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ORIGINAL PAPER

Mindfulness Training Improves Attention: Evidence from Behavioral and Event-related Potential Analyses

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Abstract
Mindfulness meditation helps to improve attentional capacity. However, the neural correlates that indicate the mechanism through which mindfulness improves attention are unclear. To address this gap, we aimed to assess the effects of mindfulness training on sustained attentional capacity. Event-related potentials (ERPs) associated with the modified sustained attention response task (mSART) were used in this study. A total of 45 college students were randomly assigned to either the mindfulness group (n = 21) or the control group (n = 24). Participants in the mindfulness group received a three-week mindfulness training. The self-report results showed that the mindfulness group reported higher mindfulness scores (observing and non-judgment of inner experiences) after the training. The mindfulness group also scored lower on the state anxiety than the control group. Behavioral results also showed that self-caught mind wandering in the mindfulness group significantly decreased after the training, and the mindfulness group showed a faster response after the training. The ERP results showed that N2 amplitudes in the post-test were significantly greater than those in the pre-test in the mindfulness group. We did not find any interactions between group and time for P3. The findings suggest that mindfulness training can effectively improve sustained attentional capacity, as indicated by reduced mind wandering and increased N2 responses.

Keywords Mindfulness · Mind wandering · Neural correlates · ERPs

Introduction

Attention is the ability to flexibly utilize one's cognitive resources in a focal manner to attend to tasks at hand, and tune out other stimuli (Lindsay 2020; Posner and Rothbart 2007). However, attention is not always easily directed to a specific task, regardless of the task's importance. Mind wandering (MW) often occurs during these attentional slips (Denkova et al. 2019). MW encompasses task-unrelated thoughts and affects that direct the attention away from the task at hand (Smallwood and Schooler 2006; Mason et al., 2007) and is a common phenomenon that occupies almost half of the waking hours of an individual (Bower 2010). MW was found to be related to the ineffectiveness of executive control (McVay and Kane 2010). Previous studies have shown that MW impairs reading comprehension, increases target difficulty, reduces distractor inhibitions (Feng et al. 2013; Mooneyham and Schooler 2013; Smallwood 2011a, b; Thomson et al. 2013), and disrupts working memory performances (Rummel and Boywitt 2014; Stawarczyk et al. 2013).

MW is commonly measured via the sustained attention response task (SART). SART is similar to the go/no-go task, where participants are presented with a series of numbers (from 0 to 9) and instructed either to press a button (go trials, 0 to 9 except 3) when the stimuli are presented at the

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center of the screen or to inhibit their responses when the number 3 is presented (no-go trials). Failure to withhold responses when viewing the target stimuli (the number 3) was considered a commission error or target error, which has been regarded as an objective behavioral indicator of MW (Denkova et al. 2018). Additionally, SART can measure MW by probing questions presented intermittently during the task. During the task, participants were asked a random probing question regarding what they were experiencing (i.e., on-task or off-task). If they selected off-task (indicating MW), they were asked whether they were aware of MW (Smallwood et al. 2003, 2004, 2008). It has been stated that one's mental state tends to be mostly task-unrelated or stimulus-independent and it is not clear how such a state arises or changes over time (Irving 2015). Only once we consider the dynamics of thoughts can we make crucial distinctions among different thought types (Christoff et al. 2016). Therefore, it is necessary to explore the dynamics of thought during the SART, which requires modifying the typical SART. Liu et al. explored the dynamics of attention during the SART and modified the typical SART. During the modified SART, participants were asked to press a button whenever they realized MW, which was classified as self-caught MW, and MW identified by probes was defined as probe-caught MW. (The details can be found in Methods or Liu et al. 2021).

Meta-awareness refers to the conscious awareness of the explicit contents of the current thoughts, that is, one is aware of the ongoing experience at the very moment (Christoff et al. 2016), which is a core process related to MW (Ibaceta and Madrid 2021). Meta-awareness plays an important role in the self-regulation of attention, resulting in either decreasing MW directly or indirectly controlling conscious thought (Schooler 2002). Meta-awareness could be improved by mindfulness training, while the level of meta-awareness was found to be significantly correlated with attentional control (Bernstein et al. 2019; Dunne et al. 2019; Giannandrea et al. 2018; Lutz et al. 2015). Smallwood and Schooler argued that, in the absence of effective meta-awareness monitoring, MW tends to occupy executive resources and directs them away from one's primary task (Smallwood and Schooler 2006). Mindfulness practitioners demonstrated better accuracy in recognizing their affective states and body sensations compared to the controls in a cross-sectional study, suggesting that individuals with contemplative mental practices tended to have higher introspection ability (Baird et al. 2014; Fox et al. 2012).

Since MW has strong negative effects on many aspects of human cognitive abilities, including reading, inhibition, and working memory, it is crucial to explore effective interventions to reduce MW. Mindfulness meditation has been proposed as an effective method for attenuating MW. Mindfulness refers to the ability to be aware of one's experiences and pays attention to the present moment in a purposeful, accepting, and nonjudgmental manner (Crane et al. 2017; Kabat-Zinn 2003). Mindfulness meditation facilitates the efficiency of cognitive resource allocation and enhances the self-regulation of attention, contributing to better performance in typical SART. Mindfulness meditation also helps one gain control over task-unrelated thoughts (MW), and enables individuals to observe MW activities with lowered emotional responses (Zanesco et al. 2019). Additionally, mindfulness meditation enhanced metacognitive awareness (Beeney and Dunn 1990). A lack of metacognitive awareness could indicate MW (*Yearbook of international psychiatry and behavioral neurosciences – 2009*, 2011). Zanesco et al. found that participants in an intensive meditation training group engaged in less MW and less mindless reading during a reading task, suggesting that intensive meditation training may promote reductions in MW during a complex cognitive task (Zanesco et al. 2016). There have been accumulating empirical support for the positive effect of mindfulness on MW during the SART (Banks et al. 2019; Brandmeyer and Delorme 2018; Deng et al. 2019; Hasenkamp et al. 2012; Kirk et al. 2018; Mrazek et al. 2013, 2019; Ortet et al. 2020; Sanger and Dorjee 2016).

ERPs can be obtained from electroencephalographic (EEG) measures of brain activities, which have been popularly used in the field of clinical and experimental psychology for observing the changes in neural activities after the onset of a specific stimulus, ranging from perception to emotions (Bradley and Keil 2012; Norton et al. 2021). N2 and P3 potentials are two EEG components that are closely related to the research field of mindfulness and MW. The N2 is a negative potential with a 180–325 ms latency and represents inhibitory control and conflict monitoring (Gajewski et al. 2018; Alho 1995; Shinagawa et al. 2019). Studies have found a decrease in N2 amplitudes during MW (Braboszcz and Delorme 2011). Focused-attention meditation elicited an increase in N2 and increased cognitive control (Chan et al. 2020). Brief mindfulness meditation training also improved N2 amplitudes, indicating that mindfulness improves the focus of attentional resources (Bateman et al. 2016). Furthermore, the increase in N2 amplitudes would indicate that mindfulness improves meta-cognitive processes and enhances the capacity for allocating neural resources to task demands (Lin et al. 2019; Pozuelos et al. 2019). P3 is a positive potential typically with 300–400 ms latency (Crowley and Colrain 2004; Patel and Azzam 2005). Previous studies indicated that MW attenuates P3 amplitudes during deep semantic tasks (Haubert et al. 2018; Goncalves et al. 2018; Xu et al. 2018). Smallwood et al. found that P3 amplitudes were reduced before both behavioral and subjective reports of MW during a typical SART (Smallwood et al. 2008).

With an increase in P3 amplitudes, other study results indicated that mindfulness training enhances the capacity to mobilize attention resources during the SART (Isbel et al. 2020; Lasaponara et al. 2019). Another study has shown that individuals in the intensive meditation training group exhibited increased P3 amplitudes during an attentional performance task and were more able at noticing target cues that are less salient, indicating improved visual and perceptual ability baseline. Thus, the study concluded meditation training facilitated attentional detection and the processing of visual targets (Zanesco et al. 2019).

Although previous studies have explored the impact of mindfulness meditation on MW, the research has been largely restricted to experience sampling and behavior indices (Steindorf & Rummel, 2020; Uzzaman & Joordens, 2011). To date, e mindfulness training's influences on MW have not yet been examined in the existent research on a neural correlates' level. A bibliometric analysis conducted on studies published between 2012 and 2020 found that the majority of the existing literatures on mindfulness intervention have been focused on measuring mindfulness levels (Baer 2003; Bishop et al. 2004) and the therapeutic effects of mindfulness-based intervention (Kabat-Zinn 1982). Out of the 410 articles the study included, only less than 10% of them were conducted using the electroencephalogram technique (Bunjak et al. 2022). Moreover, with the added ERP data, which have been deemed reliable and accurate historically, the neural correlates of mindfulness can be investigated in a timely, noninvasively, and focal manner (Helfrich and Knight 2019; Hillyard 2017; Rugg 2009). Therefore, the present study set out to explore the effect of a mindfulness intervention on MW from neural correlates' perspective and is the first study to investigate the efficacy of the intervention by combining the modified SART with ERP. The current study modified the classical SART by adding a self-caught MW section to explore the concept of meta-awareness to further investigate the dynamics of MW during the SART (Liu et al. 2021). Based on the previous studies described above, the present study chose N2 and P3 as the neural correlates of focus and hypothesized that (1) mindfulness contributes to sustained attention, which would be represented by decreased MW (both self- and probe-caught MW); and (2) mindfulness improves sustained attention by enhancing executive function, which would be reflected by enhanced N2 and P3 amplitudes.

Methods

Participants

Participants (N = 45) were recruited through campus advertisements at Southwest University, Chongqing, China. They were randomly assigned to the mindfulness (n = 21; 6 males; age: 18–27 years, M = 21.38, SD = 2.46) and the control groups (n = 24; 11 males; age: 18–24 years, M = 20.67, SD = 1.76). Participants in the current study were required to stay abstinent from any substances or medications that could potentially alter their attention or concentration. Additionally, they were required to disclose any history of major psychological disorders. All participants reported normal or corrected-to-normal vision. Before starting the experiment, all participants read the instructions, and any questions about the experiment were addressed in their entirety before they signed the informed consent form.The Southwest University Ethics Committee approved this study.

Measurements

Five-Facet Mindfulness Questionnaire (FFMQ)

The Chinese version of the Five-Facet Mindfulness Questionnaire (Deng et al. 2011; Baer et al. 2008; Hou, Wong, Lo, Mak, & Ma, 2014; Meng et al. 2020) assesses the general tendency to be mindful in daily life. This measure consists of 39 items rated on a 5-point Likert scale from 1 (never or very rarely true) to 5 (very often or always true). This scale consists of five subscales: observing (e.g., "I notice the smells and aromas of things"), describing (e.g., "I am good at finding the words to describe my feelings"), acting with awareness (e.g., "I find myself doing things without paying attention"), non-reactivity to inner experience (e.g., "I think some of my emotions are bad or inappropriate and I should not feel them"), and non-judgment of inner experience (e.g., "I perceive my feelings and emotions without having to react to them") (Gu et al. 2016; Williams et al. 2014). Higher scores indicated higher mindfulness levels (Giannandrea et al. 2018). The internal consistency in the present study was good (Cronbach's αT1/T2 = 0.89/0.87).

State-Trait Anxiety Inventory (STAI)

STAI is a self-report measure of state and trait anxiety (Hallit et al. 2019; Hoffmann et al. 2016; Zingano et al. 2019). The experiment took place around finals week and participants were preparing and taking their final exams, the measure was required to control for participants' anxiety levels. We used the Chinese version of the STAI adapted by Tsoi and Tam (Tsoi and Tam 1983). Its validity and reliability

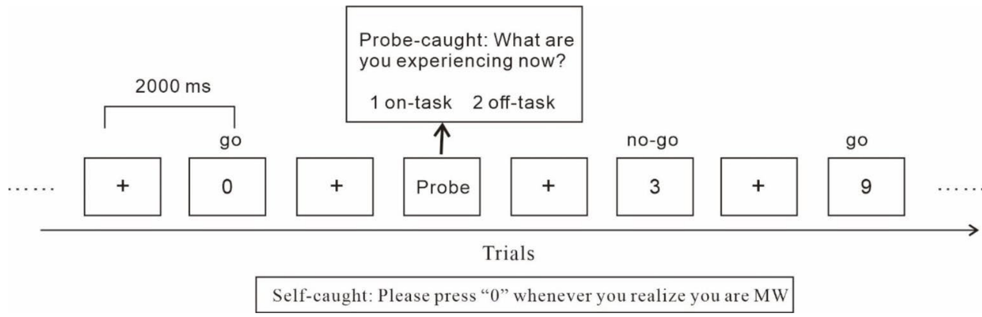

Fig. 1 The modified sustained attention to response task (SART; Liu et al. 2021; MW, mind wandering)

are empirically supported (Shek 1988). This scale consists of 40 items, with 20 items each measuring state and trait anxiety, which are rated on a 4-point Likert scale from 1 (almost never) to 4 (almost always). State anxiety is conceptualized as a transient and fleeting emotional state produced by the perception of tension or a wide range of threatening stimuli. Accordingly, its severity varies with time and the situation. Subsequently, trait anxiety is identified as a relatively stable characteristic of an individual's personality and a constant behavioral tendency toward anxiety proneness. The items of both subscales were framed bidirectionally. For instance, state anxiety items contain "I feel calm" versus "I am tense," and trait anxiety items include "I feel nervous and uneasy too much" versus "I feel at ease." In our study, the internal consistency reliability for state and trait anxiety was Cronbach's $\alpha T1/T2 = 0.90/0.85$ and Cronbach's $\alpha T1/T2 = 0.83/0.73$, respectively.

Sustained attention response task

Participants completed the task in a quiet room designed for EEG experiments. An E-prime-based version of the modified SART (Liu et al. 2021) was used in the current study. Digits from "0" to "9" were presented at the center of the screen in a pseudo-random order (Christoff et al. 2009). Participants were required to press the button "1" every time a number appeared on the screen except for "3" (go trials). Targets of the number "3," appeared in 5% of trials. The total number of "3" instances was 64 (Riby et al. 2008; Smallwood et al. 2008). When the number "3" appeared on the screen, participants had to inhibit their response (no-go trials). During the task, participants were asked to press the "0" button whenever they realized that they were MW (Fig. 1), which was defined as self-caught MW. Occasionally, the probes asked participants "What are you experiencing now?" (1. on-task; 2. off-task). Participants were asked to respond to the probes. If participants did not respond, the probes would automatically disappear after 2000 ms. The selection of "off-task" was defined as probe-caught MW. The probe questions appeared for a total of 64 times and each probe had the same content. The probes were presented in pseudo-random order and takes up 5% of all trials. The average number of trials between each probe is 19.61. During the task, a fixation appeared first, after which the stimuli were presented on the monitor until participants responded. The total duration of the fixation and stimulus appearance was 2000 ms. The task consisted of four test blocks of 14 min. Each block consisted of 329 trials (approximately 313 go trials, 16 no-go trials, and 16 probes). There was a 3-minute rest between each block.

Stimuli were presented on a 19-inch Dell computer monitor, with the center of the screen set at eye level. Participants were instructed to remain as still as possible and minimize their eye blinks to reduce experimental artifacts during EEG data collection.

Procedure

Participants in both groups completed the FFMQ, the STAI, and the SART in the pre- and post-tests. Participants in the mindfulness group received 30-min mindfulness training each day for 21 days (average training days: 20.3). The training included mindful breathing, body scanning, mindful walking, and mindful eating. The training was conducted by a professional expert who is certificated in Mindfulness-Based Cognitive Therapy and Mindfulness-Based Stress Reduction. Participants in the mindfulness group participated in group training in a room at Southwest University. At the end of the daily training, participants shared their experiences among the group. The research group did not provide additional materials to facilitate the training. Throughout the training, the expert provided the necessary psychoeducation and feedback based on clinical observations as well as participant reactions. The control group did not receive any mindfulness training. The participants in the control group were instructed to sit in a chair for 30-min each day for 21 days while having the freedom to do whatever they pleased as long as they remain in the lab. This was to make sure that the control group and mindfulness group committed the same amount of time towards the study. All participants received 500 RMB after their participation.

Self-report and Behavior Analyses

Eight 2 (group: mindfulness and controls) × 2 (time: pre- and post-test) repeated-measures ANOVAs were conducted on the self-report measures (e.g., FFMQ and its five subscales and STAI and its two subscales), with the group as a between-subjects factor, and time as a within-subjects factor.

Three 2 (group: mindfulness and controls) × 2 (time: pre- and post-test) repeated-measures ANOVAs were conducted on the behavioral indexes [e.g., self-caught MW, probe-caught MW, go reaction time (RT)], with the group as a between-subjects factor, and time as a within-subjects factor. A 2 (group: mindfulness and controls) × 2 (time: pre- and post-test) × 2 (trial type: go and no-go) repeated-measures ANOVA was conducted on the accuracy (ACC), with the group as a between-subjects factor, time and trial type as within-subject factors.

One participant in the mindfulness group did not complete the post-test and was excluded from the data analysis, resulting in a final sample size of 44 participants.

EEG Recording and Analysis

ERP data were recorded using a 64-electrode cap positioned according to the 10–20 system for electrode placement with the linked reference on the left and right mastoids, and a ground electrode was placed on the medial frontal aspect (Brain Products, GmbH, Germany). The horizontal electrooculogram (HEOG) was recorded by placing electrodes outside the two eyes and the vertical electrooculogram (VEOG) was recorded by placing electrodes up and down on the left eye. The impedance of each electrode was maintained below 5 kΩ.

Data processing was performed using MATLAB R2014a and the EEGLAB toolbox14.1.1b (Delorme and Makeig 2004). Data were processed offline after continuous ERP recording. Based on a previous study (Liu et al. 2020), we first down-sampled the data from 500 Hz to 256 Hz and performed high-pass filtering at 0.01 Hz and low-pass filtering at 45 Hz. The mean values of the left and right mastoids were selected as the re-reference. Data were epoched from 0.2 s before stimulus onset to 2 s after the presentation and were baseline corrected to the pre-stimulus interval. Eye movement artifacts (blinks and eye movements) were rejected offline. Trials with electrooculographic (EOG) artifacts (ocular movements and eye blinks), artifacts due to amplifier clippings, bursts of electromyography activity, or peak-to-peak deflections exceeding ± 80μV were excluded from averaging [The remaining trials (except MW epochs): 836.57 ± 80.00 go trials and 43.77 ± 10.66 no-go trials in pre-test; 790.41 ± 99.83 go trials and 38.52 ± 10.71 no-go trials in post-test]. The components including EOG artifacts and head movement were removed from the results of the independent component analysis (ICA) after visual inspection.

In the current study, the trials that needed participants to press button "1" were go trials. The trials in which the number "3" appeared on the center of the screen were no-go trials. We processed the brain activity of N2 from the Fz site and P3 from Pz. Based on all the participants' grand-averaged ERPs activities, the ERPs and their time windows were as follows: N2 (250–380 ms) and P3 (400–600 ms). Two 2 (group: mindfulness and controls) × 2 (time: pre- and post-test) × 2 (trial type: go and no-go) repeated-measures ANOVAs were conducted on the mean amplitudes of N2 and P3, with the group as a between-subjects factor, and time and trial type as within-subject factors. All analyses were conducted using SPSS version 22.0. The p-values were adjusted for sphericity using the Greenhouse–Geisser method. Post-hoc t-tests were performed using Bonferroni adjustments for multiple comparisons.

Results

Self-report Results

A two-way repeated- measures ANOVA on the total FFMQ score showed a significant interaction of group and time (F (1, 42) = 12.09, $p < 0.01$, partial $\eta^2 = 0.22$). A simple effect analysis showed that the self-reported mindfulness scores increased from pre- to post-test in the mindfulness group (F (1, 42) = 24.98, $p < 0.01$, partial $\eta^2 = 0.37$); there is no difference between the pre and post-test of FFMQ score in the control group (F (1, 42) = 0.10, $p = 0.75$, partial $\eta^2 = 0.002$). there was no significant difference between the mindfulness and control groups in the pre-test (F (1, 42) = 1.13, $p = 0.29$, partial $\eta^2 = 0.03$) and post-test (F (1, 42) = 2.77, $p = 0.10$, partial $\eta^2 = 0.06$). We also found the mindfulness intervention effect in subscales "observing" and "non-judgment of inner experience". For the observing subscale, there was a significant group by time interaction (F (1, 42) = 6.74, $p = 0.01$, partial $\eta^2 = 0.14$), and follow-up simple effect analysis indicated that the scores increased from pre- to post-test in the mindfulness group (F (1, 42) = 8.00, $p < 0.01$, partial $\eta^2 = 0.16$); no difference were found in the control group (F (1, 42) = 0.57, $p = 0.46$, partial $\eta^2 = 0.01$). There was no significant difference between the mindfulness and control groups in the pre-test (F (1, 42) = 0.72, $p = 0.40$, partial $\eta^2 = 0.02$) and post-test (F (1, 42) = 1.43, $p = 0.24$, partial $\eta^2 = 0.03$). For the non-judgment of inner experience subscale, there was a significant group by time interaction (F (1, 42) = 4.36, $p = 0.04$, partial $\eta^2 = 0.10$), and a simple effect analysis showed an increase in the mindfulness group

(F (1, 42) = 11.84, $p < 0.01$, partial $\eta^2 = 0.22$), and no difference were found between the pre and post-test in the control group (F (1, 42) = 0.45, $p = 0.51$, partial $\eta^2 = 0.01$). Additionally, the score of the non-judgment of inner experience subscale in the mindfulness group was greater than that in the control group in the post-test (F (1, 42) = 8.65, $p = 0.005$, partial $\eta^2 = 0.17$); there was no significant group difference in the pre-test (F (1, 42) = 0.08, $p = 0.77$, partial $\eta^2 = 0.002$). There was no significant effect in the control group, with all $ps > 0.05$.

Results on the TAI showed a significant interaction of group and time (F (1, 42) = 9.98, $p = 0.003$, partial $\eta^2 = 0.19$), and a simple effect analysis showed that the TAI score in the post-test was significantly lower than that in the pre-test in the mindfulness group (F (1, 42) = 13.34, $p = 0.001$, partial $\eta^2 = 0.24$); the difference in the control group was found to be insignificant (F (1, 42) = 0.47, $p = 0.50$, partial $\eta^2 = 0.01$). The TAI score in the mindfulness group was significantly lower than that in the control group in the post-test (F (1, 42) = 18.24, $p < 0.001$, partial $\eta^2 = 0.30$); there was no significant group difference in the pre-test (F (1, 42) = 1.31, $p = 0.26$, partial $\eta^2 = 0.03$). Results on TAI showed a main effect of group (F (1, 42) = 10.59, $p = 0.002$, partial $\eta^2 = 0.20$), the TAI score in the mindfulness group was lower than that in the control group; and the main effect of time (F (1, 42) = 4.99, $p = 0.03$, partial $\eta^2 = 0.11$), the TAI score in the post-test was lower than that in the pre-test.

Results on SAI showed a main effect of group (F (1, 42) = 6.79, $p = 0.01$, partial $\eta^2 = 0.14$). No significant difference between the pre and post-test of SAI was found in the mindfulness group (F (1, 42) = 0.11, $p = 0.74$, partial $\eta^2 = 0.003$), while it was also not found in the control group (F (1, 42) = 0.006, $p = 0.94$, partial $\eta^2 < 0.001$). The SAI score in the mindfulness group was lower than that in the control group. No significant interaction of group and time was found (F (1, 42) = 0.038, $p = 0.85$, partial $\eta^2 = 0.001$).

Behavioral Results

Self-caught MW

Results on self-caught MW (Fig. 2) showed an interaction of group and time, F (1, 42) = 9.46, $p = 0.004$, partial $\eta^2 = 0.18$, and a simple effect analysis showed that self-caught MW decreased significantly from pre- to post-test in the mindfulness group (F (1, 42) = 12.85, $p < 0.001$, partial $\eta^2 = 0.23$), indicating that mindfulness training contributed to individuals' sustained attention. There was no difference between pre- and post-tests in the control group (F (1, 42) = 0.40, $p = 0.53$, partial $\eta^2 = 0.009$). There was no significant difference between the mindfulness and control groups in the pre-test (F (1, 42) = 3.44, $p = 0.07$, partial $\eta^2 = 0.076$) and post-test (F (1, 42) = 0.12, $p = 0.74$, partial $\eta^2 = 0.003$). There was a main effect of time (F (1, 42) = 4.93, $p = 0.03$, partial $\eta^2 = 0.11$), the post-hoc t-test showed that self-caught MW during the post-test was significantly lower compared to the pre-test.

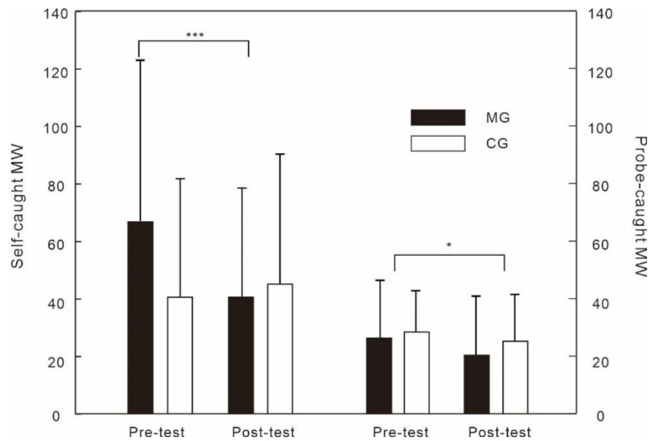

Fig. 2 Self- and probe-caught mind wandering (MG: mindfulness group; CG: control group)

Probe-caught MW

Results on probe-caught MW (Fig. 2) showed a main effect of time (F (1, 42) = 5.50, $p = 0.02$, partial $\eta^2 = 0.12$), which showed that probe-caught MW was significantly lower during the post-test compared to the pre-test. There was no interaction of group and time (F (1, 42) = 0.49, $p = 0.49$, partial $\eta^2 = 0.01$).

Go reaction time

Results on go RT showed an interaction of group and time, F (1, 42) = 9.58, p = 0.004, partial $\eta^2 = 0.19$, and a simple effect analysis showed that go RT decreased significantly from pre- to post-test in the mindfulness group, F (1, 42) = 10.59, p = 0.002, partial $\eta^2 = 0.20$. No same effect was observed in the control group (F (1, 42) = 1.05, $p = 0.31$, partial $\eta^2 = 0.02$). There was no significant difference between the mindfulness and control groups in the pre-test (F (1, 42) = 2.85, $p = 0.10$, partial $\eta^2 = 0.06$) and post-test (F (1, 42) = 0.07, $p = 0.80$, partial $\eta^2 = 0.002$).

In addition, we did not find the difference between pre- and post-test on go ACC and no-go ACC, all $ps > 0.05$. However, we found that go ACC was significantly greater than no-go ACC, $p < 0.001$. Descriptive statistics accompanying the self-report and behavior results can be found in Table 1.

Note: FFMQ, Five-Facet Mindfulness Questionnaire; Obs, observing; Des, Describing; AWA, acting with awareness; NRIE, Non-reactivity to inner experience; NJIE,

Table 1 Descriptive statistics accompanying the self-report and behavior results (M ± SD)

Variable	mindfulness group (n = 20)		control group (n = 24)	
	pre-test	post-test	pre-test	post-test
FFMQ	115.70 (9.58)	127.15 (13.85)	119.75 (14.61)	1120.42 (12.93)
Obs	22.45 (5.12)	24.85 (4.63)	23.75 (5.01)	23.17 (4.66)
Des	23.95 (3.19)	26.70 (5.69)	25.50 (5.44)	26.00 (4.72)
AWA	25.05 (4.65)	27.55 (4.26)	28.42 (5.32)	28.54 (4.39)
NRIE	21.45 (3.25)	20.95 (2.39)	19.37 (4.33)	19.25 (3.39)
NJIE	23.10 (4.64)	27.30 (4.71)	22.71 (4.29)	23.46 (3.96)
TAI	42.15 (7.52)	35.65 (7.24)	44.67 (7.03)	45.78 (8.29)
SAI	37.25 (9.00)	37.85 (7.04)	42.58 (6.51)	42.71 (7.82)
Self-caught MW	67.20 (55.86)	40.65 (41.21)	40.92 (37.69)	45.21 (46.97)
Probe-caught MW	26.45 (20.09)	20.45 (20.57)	28.58 (14.33)	25.33 (16.34)
Go ACC	0.93 (0.05)	0.95 (0.05)	0.94 (0.05)	0.93 (0.06)
Go RT	447.61 (89.38)	415.49 (91.97)	411.65 (49.27)	420.87 (43.33)
Nogo ACC	0.56 (0.22)	0.60 (0.20)	0.50 (0.18)	0.54 (0.17)

Table 2 The values of N2 and P3 amplitudes (M ± SD)

ERPs	mindfulness group (n = 20)		control group (n = 24)	
	pre-test	post-test	pre-test	post-test
go N2	-1.38 (2.47)	-2.78 (4.61)	-1.25 (2.23)	-0.71 (2.48)
nogo N2	-0.89 (3.12)	-2.58 (4.51)	-0.36 (3.29)	0.86 (4.36)
go P3	0.14 (2.45)	-0.15 (4.13)	-0.27 (2.26)	-0.97 (3.81)
nogo P3	3.94 (4.26)	5.53 (7.16)	4.51 (4.73)	5.42 (5.71)

Non-judgment of inner experience; TAI, Trait Anxiety Inventory; SAI, State Anxiety Inventory.

ERP Results

The values of N2 and P3 amplitudes can be found in Table 2. Grand average ERPs for N2 and P3 at Fz and topography plots are shown in Fig. 3.

N2

Repeated-measures ANOVA on N2 showed a significant interaction between group and time *(F* (1, 42) = 7.10, $p = 0.01$, partial $\eta^2 = 0.15$), and simple effect analysis showed that N2 mean amplitudes in the post-test were significantly greater than those in the pre-test in the mindfulness group *(F* (1, 42) = 5.29, p = 0.03, partial $\eta^2 = 0.11$). No similar effect was observed in the control group *(F* (1, 42) = 2.06, $p = 0.16$, partial $\eta^2 = 0.05$). Moreover, N2 amplitudes in the mindfulness group were significantly greater than that in the control group in the post-test (*F* (1, 42) = 6.43, $p = 0.02$, partial $\eta^2 = 0.13$). There was no significant group-difference in the pre-test (*F* (1, 42) = 0.18, $p = 0.67$, partial $\eta^2 = 0.004$). There was no main effect of the trial type (*F* (1, 42) = 3.78, $p = 0.06$, partial $\eta^2 = 0.08$). We did not find a significant interaction between the group, time, and trial type (*F* (1, 42) = 0.89, $p = 0.35$, partial $\eta^2 = 0.02$).

P3

The results on P3 showed a significant interaction between time and trial type (*F* (1, 42) = 8.74, $p = 0.005$, partial $\eta^2 = 0.17$), and a simple effect analysis showed that P3 amplitudes in no-go trials were significantly greater than those in go trials in both pre-test and post-test, all *p*s < 0.001; no-go P3 amplitudes in post-test were greater than that in pre-test (*F* (1, 42) = 5.75, $p = 0.02$, partial $\eta^2 = 0.12$). The results also showed a significant interaction between group and time, *F* (1, 42) = 5.49, $p = 0.02$, partial $\eta^2 = 0.12$, and a simple effect analysis showed that P3 amplitudes in the post-test were greater than that in the pre-test in mindfulness group (*F* (1, 42) = 6.93, $p = 0.01$, partial $\eta^2 = 0.14$); while no significant difference was found in the control group (*F* (1, 42) = 0.35, $p = 0.56$, partial $\eta^2 = 0.008$). there was no significant between-group difference in the pre-test (*F* (1, 42) = 0.03, $p = 0.87$, partial $\eta^2 = 0.001$); P3 amplitudes in the mindfulness group were greater than that in the control group in the post-test (*F* (1, 42) = 4.79, $p = 0.03$, partial $\eta^2 = 0.10$).

Discussion

This study aimed to explore the impact of mindfulness meditation on MW and elucidated the underlying neural correlates. Based on previous studies, we used a modified SART with ERPs to explore changes in MW in the current study. The self-caught and probe-caught MW of the SART are behavioral indices. The change in N2 and P3 amplitudes are neural correlates. The self-caught MW significantly decreased in the mindfulness group, while no significant effect was found in the control group. Probe-caught MW in the post-test was significantly lower than that in the pre-test. Additionally, N2 and P3 amplitudes were significantly enhanced in the mindfulness group after mindfulness training.

The findings showed that two subscales of the FFMQ increased significantly after the mindfulness training, including observing, and non-judgment of the inner experience, while no difference was found for the control group. The results stay consistent with a previous study that the FFMQ score significantly increased after mindfulness

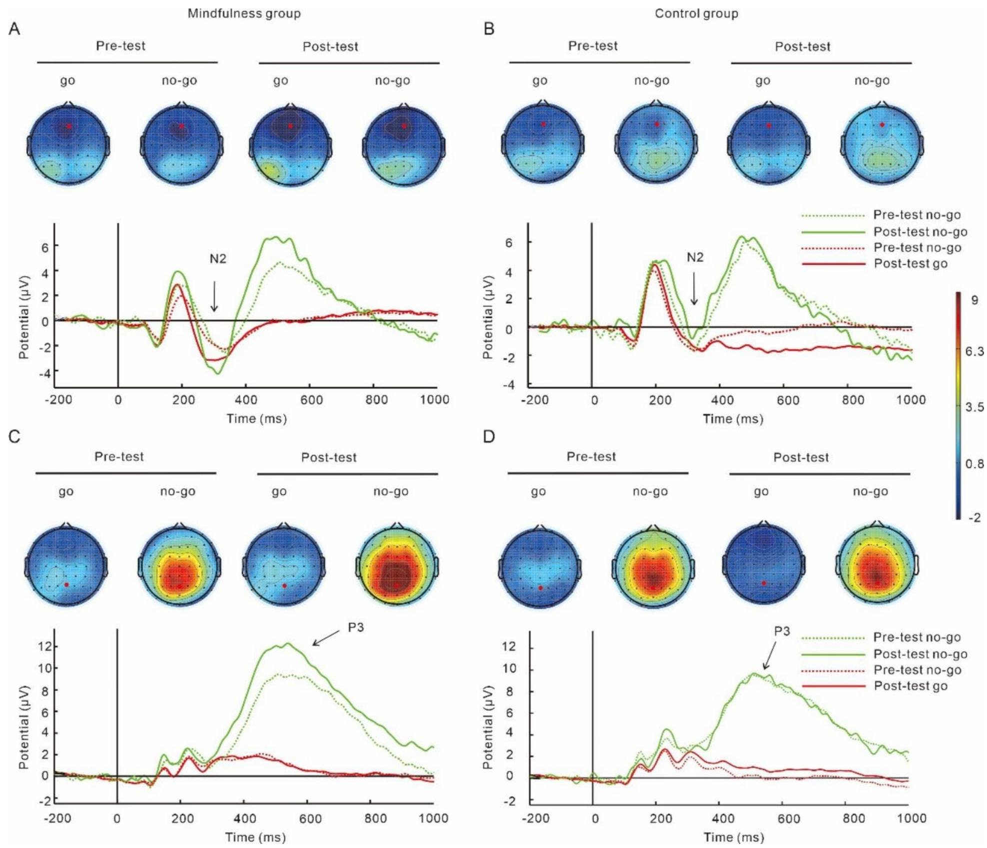

Fig. 3 Effect of mindfulness on the grand-average ERP for go and no-go stimuli. (A, B) ERP at electrode site Fz and topographical maps for the go and no-go stimuli in pre- and post-test in mindfulness group (A) and control group (B). (C, D) ERP at electrode site Pz and topographical maps for the go and no-go stimuli in pre- and post-test in mindfulness group (C) and control group (D). The red point represents electrode site Fz (A, B) and Pz (C, D). The time window of N2 was 250–380 ms, and the time window of P3 was 400–600 ms.

training (Goldberg et al. 2016), implying that mindfulness training contributed to the enhancement of trait-mindfulness (Baer et al. 2006). Indicating the effectiveness of the training while supporting the previous findings that mindfulness training improved sustained attention (Brandmeyer and Delorme 2018; Giannandrea et al. 2018; Kirk et al. 2018; Mrazek et al. 2013, 2019).

The results also showed that the TAI decreased significantly after the mindfulness training, while no such pattern was found in the control group. Moreover, both TAI and SAI score was significantly less than the scores in the control group. Considering the combined evidence of higher mindfulness scores and lower anxiety scores, the current findings are consistent with previous research that individuals who score high on mindfulness report less anxiety (Ghahari et al. 2020; Kwok et al. 2019; Stinson et al. 2020). Previous research have found similar results suggesting the impact of mindfulness on enhancing emotional regulation and reducing trait anxiety (Fazia et al. 2020; Hallit et al. 2019).

The results indicated that both self-caught and probe-caught MW decreased significantly after the mindfulness training. This once again supports the claim that mindfulness training was effective at improving sustained attention. Moreover, we believe that reporting a self-caught MW requires the involvement of meta-awareness ability. Therefore, the decreased self-caught MW after the mindfulness training indicated enhanced sustained attention, which may be because of an increase in meta-awareness ability.

The results also demonstrated that the Go RT post-mindfulness training decreased significantly, while no difference was found in the control group. This indicates that participants in the mindfulness group were able to elicit faster responses, indicating an improved cognitive ability. Moreover, combing with their decreased MW, this could be due to their focused sustained attention on the task at hand. However, no significant difference was found between the two groups regarding the Go trial's RT, this could be due to the fact that the three-week mindfulness training was effective at improving focus and cognitive response, while those improvements were not noticeable enough to exhibit any significant differences between individuals with the training and individuals without the training at the response time levels.

The ERP results showed that the mean N2 amplitudes increased significantly post-mindfulness training while being significantly greater than the N2 amplitudes in the post-test of the control group as well. The current study remains consistent with previous findings that mindfulness training induced higher N2 amplitudes (Atchley et al. 2016; Zhang et al. 2019). The greater N2 would imply greater awareness and focus devoted to the current task. The enhancement of N2 would also indicate attention monitoring, response inhibition and attentional control indicated by the increased N2 amplitudes (Andreu et al. 2019; Cahn and Polich 2006; Dickter and Bartholow 2010; Folstein & Van, 2008; Posner et al. 2015; Sabri et al. 2006).

The ERP results also showed that P3 amplitudes in No-go trials were significantly greater than that of Go trials regardless of group and time, which might indicate that participants recruited more attentional resources to the no-go trials. Moreover, the P3 amplitudes were significantly greater after the mindfulness training, while being significantly greater than that of the control group in the post-test. Similar to the increased N2, the increase in P3 would indicate a more conscious awareness as well as attention to the task at hand. Moreover, the increase in P3 also indicates an increased detection of inhibition (Owens et al. 2021). The findings on P3 were consistent with the previous studies that indicated these amplitudes were associated with attentional stability (Lee et al. 2014), implying that P3 may be the neural correlate of attention allocation, and enhanced P3 amplitudes were likely to reflect attentional resource distribution to incoming stimuli. The findings are aligned with a previous study that reported that MW decreased P3 (Dias da Silva et al. 2022) and mindfulness increased P3 (Bailey et al. 2019).

In sum, the current study provides additional supporting evidence for previous research on the advantageous influence of mindfulness training on attention allocation and mind wandering. Mindfulness effectively improved self-reported mindfulness and lowered self-reported anxiety. Moreover, the increased N2 and P3 amplitudes after mindfulness training indicate lowered MW, and improved sustained attention and awareness.

Some limitations of this study should be acknowledged. First, it lacked an active control group. The study provided new insights into the effectiveness of mindfulness intervention on MW but provide no evidence of the differences between mindfulness and other interventions. Therefore, the results of the current study should be viewed within the context of mindfulness, and no other clinical fields since no comparisons were made. Future studies should include an active control group for results that could be applied more generally. Second, mindfulness training was conducted during the month in which final exams were held, and participants may have had more intense and constant anxiety than usual because of the stress from the final exams. This may have affected the participants' sustained attention. Third, the stimuli and the response keys are both numbers, which may have affected participants' task performance, since the participants might have reacted faster when the response keys and stimuli shown are the same. Future studies should use different types of stimuli and response keys.

Conclusion

This study showed that mindfulness had a positive effect on improving sustained attention, which was supported by decreased MW and increased N2 and P3 amplitudes. This study extended the previous studies by using a modified SART and examining the neural correlates that can inform the mechanism of the influence of mindfulness on MW and sustained attention.

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Data Availability The datasets used in this study are available on reasonable request to the corresponding author.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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