the shortest period in which two successive stimuli are discriminable. Slagter et al. demonstrated that mindfulness training resulted in faster processing times together with reductions in P3 amplitude, indicating enhanced efficiency of attention resource allocation to the first of two stimuli presented. However, Slagter et al. did not report changes in P3 latency following mindfulness training. The reductions in frontal P3 latency reported in the current study were of small-to-moderate effect size, indicating that the neural networks underlying inhibitory control processes activated in response to no-go stimuli during the SART responded faster after 8 weeks of mindfulness training compared to the CT group. These results suggest that mindfulness training may enhance the speed of attentional processes which are known to decline in ageing.

While it was hypothesised that the MT group would show increases in ERP amplitude after training, greater N2 amplitudes were observed in the CT group while the MT group showed reductions in N2 amplitude. Thus, while both groups demonstrated improved inhibitory control performance as indexed by errors of commission, the neural processes underlying these improvements appear to differ between the groups. Enhanced N2 amplitude in the CT group suggests greater attention resource allocation to response inhibition after training in this group, whereas reductions in N2 amplitude in the MT group suggest a reduced requirement of attentional resources for inhibitory processing after training. Larger amplitudes indicate greater neural resources contributing to the production of the N2 component are activated to meet attentional demands, since ERP components reflect the relative activation of cortical pyramidal cells during information processing (Luck and Kappenman 2011; Polich 2007). This interpretation is in line with previously reported reduction in P3 amplitude after mindfulness training indicating improved efficiency of attentional resource allocation during an attentional blink task (Slagter et al. 2007). In further support of improved efficiency of information processing resulting from mindfulness training, it was observed in the present study that reductions in N2 amplitude in the MT group were accompanied by improved attentional performance on the SART, suggesting that following mindfulness training, older adults are able to perform at a higher level while activating fewer neural resources.

Ageing is known to be associated with reductions in attentional efficiency together with a decline in both the speed and performance of attentional processes (West 2004). Deterioration of inhibitory control is thought to underpin many of the declines in cognitive function observed in age-related cognitive decline (Sarter et al. 2001). As such, our finding of improved inhibitory control performance suggests that cognitive training programs may have a role in combating age-related cognitive decline, with mindfulness in particular providing protective benefits against the slowing of attentional processes that occur in normal ageing. Since sustained attention and inhibitory control are central to attentional and cognitive processes, the finding of enhanced attentional outcomes resulting from these interventions suggests that such training may enhance older adult's ability to perform activities of daily living. Future investigation into the transfer of benefit from cognitive training targeting sustained attention and inhibitory control to activities of daily living is thereby indicated based on the findings reported here.

Limitations and Future Research Directions

While the current study recruited healthy older adults, the generalisability of these findings to older adults with health complaints is limited. However, having demonstrated that cognitive training is capable of enhancing attention in a high functioning group, it would be reasonable to expect that those with some form of impairment resulting from an underlying health condition may show equal benefit. Future studies examining attentional benefits of cognitive training in older adults with health conditions or mild cognitive impairment is warranted based upon the findings presented here.

The present study lacks post-intervention follow-up assessments which limit our ability to determine the long-term stability of the effects reported. Long-term maintenance of these attentional benefits is crucial if such interventions are to have a role in combating age-related cognitive decline. The absence of an additional control group not engaged in any training limits the ability to determine if the benefits observed are a product of non-specific intervention effects, such as social engagement and mental stimulation. However, previous research (Malinowski et al. 2017) utilising a brain training control group reported no change in ERP component amplitude or latency, suggesting the findings reported here were not due to non-specific intervention factors. The presence of unique benefits in the MT group not observed in the CT group in the present study supports this interpretation. Furthermore, while participant attrition was significant during the intervention period (MT = 12; CT = 4), only three participants dropped out due to a lack of interest, with all others failing to complete the program due to health or family concerns. Nevertheless, such attrition may have had an influence upon the outcomes observed in the current study.

Lastly, in order to prevent any bias resulting from the authors of this study being involved in the intervention delivery and data analysis, all analytical decisions were determined a priori based upon previous empirical evidence. In addition, ERP peak detection measures were reviewed by an independent researcher in order to limit any such bias that might affect the current work.

Author Contributions BI designed and conducted the study, delivered the interventions, performed the data analysis, and wrote the paper. JL collaborated in the data analysis, writing, and editing of the final manuscript. DH collaborated in the data analysis, writing, and editing of the final manuscript. KS reviewed all ERP component data analysis and collaborated in editing the final manuscript. MS collaborated in the design, data analysis, writing, and editing of the final manuscript.

Funding Information BI conducted this work with the support of the Judy Henzell Memorial Scholarship. MS reports personal fees from Eli Lily (Australia) Pty Ltd. and grants from Novotech Pty Ltd., outside the submitted work.

Compliance with Ethical Standards

Conflict of Interest The authors declare no conflicts of interest.

Ethics Statement All procedures were performed in accordance with the ethical standards of the University of the Sunshine Coast Human Research Ethics Committee (approval: HREC A-15-748), the Australian *National Statement on Ethical Conduct in Human Research*, and the *Code of Ethics of the World Medical Association (Declaration of Helsinki)*. In accordance with the latter two ethical statements which proscribe the use of no-treatment or placebo controls when existing effective treatment conditions exist, an active control condition consisting of a program of cognitive training was used as a comparison condition to assess the benefits of mindfulness training.

Informed Consent Informed consent was obtained from all individual participants included in the study.

References

Adam, K. C. S., Mance, I., Keisuke, F., & Vogel, E. K. (2015). The contribution of attentional lapses to individual differences in visual working memory capacity. *Journal of Cognitive Neuroscience, 27*(8), 1601–1616. https://doi.org/10.1162/jocn_a_00811.

Ambrosini, E., & Vallesi, A. (2016). Asymmetry in prefrontal resting-state EEG spectral power underlies individual differences in phasic and sustained cognitive control. *NeuroImage, 124*, 843–857. https://doi.org/10.1016/j.neuroimage.2015.09.035.

Anderer, P., Semlitsch, H. V., & Saletu, B. (1996). Multichannel auditory event-related brain potentials: Effects of normal aging on the scalp distribution of N1, P2, N2 and P300 latencies and amplitudes. *Electroencephalography and Clinical Neurophysiology, 99*(5), 458–472. https://doi.org/10.1016/S0013-4694(96)96518-9.

Andrés, P., Guerrini, C., Phillips, L. H., & Perfect, T. J. (2008). Differential effects of aging on executive and automatic inhibition. *Developmental Neuropsychology, 33*(2), 101–123. https://doi.org/10.1080/87565640701884212.

Bellgrove, M. A., Hester, R., & Garavan, H. (2004). The functional neuroanatomical correlates of response variability: evidence from a response inhibition task. *Neuropsychologia, 42*(14), 1910–1916. https://doi.org/10.1016/j.neuropsychologia.2004.05.007.

Delgado-Pastor, L. C., Perakakis, P., Subramanya, P., Telles, S., & Vila, J. (2013). Mindfulness (Vipassana) meditation: effects on P3b event-related potential and heart rate variability. *International Journal of Psychophysiology, 90*(2), 207–214. https://doi.org/10.1016/j.ijpsycho.2013.07.006.

Desbordes, G., Gard, T., Hoge, E. A., Hölzel, B. K., Kerr, C. E., Lazar, S. W., Olendzki, A., & Vago, D. R. (2015). Moving beyond mindfulness: defining equanimity as an outcome measure in meditation and contemplative research. *Mindfulness, 6*(2), 356–372. https://doi.org/10.1007/s12671-013-0269-8.

Donkers, F. C. L., & van Boxtel, G. J. M. (2004). The N2 in go/no-go tasks reflects conflict monitoring not response inhibition. *Brain and Cognition, 56*(2), 165–176. https://doi.org/10.1016/j.bandc.2004.04.005.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics, 16*(1), 143–149. https://doi.org/10.3758/bf03203267.

Gaeta, H., Friedman, D., & Hunt, G. (2003). Stimulus characteristics and task category dissociate the anterior and posterior aspects of the novelty P3. *Psychophysiology, 40*(2), 198–208. https://doi.org/10.1111/1469-8986.00022.

Gajewski, P., & Falkenstein, M. (2012). Training-induced improvement of response selection and error detection in aging assessed by task switching: effects of cognitive, physical, and relaxation training. *Frontiers in Human Neuroscience, 6*(130). https://doi.org/10.3389/fnhum.2012.00130.

Gajewski, P., Ferdinand, N. K., Kray, J., & Falkenstein, M. (2018). Understanding sources of adult age differences in task switching: evidence from behavioral and ERP studies. *Neuroscience & Biobehavioral Reviews, 92*, 255–275. https://doi.org/10.1016/j.neubiorev.2018.05.029.

Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology, 55*(4), 468–484. https://doi.org/10.1016/0013-4694(83)90135-9.

Hedden, T., & Gabrieli, J. D. E. (2004). Insights into the ageing mind: a view from cognitive neuroscience. *Nature Reviews Neuroscience, 5*(2), 87–96. https://doi.org/10.1038/nrn1323.

Isbel, B., & Summers, M. J. (2017). Distinguishing the cognitive processes of mindfulness: developing a standardised mindfulness technique for use in longitudinal randomised control trials. *Consciousness and*

Cognition, 52(Supplement C), 75–92. https://doi.org/10.1016/j.concog.2017.04.019.

Jha, A. P., Morrison, A. B., Dainer-Best, J., Parker, S., Rostrup, N., & Stanley, E. A. (2015). Minds "at attention": mindfulness training curbs attentional lapses in military cohorts. *PLoS One, 10*(2), 1–19. https://doi.org/10.1371/journal.pone.0116889.

Kabat-Zinn, J. (1990). *Full catastrophe living: using the wisdom of your mind to face stress, pain and illness*. New York: Delta.

Kelly, M. E., Loughrey, D., Lawlor, B. A., Robertson, I. H., Walsh, C., & Brennan, S. (2014). The impact of cognitive training and mental stimulation on cognitive and everyday functioning of healthy older adults: a systematic review and meta-analysis. *Ageing Research Reviews, 15*, 28–43. https://doi.org/10.1016/j.arr.2014.02.004.

Kiesel, A., Steinhauser, M., Wendt, M., Falkenstein, M., Jost, K., Philipp, A. M., & Koch, I. (2010). Control and interference in task switching—a review. *Psychological Bulletin, 136*(5), 849–874. https://doi.org/10.1037/a0019842.

Luck, S. J., & Kappenman, E. S. (2011). *The Oxford handbook of event-related potential components*. New York: Oxford University Press.

MacLean, K. A., Ferrer, E., Aichele, S. R., Bridwell, D. A., Zanesco, A. P., Jacobs, T. L., et al. (2010). Intensive meditation training improves perceptual discrimination and sustained attention. *Psychological Science, 21*(6), 829–839. https://doi.org/10.1177/0956797610371339.

Malinowski, P., Moore, A. W., Mead, B. R., & Gruber, T. (2017). Mindful aging: the effects of regular brief mindfulness practice on electrophysiological markers of cognitive and affective processing in older adults. *Mindfulness, 8*(1), 78–94. https://doi.org/10.1007/s12671-015-0482-8.

Milner, B. (1971). Interhemispheric differences in the localization of psychological processes in man. *British Medical Bulletin, 27*(3), 272–277.

Miyake, A., & Friedman, N. P. (2012). The nature and organization of individual differences in executive functions: four general conclusions. *Current Directions in Psychological Science, 21*(1), 8–14. https://doi.org/10.1177/0963721411429458.

Mrazek, M. D., Smallwood, J., & Schooler, J. W. (2012). Mindfulness and mind-wandering: finding convergence through opposing constructs. *Emotion, 12*(3), 442. https://doi.org/10.1037/a0026678.

Pessoa, L. (2008). On the relationship between emotion and cognition. *Nature Reviews Neuroscience, 9*, 148–158. https://doi.org/10.1038/nrn2317.

Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology, 118*(10), 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual Review of Neuroscience, 13*(1), 25–42. https://doi.org/10.1146/annurev.ne.13.030190.000325.

Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). 'Oops!': performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia, 35*(6), 747–758. https://doi.org/10.1016/S0028-3932(97)00015-8.

Sahdra, B. K., MacLean, K. A., Ferrer, E., Shaver, P. R., Rosenberg, E. L., Jacobs, T. L., … Saron, C. D. (2011). Enhanced response inhibition during intensive meditation training predicts improvements in self-reported adaptive socioemotional functioning. *Emotion, 11*(2), 299–312. doi:https://doi.org/10.1037/a0022764.

Sarter, M., Givens, B., & Bruno, J. P. (2001). The cognitive neuroscience of sustained attention: where top-down meets bottom-up. *Brain Research Reviews, 35*(2), 146–160. https://doi.org/10.1016/S0165-0173(01)00044-3.

Seli, P. (2016). The attention-lapse and motor decoupling accounts of SART performance are not mutually exclusive. *Consciousness and Cognition, 41*, 189–198. https://doi.org/10.1016/j.concog.2016.02.017.

Slagter, H. A., Lutz, A., Greischar, L. L., Francis, A. D., Nieuwenhuis, S., Davis, J. M., & Davidson, R. J. (2007). Mental training affects distribution of limited brain resources. *PLoS Biology, 5*(6), 1228–1235. https://doi.org/10.1371/journal.pbio.0050138.

Smallwood, J., & Schooler, J. W. (2015). The science of mind wandering: empirically navigating the stream of consciousness. *Annual Review of Psychology, 66*(1), 487–518. https://doi.org/10.1146/annurev-psych-010814-015331.

Staub, B., Doignon-Camus, N., Bacon, É., & Bonnefond, A. (2014). The effects of aging on sustained attention ability: an ERP study. *Psychology and Aging, 29*(3), 684. https://doi.org/10.1037/a0037067.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*(6), 643–662. https://doi.org/10.1037/h0054651.

Sturm, W., & Willmes, K. (2001). On the functional neuroanatomy of intrinsic and phasic alertness. *NeuroImage, 14*(1), S76–S84. https://doi.org/10.1006/nimg.2001.0839.

Tang, Y. Y., Hölzel, B. K., & Posner, M. I. (2015). The neuroscience of mindfulness meditation. *Nature Reviews Neuroscience, 16*(4), 213–225. https://doi.org/10.1038/nrn3916.

Treisman, A. (1982). Perceptual grouping and attention in visual search for features and for objects. *Journal of Experimental Psychology: Human Perception and Performance, 8*(2), 194–214. https://doi.org/10.1037/0096-1523.8.2.194.

Treisman, A., & Gormican, S. (1988). Feature analysis in early vision: evidence from search asymmetries. *Psychological Review, 95*(1), 15–48. https://doi.org/10.1037/0033-295X.95.1.15.

Unsworth, N., Redick, T. S., Lakey, C. E., & Young, D. L. (2010). Lapses in sustained attention and their relation to executive control and fluid abilities: an individual differences investigation. *Intelligence, 38*(1), 111–122. https://doi.org/10.1016/j.intell.2009.08.002.

Van den Hurk, P. A. M., Giommi, F., Gielen, S. C., Speckens, A. E. M., & Barendregt, H. P. (2009). Greater efficiency in attentional processing related to mindfulness meditation. *The Quarterly Journal of Experimental Psychology, 63*(6), 1168–1180. https://doi.org/10.1080/17470210903249365.

van Veen, V., & Cameron, C. S. (2002). The timing of action-monitoring processes in the anterior cingulate cortex. *Journal of Cognitive Neuroscience, 14*(4), 593–602. https://doi.org/10.1162/08989290260045837.

Verleger, R., Jaśkowski, P., & Wascher, E. (2005). Evidence for an integrative role of P3b in linking reaction to perception. *Journal of Psychophysiology, 19*(3), 165–181. https://doi.org/10.1027/0269-8803.19.3.165.

Weeks, J. C., & Hasher, L. (2015). Aging and inhibition. In N. A. Pachana (Ed.), *Encyclopedia of Geropsychology*. Singapore: Springer.

Weissman, D. H., Roberts, K. C., Visscher, K. M., & Woldorff, M. G. (2006). The neural bases of momentary lapses in attention. *Nature Neuroscience, 9*, 971–978. https://doi.org/10.1038/nn1727.

West, R. (2004). The effects of aging on controlled attention and conflict processing in the stroop task. *Journal of Cognitive Neuroscience, 16*(1), 103–113. https://doi.org/10.1162/089892904322755593.

Zanesco, A. P., King, B. G., Maclean, K. A., & Saron, C. D. (2013). Executive control and felt concentrative engagement following intensive meditation training. *Frontiers in Human Neuroscience, 7*, 1–13. https://doi.org/10.3389/fnhum.2013.00566.

Zigmond, A. S., & Snaith, R. P. (1983). The hospital anxiety and depression scale. *Acta Psychiatrica Scandinavica, 67*(6), 361–370. https://doi.org/10.1111/j.1600-0447.1983.tb09716.x.