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ORIGINAL PAPER

Temporal Changes in the State Effect of Meditation on Response Inhibition Processes

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Abstract

Objectives A single session of brief focused attention meditation (FAM) has a state effect, which temporarily enhances response inhibition processes. However, previous research has two unanswered questions: (i) How long does the state effect last? (ii) How does effort toward FAM relate to the resulting state effect?

Method Thirty-nine healthy participants participated in two sessions: FAM and sham meditation (SHAM). The participants conducted each meditation for 10 min. The state effect on response inhibition processes was observed as Stroop task performance immediately before and after each meditation, and 20, 40, and 60 min after each meditation. In addition, the subjective effort toward meditation was evaluated using a questionnaire immediately after each meditation.

Results An analysis of variance revealed a significant interaction between session and time. In the post-hoc analysis, FAM showed significantly better Stroop task performance than the SHAM 60 min after meditation. Furthermore, using correlational analysis, we found that at 60 min, the higher the subjective effort, the better Stroop task performance.

Conclusions In contrast to previous findings, the state effect was not found immediately after FAM but instead 60 min after. The results can be partially explained by cognitive fatigue; that is, the FAM may have the state effect of preventing cognitive fatigue. This state effect is greater when the subjective effort is greater.

Keywords Focused attention meditation · State effect · Response inhibition processes · Cognitive fatigue

Focused attention meditation (FAM) aims to improve psychological abilities such as self-regulation of attention and emotion (Lutz et al., 2008; Tang et al., 2015). FAM requires participants to focus on a particular object (e.g., their breath) and return it to the object if their mind wanders (Lutz et al., 2008). Since FAM does not need any unique tool or environment, people can easily perform it daily (Mantzios & Giannou, 2019). In the future, it is believed that there will be an increase in the number of people who utilize FAM in various situations, such as workplaces and schools (Hafenbrack, 2017).

FAM seems to have a state effect, a temporal effect on cognitive function that can be obtained through a single brief FAM (e.g., 20 min). It can be observed irrespective of the presence or absence of meditation experience (Cahn & Polich, 2006; Fingelkurts et al., 2016). The state effect of naïve meditators is expressed in the improvement of response inhibition processes (Colzato et al., 2016; Wenk-Sormaz, 2005), working memory capacity (Yamaya et al., 2021), and working memory performance (Ma et al., 2021). Provided that FAM may be utilized by a variety of people in the future, the state effect observed even in beginners seems important.

However, there are two questions. One question that persists is the duration of the state effect. A previous study suggested that the state effect on cognitive control

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lasts for at least 20 min (Chan et al., 2017). However, it remains unclear when the state effect disappears (Chan et al., 2017), and to the best of the authors' knowledge, no studies have investigated it directly.

Another question is the relationship among three factors: the state effect on response inhibition processes, the extent to which participants make an effort to perform FAM (i.e., subjective effort), and spontaneous thought during FAM. Spontaneous thought is "a mental state, or a sequence of mental states, that arises relatively freely due to an absence of strong constraints on the contents of each state and on the transitions from one mental state to another" (Christoff et al., 2016, p. 719). This mental state includes day-dreaming, mind-wandering, and creative thinking (Christoff et al., 2016) and occurs multiple times during FAM (Brandmeyer & Delorme, 2020).

Previous findings suggested that the repetitive suppression of spontaneous thought and return of attention to a particular object leads to enhanced response inhibition processes (Malinowski, 2013). Although individuals with higher spontaneous thought during FAM may exert greater effort to suppress it and return attention to an object, as compared to individuals with lower spontaneous thought, no study has directly examined the relationships among the state effect, subjective effort, and spontaneous thought. Therefore, the present study hypothesized that individuals with higher spontaneous thought during FAM exert higher subjective effort, leading to a greater state effect.

The purposes of the present study were (1) to investigate the temporal changes in the state effect obtained by a single brief FAM on the response inhibition processes, and (2) to investigate the relationship between the state effect, subjective effort toward FAM, and spontaneous thought. Therefore, two experimental sessions, a FAM and a sham meditation (SHAM), were employed in a crossover design. The color-word matching Stroop task (Byun et al., 2014; Stroop, 1935) was used to evaluate the state effect on response inhibition processes at the following time points: immediately before and after each meditation and at 20, 40, and 60 min after each meditation. Therefore, the temporal changes in the state effect on response inhibition processes were observed as changes in the Stroop task performance from before to each time point after meditation. Additionally, subjective effort and spontaneous thought during each meditation were evaluated immediately after each meditation (Garrison et al., 2014, 2015; Lumma et al., 2015). Therefore, it was expected that task performance would improve immediately after the FAM but not after the SHAM and that the state effect would disappear over time. Furthermore, subjective effort toward the FAM was expected to correlate positively with both the state effect and spontaneous thought.

Method

Participants

A total of 39 Japanese university or postgraduate students (26 men and 13 women, mean age in years: 22±1.29) were recruited using campus flyers, bulletin boards, and e-mails. All the participants were right-handed, were not pregnant, and had no history of psychiatric or neurological illnesses. In addition, all the participants were confirmed to be naïve meditators based on the criterion that participants had not meditated for the past 2 years (Atchley et al., 2016). It should be noted that, in this study, meditation was defined as any attention training in which one seeks to improve their ability to pay attention to the present moment (Atchley et al., 2016).

Procedure

The entire procedure in the present study is shown in Fig. 1 and was performed in a quiet room (Figure S1 A in the Supplementary Material) with two to four participants. Initially, 1 or 2 days before the main experiment, the participants were briefed about the research, provided written informed consent, and practiced the Stroop task eight times (taking a 5-min break after the fifth practice session) to habituate themselves to it. The main experiment consisted of a FAM and a SHAM session. Following previous research, each participant completed two sessions 7 to 9 days apart (Colzato et al., 2016). Several participants could not perform the entire procedure as scheduled (Supplementary Explanation 1).

The order of the sessions was counterbalanced across the participants using a blocked random assignment. At the beginning of each session, the participants practiced the Stroop task three times and took a rest for 10 min. Subsequently, the participants performed meditation (i.e., either FAM or SHAM) for 10 min. The participants were informed about the purpose of examining the effects of the two meditation types, and they were informed that both the FAM and SHAM were authentic meditations. After each meditation, the participants performed the Stroop task at the following four time points: immediately after each meditation (T0), approximately 20 (T20), 40 (T40), and 60 (T60) min later. The participants also performed the Stroop task immediately before each meditation, which was the baseline (BL) assessment for task performance. The 20-min intervals were decided based on the previous findings that the particular mental state induced by FAM persisted for approximately 20 min (Chan et al., 2017). During each 20-min interval, the participants were instructed to watch a documentary to maintain their

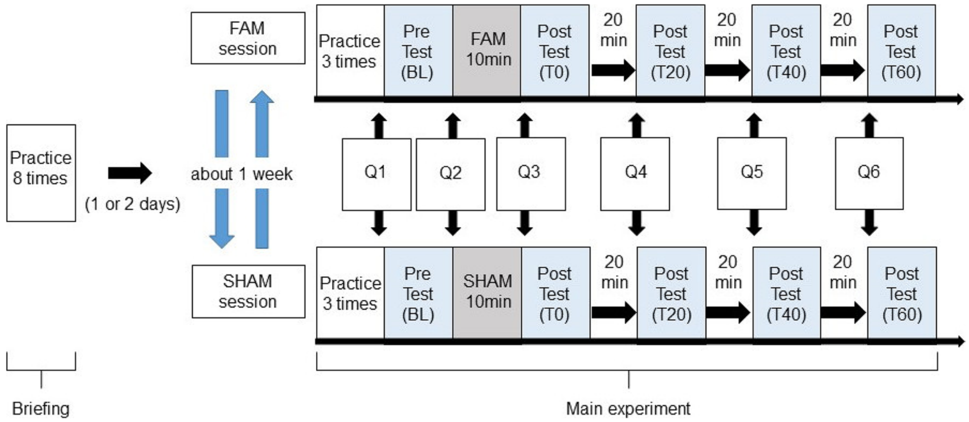

Fig. 1 Overview of the experimental procedure. *Note*. The entire procedure included the briefing and the main experiment consisting of the FAM and SHAM sessions. Each participant was given a briefing on the study and practiced the Stroop task eight times. The main experiment was performed 1 or 2 days after the briefing. The two sessions of the main experiment were conducted 7 to 9 days apart. In each session, participants practiced the Stroop task three times and performed a meditation; after that, the participants performed the Stroop task at five time points: baseline (BL), T0, T20, T40, and T60. During each interval (20 min), the participants watched a video and answered a 10-item quiz related to the videos while watching them. In addition, the TDMS was administered at the following six time points: before BL (Q1), after BL (Q2), after meditation (Q3), before T20 (Q4), before T40 (Q5), and before T60 (Q6). Four subjective assessments (i.e., subjective effort, spontaneous thought, meditation quality, and sleepiness) were administered in Q3

arousal level and answer 10-item quizzes related to the videos while watching them (NHK ENTERPRISES, 2013). In addition, the participants completed subjective assessments of their mood states at six time points: before BL (Q1), after BL (Q2), after meditation (Q3), before T20 (Q4), before T40 (Q5), and before T60 (Q6) (Fig. 1). In Q3, the participants underwent additional subjective assessments of mental state during each meditation: subjective effort, spontaneous thought, meditation quality, and sleepiness.

Measures

Meditation

Before each meditation, the participants were provided verbal instructions using a paper-based manual developed by the authors based on previous studies (Komuro, 2016; Lutz et al., 2008; Milz et al., 2014; Yamamoto & Nomura, 2010). Next, the participants closed the laptop and maintained an upright posture in their chairs in front of a bookstand, facing the fixation point (Figure S1 B and C). The participants performed each meditation while observing the fixation point. Web cameras were used to monitor whether they had fallen asleep or were sitting calmly (Logicool®HD Webcam C270m, Logitech, Switzerland; AW615, AUSDOM, China).

The Su-soku meditation was used as the FAM, which enhances response inhibition processes (Malinowski, 2013). This type of meditation is suitable for naïve meditators since it requires no special training, and attention control is easy while performing it (Chiesa, 2009; Kubota et al., 2001). Additionally, it requires participants to pay attention to their breathing, by counting the number of breaths as a set of exhalations and inhalations (Chiesa, 2009). The participants were required to refocus their attention on the breath whenever thoughts arose and the attention wandered away from the breath. Additionally, the participants were instructed to focus on a point in front of them, to breathe naturally, not to move their bodies, and not to sleep. They were also instructed to restart counting the number of breaths if they had lost track of them (e.g., forgot to count, repeated the same number, or skipped a number) (Yamamoto & Nomura, 2010; Yamaya et al., 2021). The participants performed FAM for 10 min. This meditation dose was decided because a previous study found several participants had fallen asleep during a 15-min FAM (Yamaya et al., 2021).

Spontaneous thought (during SHAM) was used as active control condition for the FAM (Noone & Hogan, 2018; Zeidan et al., 2010). Since spontaneous thought accounts for 30–50% of people's daily lives (Killingsworth & Gilbert, 2010), SHAM was highly similar to the phenomena that occur naturally in the real world compared with other active controls (e.g., reading and listening to teaching materials). Therefore, it is easy to generalize the results of this study to everyday life (Noone & Hogan, 2018). For the SHAM, the participants were instructed to focus on a point in front of them, to breathe naturally, not to move their bodies, and not to sleep. The participants performed the SHAM for 10 min, during which spontaneous thoughts were not explicitly discouraged.

The distinguishing feature between the FAM and SHAM is whether the participants needed attention regulation. To make a comparison under the same conditions, the participants were informed that both the FAM and SHAM were authentic meditations.

Stroop Task

This study employed the color-word matching Stroop task, the same type as Byun's (2014). The Stroop task assessed response inhibition processes, which meditation could improve (Malinowski, 2013). Therefore, the state effect obtained from the FAM should be expressed in improving task performance. The participants performed the Stroop task using a laptop (Figure S1 A). In the Stroop task, the participants were shown two rows of letters on a screen and asked to answer whether the color of the letters in the top row matched the color name in the bottom row by pressing a "Yes" or "No" button with their index fingers. The Stroop task consisted of neutral, congruent, and incongruent conditions; each condition was comprised of 10 trials. Each trial was presented randomly (for details, see Supplementary Explanation 2). The average reaction time for correct responses to each condition was assessed. Trials at which reaction times were less than 150 ms were excluded because they were considered anticipatory responses (Egly et al., 1994).

Subjective Assessments for Mental States During the Meditations

Four subjective assessments (i.e., subjective effort, spontaneous thought, meditation quality, and sleepiness) were performed in Q3. For the subjective effort questionnaire, the participants were asked, "How much effort did you need to perform meditation?"; for a spontaneous thought, "How much did you imagine or think about something?" (Brewer et al., 2011; D'Argembeau et al., 2005; Garrison et al., 2014, 2015); and for subjective meditation quality, "How well did you follow the instructions?" (Brewer et al., 2011; Garrison et al., 2014, 2015). All these questions were rated on an 11-point Likert scale (0 = *not at all* to 10 = *very much*, *always*, *completely*, respectively). Finally, for subjective sleepiness, the participants were asked to complete the Stanford Sleepiness Scale (SSS) (Hoddes et al., 1972). The SSS was composed of a 7-point Likert scale (1 = *feeling active*, *vital*, *alert*, *and fully awake* to 7 = *almost in slumber*, *sleep onset soon, and lost struggle to remain awake*).

Two-dimensional Mood Scale (TDMS)

A previous study has reported that a single brief meditation can affect participants' mood states (Edwards & Loprinzi, 2018). These results suggest that changes in mood states influenced the Stroop task performance. Therefore, the participants' mood states were evaluated from Q1 to Q6 using the TDMS (Sakairi et al., 2009, 2013). The TDMS assesses four mood states (vitality, stability, pleasure, and arousal) and consists of eight questions measured on scale ranging from 0 to 5. Vitality, which indicates a mental state ranging from comfortable excitement to uncomfortable calm, is evaluated by four of the eight questions. The other four questions are used to assess stability, which indicates a mental state ranging from comfortable calm to uncomfortable excitement. The summation of vitality and stability evaluates pleasure while the subtraction of stability from vitality evaluates arousal.

10-Item Quizzes Related to the Videos

During the 20-min intervals (Fig. 1), the participants were instructed to complete the 10-item quizzes related to the videos while watching them (for details, see Supplementary Explanation 3). The participants were seated in a chair, wore headphones, and watched the videos on a TV monitor (a monitor in the center of Figure S1 A). Six videos produced by a Japanese documentary TV broadcaster were showcased (NHK ENTERPRISES, 2013). One of the six videos was played randomly at individual intervals, and the participants watched the first 20 min of each video; every video was played only once.

Data Analyses

Eleven of the 39 participants were excluded from the analysis of the main experiment for two reasons. First, five participants were excluded because they failed to complete the main experiment. Second, six participants were excluded because the number of no responses to task stimuli exceeded a threshold, defined as the mean + 2 × standard deviation (i.e., ≥ 2 non-responses), and the mean and standard deviation were computed using the practice data. All statistical analyses were performed using R version 3.5.2 (R Core Team, 2018); an analysis of variance (ANOVA) was implemented with the R function "anovakun" version 4.8.5 (Iseki, 2020). In the ANOVA, if the assumption of sphericity was violated, Greenhouse-Geisser-corrected *p*-values were adopted. If a significant interaction in the ANOVA was identified, pairwise multiple comparison procedures were carried out using the Keselman-Keselman-Shaffer and degrees of freedom method based on Welch-Satterthwaite (Keselman et al., 1991). The significance level was set at $p < 0.05$.

Analysis of the Temporal Changes in the State Effect

Only incongruent and neutral conditions were used to assess Stroop interference, defined as the mean reaction time of the incongruent condition minus that of the neutral condition (Byun et al., 2014; Hyodo et al., 2016). Stroop interference is called "RT" hereafter. To evaluate how the state effect of the FAM changed over time, we calculated changes in Stroop interference (i.e., ΔRT) at each time point, i.e., $\Delta RT = RT_i - RT_{BL}$; here, i = T0, T20, T40, and T60, and BL represents the baseline for RT (Fig. 1) (Tsukamoto et al., 2018). This subtraction allowed us to control for interindividual baseline differences in response inhibition processes (Henderson et al., 2012). ΔRT was analyzed using two-way repeated measures ANOVA with session (FAM and SHAM) and time point (T0, T20, T40, and T60) as within-subject factors.

Analysis of Relationships Among the State Effect and Subjective Assessments

The correlation coefficients among three factors — the state effect obtained from the FAM (i.e., ΔRT), subjective effort, and spontaneous thought — were calculated using Spearman's rank correlation coefficient. Only ΔRT that showed statistically significant differences between the sessions was used in the correlational analysis. The reason for choosing a non-parametric correlation method was that the behavioral data of this study did not follow a normal distribution.

Supplementary Analyses

In addition to the primary analyses mentioned above, we conducted five supplementary analyses. First, we verified temporal changes in the RT obtained from the practice of the Stroop task (Supplementary Analysis 1). Second, we investigated whether different session orders showed different temporal changes in ΔRT (Supplementary Analysis 2). Third, we investigated differences in individual subjective assessments between the sessions (Supplementary Analysis 3). Fourth, we confirmed whether the temporal changes in mood states differed between the sessions (Supplementary Analysis 4). Last, we confirmed the differences in the participants' concentration in each video between the sessions (Supplementary Analysis 5).

Results

Temporal Changes in ΔRT of the FAM and SHAM Sessions

Two-way repeated measures ANOVA showed a statistically significant session × time interaction ($F(3, 81) = 3.30$, $p = 0.02$, $\eta_p^2 = 0.11$) but showed no main effects, that is, for session ($F(1, 27) = 1.47$, $p = 0.24$, $\eta_p^2 = 0.05$) and time ($F(3, 81) = 0.19$, $p = 0.90$, $\eta_p^2 = 0.01$) (Fig. 2). A post hoc analysis revealed a statistically significant difference between the FAM and SHAM sessions at T60 ($F(1, 27) = 6.61$, $p = 0.02$, $\eta_p^2 = 0.20$). ΔRT in the FAM session

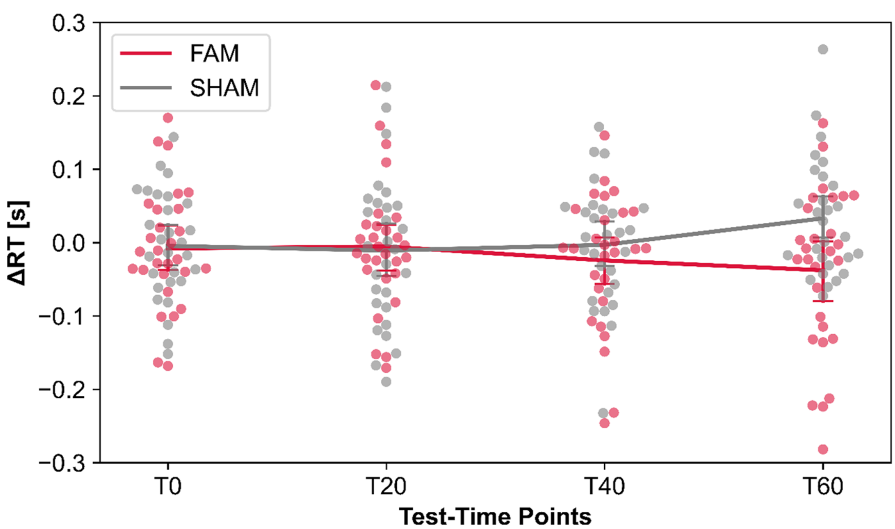

Fig. 2 Comparison of the temporal changes in Stroop task performance (ΔRT) between the FAM and SHAM sessions. *Note.* Four time points (T0, T20, T40, and T60) correspond to those shown in Fig. 1. Each dot indicates the Stroop task performance (ΔRT) of each participant. Note that the lower the ΔRT, the higher the task performance. The solid lines indicate the mean at each time point, and the error bars represent 95% confidence interval at each time point. Two-way repeated measures analysis of variance revealed a significant session × time interaction ($p < 0.05$) but no main effects for session and time. Furthermore, a post hoc analysis revealed a significant difference between the sessions at T60 ($p < 0.05$)

Table 1 The Stroop task performance in the FAM and the SHAM sessions at each time point

Time points	FAM			SHAM		
	ΔRT		RT	ΔRT		RT
	M (*SD*)	95% CI	*M* (*SD*)	*M* (*SD*)	95% CI	*M* (*SD*)
T0	−0.01 (0.08)	[−0.03, 0.02]	0.13 (0.09)	−0.00 (0.07)	[−0.03, 0.02]	0.12 (0.09)
T20	−0.01 (0.09)	[−0.03, 0.02]	0.13 (0.11)	−0.01 (0.10)	[−0.03, 0.01]	0.11 (0.09)
T40	−0.02 (0.09)	[−0.05, −0.00]	0.11 (0.07)	−0.00 (0.08)	[−0.03, 0.02]	0.12 (0.11)
T60	−0.04 (0.11)	[−0.06, −0.01]	0.10 (0.10)	0.03 (0.08)	[0.01, 0.06]	0.15 (0.11)

Four time points (T0, T20, T40, and T60) correspond to those shown in Fig. 1

ΔRT, changes in Stroop interference (T0, T20, T40, T60 minus baseline, separately). *RT*, raw score of Stroop interference at each time point. *M*, mean value. *SD*, standard deviation. CI, confidence interval

seemed to decrease gradually after T40, whereas ΔRT in the SHAM session seemed to increase gradually after T40 (Table 1). Those results indicated that the participants in the FAM improved their performance after T40, while those in the SHAM deteriorated their performance after T40.

Relations Among the Subjective Effort, Spontaneous Thought, and ΔRT

Spearman's rank correlation coefficient showed that a statistically significant negative correlation between subjective effort and ΔRT was found in the FAM (*rho* = −0.39, $p = 0.04$; Fig. 3A), but not in the SHAM (*rho* = 0.01, $p = 0.97$; Fig. 3B). A statistically significant positive correlation was found between spontaneous thought and subjective effort in the FAM (*rho* = 0.48, $p = 0.01$; Fig. 3C), but not in the SHAM (*rho* = 0.14, $p = 0.48$; Fig. 3D). No significant correlations were found between spontaneous thought and ΔRT in either the FAM (*rho* = 0.10, $p = 0.60$; Fig. 3E) or the SHAM (*rho* = 0.07, $p = 0.71$; Fig. 3F).

Supplementary Results

The results obtained by the five supplementary analyses are briefly shown below. First, the RT in the practice of the Stroop task continued to decrease throughout the practice (Supplementary Analysis 1). Second, no influences of session orders on ΔRT were observed (Supplementary Analysis 2). Third, the FAM showed lower spontaneous thought than the SHAM, while no significant differences were observed in the other subjective assessments (Supplementary Analysis 3). Fourth, the temporal changes in mood states were similar between the FAM and SHAM sessions (Supplementary Analysis 4). Finally, the participants paid equal attention to all the videos in the two sessions (Supplementary Analysis 5).

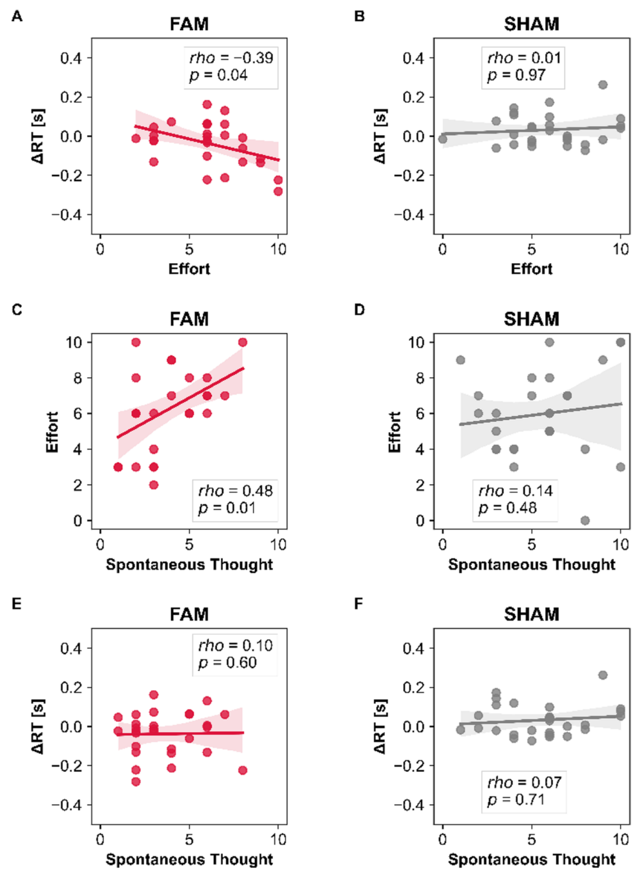

Fig. 3 Relations among the subjective effort, spontaneous thought, and Stroop task performance (ΔRT) at T60 in the FAM and SHAM sessions. *Note.* **A** Subjective effort versus ΔRT in the FAM. **B** Subjective effort versus ΔRT in the SHAM. **C** Spontaneous thought versus subjective effort in the FAM. **D** Spontaneous thought versus subjective effort in the SHAM. **E** Spontaneous thought versus ΔRT in the FAM. **F** Spontaneous thought versus ΔRT in the SHAM. Shading, 95% confidence interval. *rho*, Spearman's rank correlation coefficient. *p*, *p*-value. There were two significant relations: a negative correlation between the subjective effort and ΔRT in the FAM ($p < 0.05$) and a positive correlation between spontaneous thought and subjective effort in the FAM ($p < 0.05$). No other significant correlations were found

Discussion

This study investigated how the state effect induced by a single brief FAM changed temporally. Temporal changes in the state effect were evaluated as temporal changes in the Stroop task performance (i.e., ΔRT). Note that the lower ΔRT, the higher the task performance. It was hypothesized that ΔRT would decrease immediately after the FAM (i.e., T0) and increase over time. Contrary to our hypothesis, a statistically significant difference in the ΔRT between the sessions was not identified at T0. Intriguingly, it was observed that the ΔRT 60 min after the FAM (i.e., T60) was significantly lower than that of the SHAM. In particular, the ΔRT in the FAM session seemed to decrease gradually after T40, while the ΔRT in the SHAM session seemed to increase progressively after T40. These results can be explained by cognitive fatigue and learning effects. Since significant differences in mood states, meditation quality, and sleepiness were not observed between sessions, these factors cannot explain the significant changes in the state effect between sessions. Furthermore, the relationship among three factors, namely the state effect at T60 in FAM, the subjective effort for FAM, and spontaneous thought during FAM, was examined. We found a statistically significant negative correlation between the ΔRT and subjective effort and a statistically significant positive correlation between subjective effort and spontaneous thought. These results support the expectation that individuals with a higher degree of spontaneous thought during FAM exert greater subjective effort, leading to a greater state effect. This finding suggests that subjective effort can be used to evaluate the state effect induced by FAM. The present study showed unexpected findings regarding the state effect of the FAM, suggesting the importance of understanding temporal changes in the meditation effect.

The FAM showed a lower ΔRT than the SHAM, not at T0 but at T60, which was inconsistent with our expectations. These results seem to stem from the effects of cognitive fatigue and learning. The SHAM session showed a gradual increase in the ΔRT after T40, suggesting that it may have been caused by cognitive fatigue induced by prolonged task engagement. When participants perform a prolonged task, for example, a 60-min Go/NoGo task (Kato et al., 2009, 2012), their task performance declines with time, referred to as the time-on-task effect (Mackworth, 1948), and therefore, cognitive fatigue is expressed as the time-on-task effect (DeLuca, 2005). According to resource control theory (Thomson et al., 2015), cognitive control was a crucial factor in the mechanism of cognitive fatigue, involving the maintenance of relevant task goals and suppression of irrelevant ones (Gratton et al., 2018). Cognitive control is disturbed by an increase in time-on-task, resulting in an insufficient allocation of cognitive resources to the tasks at hand, causing the deterioration of task performance. A previous study reported that cognitive fatigue was observed 20–40 min after the beginning of a 60-min continuous task (Kato et al., 2009). The present study required participants to engage in tasks' sustainably for approximately 60 min. Prolonged engagement may disturb cognitive control and, consequently, cause gradual deterioration of task performance (i.e., an increase in ΔRT).

However, the FAM session did not show such a gradual deterioration in task performance. A previous study showed that an 11-min FAM could improve the maintenance of relevant task goals (Ma et al., 2021). These findings have suggested that FAM enhances the efficiency of cognitive resource allocation, which leads to the prevention of cognitive fatigue. In addition, the FAM session showed a gradual decrease in the ΔRT after T40. This result may have been derived from a learning effect. The supplementary analysis of the practice data showed that the RT continued to decrease throughout the practice, suggesting that the participants could obtain a learning effect even after completing the practice. Overall, it is believed that the FAM session showed a gradual improvement in task performance because prevention of cognitive fatigue brought out the learning effect, while the SHAM session showed a gradual deterioration of task performance due to cognitive fatigue.

Contrary to the expectations of this study, a statistically significant difference in the ΔRT was not found at T0, which is inconsistent with previous findings (Colzato et al., 2016; Wenk-Sormaz, 2005). There are two potential reasons for the unexpected results. First, although the present study employed a 10-min FAM, previous studies used 17- and 20-min FAMs, respectively. Inducing a state effect on response inhibition processes may require performing FAM for approximately 20 min. However, the results of this study suggested that a 10-min FAM induces a state effect on the maintenance of relevant task goals because participants in the FAM did not show a time-on-task effect (Ma et al., 2021; Unsworth & Robison, 2020). Second, although this study employed a paper-based manual to instruct the participants, previous studies used audio-guided instruction, and meditation was practiced while listening to those instructions. Since naïve meditators find it difficult to be aware of their spontaneous thought during meditation (Zheng et al., 2019), audio-guided instruction may be highly effective in suppressing it and returning their attention to an object than to prior provided instructions. The difference in the methods of providing instructions may be partially responsible for these unexpected results.

For the FAM, subjective effort was negatively correlated with the ΔRT at T60 and positively correlated with spontaneous thought. Theoretical and neuroscientific perspectives suggest that naïve meditators must make a mental effort to suppress spontaneous thought during meditation (Lutz et al., 2008; Tang et al., 2012; Tang & Posner, 2009), and the participants in this study were all naïve meditators. Therefore, individuals with high subjective spontaneous thought scores must have made greater efforts to suppress spontaneous thought during FAM than individuals with low scores. Furthermore, since repetitive suppression of spontaneous thought and return of attention to meditation during FAM leads to increased cognitive control (Brandmeyer & Delorme, 2020; Malinowski, 2013), participants who made a greater effort to suppress spontaneous thought during the FAM may have shown better cognitive control. These findings suggest that subjective effort can be used as an indicator to evaluate the state effect induced by the FAM. If naïve meditators feel that they have to make an effort while practicing FAM, it could induce the state effect.

There was no difference in subjective effort between the FAM and SHAM. This finding was inconsistent with our expectation that the SHAM showed lower subjective effort than the FAM because the SHAM did not require regulation of attention. The fact suggests that the SHAM requires an effort different from what the FAM requires. For example, the effort required to perform the SHAM may stem from boredom. The boredom conditions are defined as meaningless tasks with inhibition of behavior, e.g., rest (Danckert & Merrifield, 2018; Mercer-Lynn et al., 2014; Westgate, 2020). The boredom conditions require an effort to stay on task (Inzlicht et al., 2018; Milyavskaya et al., 2019). Because the SHAM is similar to the boredom conditions, the participants may need the effort to perform the SHAM, which may be why no difference was detected in the effort between the FAM and SHAM.

Limitations and Directions for Future Research

Several limitations of the present study need to be noted. First, contrary to our expectation, FAM showed better Stroop task performance than SHAM only at 60 min after the meditation. Although we explained the result using cognitive fatigue, this explanation was supported only by behavioral data (i.e., temporal changes in the ΔRT). Further research should investigate cognitive fatigue from a physiological perspective and behavioral data to corroborate this explanation (Hockey & Hockey, 2013; Smith et al., 2019). For example, cognitive fatigue can be evaluated using an accelerated photoplethysmograph to assess autonomic nervous function (Mizuno et al., 2011).

Second, we could not confirm a state effect of a 10-min FAM on response inhibition processes because an improvement in Stroop task performance was not identified at T0. Therefore, it remains unclear how long the state effect lasts on response inhibition processes. Further studies are required to address this question.

Third, although it is reasonable to think that the positive correlation between spontaneous thought and subjective effort suggests that those with a higher frequency of spontaneous thought exert more effort to suppress it, we have two problems with the interpretation. The first problem is not to investigate the direction of relationships between spontaneous thought, subjective effort, and state effect. Further research needs a mediation and/or moderation analysis to clarify the direction of relationships. The second problem is that the questionnaire on spontaneous thought may reflect not only the frequency of spontaneous thought but also its duration. We need a way to evaluate the frequency and duration of spontaneous thought separately, but, at present, no such method exists.

Finally, in addition to subjective effort, cognitive fatigue can be influenced by other factors such as trait mindfulness and attentional function. “Trait mindfulness refers to an individual’s characteristic tendency to maintain awareness of the present moment in a nonreactive and nonjudgmental manner” (Carpenter et al., 2019, p. 1). Trait mindfulness has conceptual relevance to FAM (Tang & Tang, 2020). Attentional function is an individual trait involved in FAM (Malinowski, 2013). Individual variability in trait mindfulness and attentional function may change the state effect of one-session FAM, influencing cognitive fatigue (Greif & Kaufman, 2021; Tanaka et al., 2021). Thus, further research is needed to investigate the influences of individual variability (including subjective effort and spontaneous thoughts) on cognitive fatigue (Tang & Tang, 2020).

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Author Contribution NY: conceptualized, designed, and executed the study; analyzed and visualized the data; acquired funding; and co-authored the paper. SI: conceptualized and designed the study and collaborated in the writing and editing of the paper. YH: executed the study. HT: conceptualized and designed the study. RK: conceptualized, designed, supervised, and administered the study and acquired funding and provided resources. All authors approved the final version of the manuscript for submission.

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Data Availability The data are not publicly available because we did not obtain permission from the study participants to share their data.

Declarations

Ethics Approval This study was approved by the Ethics Committee of Tohoku University Graduate School of Medicine and registered with the University Hospital Medical Information Network (ID: UMIN000034888). All the participants provided written informed consent and all the procedures performed in this study follow the principles of the Declaration of Helsinki.

Informed Consent The researcher provided the research participants with an explanatory document approved by the Ethics Review Committee, explained the research, gave them sufficient time to decide on whether to participate, and confirmed that they had a good understanding of the study before asking them to participate. If the research participants agreed to participate in the study, they were asked to sign the consent document. The principal investigator kept the original consent document at the research institution, and a copy was given to the research participants.

Conflict of Interest The authors declare no competing interests.

References

Atchley, R., Klee, D., Memmott, T., Goodrich, E., Wahbeh, H., & Oken, B. (2016). Event-related potential correlates of mindfulness meditation competence. *Neuroscience, 320*, 83–92. https://doi.org/10.1016/j.neuroscience.2016.01.051

Brandmeyer, T., & Delorme, A. (2020). Meditation and the wandering mind: A theoretical framework of underlying neurocognitive mechanisms. *Perspectives on Psychological Science, 16*(1), 39–66. https://doi.org/10.1177/1745691620917340

Brewer, J. A., Worhunsky, P. D., Gray, J. R., Tang, Y.-Y., Weber, J., & Kober, H. (2011). Meditation experience is associated with differences in default mode network activity and connectivity. *Proceedings of the National Academy of Sciences, 108*(50), 20254–20259. https://doi.org/10.1073/pnas.1112029108

Byun, K., Hyodo, K., Suwabe, K., Ochi, G., Sakairi, Y., Kato, M., Dan, I., & Soya, H. (2014). Positive effect of acute mild exercise on executive function via arousal-related prefrontal activations: An fNIRS study. *NeuroImage, 98*, 336–345. https://doi.org/10.1016/j.neuroimage.2014.04.067

Cahn, B. R., & Polich, J. (2006). Meditation states and traits: EEG, ERP, and neuroimaging studies. *Psychological Bulletin, 132*(2), 180–211. https://doi.org/10.1037/0033-2909.132.2.180

Carpenter, J. K., Conroy, K., Gomez, A. F., Curren, L. C., & Hofmann, S. G. (2019). The relationship between trait mindfulness and affective symptoms: A meta-analysis of the Five Facet Mindfulness Questionnaire (FFMQ). *Clinical Psychology Review, 74*, 101785. https://doi.org/10.1016/j.cpr.2019.101785

Chan, R. W., Immink, M. A., & Lushington, K. (2017). The influence of focused-attention meditation states on the cognitive control of sequence learning. *Consciousness and Cognition, 55*, 11–25. https://doi.org/10.1016/j.concog.2017.07.004

Chiesa, A. (2009). Zen meditation: An integration of current evidence. *The Journal of Alternative and Complementary Medicine, 15*(5), 585–592. https://doi.org/10.1089/acm.2008.0416

Christoff, K., Irving, Z. C., Fox, K. C. R., Spreng, R. N., & Andrews-Hanna, J. R. (2016). Mind-wandering as spontaneous thought: A dynamic framework. *Nature Reviews Neuroscience, 17*(11), 718–731. https://doi.org/10.1038/nrn.2016.113

Colzato, L. S., van der Wel, P., Sellaro, R., & Hommel, B. (2016). A single bout of meditation biases cognitive control but not attentional focusing: Evidence from the global–local task. *Consciousness and Cognition, 39*, 1–7. https://doi.org/10.1016/j.concog.2015.11.003

Danckert, J., & Merrifield, C. (2018). Boredom, sustained attention and the default mode network. *Experimental Brain Research, 236*(9), 2507–2518. https://doi.org/10.1007/s00221-016-4617-5

D'Argembeau, A., Collette, F., Van Der Linden, M., Laureys, S., Del Fiore, G., Degueldre, C., Luxen, A., & Salmon, E. (2005). Self-referential reflective activity and its relationship with rest: A PET study. *NeuroImage, 25*(2), 616–624. https://doi.org/10.1016/j.neuroimage.2004.11.048

DeLuca, J. E. (2005). *Fatigue as a window to the brain*. MIT Press.

Edwards, M. K., & Loprinzi, P. D. (2018). Experimental effects of brief, single bouts of walking and meditation on mood profile in young adults. *Health Promotion Perspectives, 8*(3), 171–178. https://doi.org/10.15171/hpp.2018.23

Egly, R., Driver, J., & Rafal, R. D. (1994). Shifting visual attention between objects and locations: Evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General, 123*(2), 161–177. https://doi.org/10.1037//0096-3445.123.2.161

Fingelkurts, A. A., Fingelkurts, A. A., & Kallio-Tamminen, T. (2016). Long-term meditation training induced changes in the operational synchrony of default mode network modules during a resting state. *Cognitive Processing, 17*(1), 27–37. https://doi.org/10.1007/s10339-015-0743-4

Garrison, K. A., Scheinost, D., Constable, R. T., & Brewer, J. A. (2014). BOLD signal and functional connectivity associated with loving kindness meditation. *Brain and Behavior, 4*(3), 337–347. https://doi.org/10.1002/brb3.219

Garrison, K. A., Zeffiro, T. A., Scheinost, D., Constable, R. T., & Brewer, J. A. (2015). Meditation leads to reduced default mode network activity beyond an active task. *Cognitive, Affective and Behavioral Neuroscience, 15*(3), 712–720. https://doi.org/10.3758/s13415-015-0358-3

Gratton, G., Cooper, P., Fabiani, M., Carter, C. S., & Karayanidis, F. (2018). Dynamics of cognitive control: Theoretical bases, paradigms, and a view for the future. *Psychophysiology, 55*(3), 1–29. https://doi.org/10.1111/psyp.13016

Greif, T. R., & Kaufman, D. A. S. (2021). Immediate effects of meditation in college students: A pilot study examining the role of baseline attention performance and trait mindfulness. *Journal of American College Health, 69*(1), 38–46. https://doi.org/10.1080/07448481.2019.1650052

Hafenbrack, A. C. (2017). Mindfulness meditation as an on-the-spot workplace intervention. *Journal of Business Research, 75*, 118–129. https://doi.org/10.1016/j.jbusres.2017.01.017

Henderson, R. K., Snyder, H. R., Gupta, T., & Banich, M. T. (2012). When does stress help or harm? The effects of stress controllability and subjective stress response on Stroop performance. *Frontiers in Psychology, 3*, 179. https://doi.org/10.3389/fpsyg.2012.00179

Hockey, B., & Hockey, R. (2013). *The psychology of fatigue: Work, effort and control*. Cambridge University Press.

Hoddes, E., Zarcone, V., & Dement, W. (1972). Development and use of Stanford Sleepiness Scale (SSS). *Psychophysiology, 9*, 150.

Hyodo, K., Dan, I., Kyutoku, Y., Suwabe, K., Byun, K., Ochi, G., Kato, M., & Soya, H. (2016). The association between aerobic fitness and cognitive function in older men mediated by frontal lateralization. *NeuroImage, 125*, 291–300. https://doi.org/10.1016/j.neuroimage.2015.09.062

Inzlicht, M., Shenhav, A., & Olivola, C. Y. (2018). The effort paradox: Effort is both costly and valued. *Trends in Cognitive Sciences, 22*(4), 337–349. https://doi.org/10.1016/j.tics.2018.01.007

Iseki, R. (2020). *Anovakun (version 4.8.5.)*. http://riseki.php.xdomain.jp/index.php?FrontPage

Kato, Y., Endo, H., & Kizuka, T. (2009). Mental fatigue and impaired response processes: Event-related brain potentials in a Go/NoGo task. *International Journal of Psychophysiology, 72*(2), 204–211. https://doi.org/10.1016/j.ijpsycho.2008.12.008

Kato, Y., Endo, H., Kobayakawa, T., Kato, K., & Kitazaki, S. (2012). Effects of intermittent odours on cognitive-motor performance and brain functioning during mental fatigue. *Ergonomics, 55*(1), 1–11. https://doi.org/10.1080/00140139.2011.633175

Keselman, H. J., Keselman, J. C., & Shaffer, J. P. (1991). Multiple pairwise comparisons of repeated measures means under violation of multisample sphericity. *Psychological Bulletin, 110*(1), 162–170. https://doi.org/10.1037/0033-2909.110.1.162

Killingsworth, M. A., & Gilbert, D. T. (2010). A wandering mind is an unhappy mind. *Science, 330*(6006), 932. https://doi.org/10.1126/science.1192439

Komuro, H. (2016). Shogakusha no susokukanmeisou ni okeru shisei no kouka [The effect of posture on Susokukan meditation in beginners]. *Komazawa Annual Reports of Psychology, 18*, 17–25.

Kubota, Y., Sato, W., Toichi, M., Murai, T., Okada, T., Hayashi, A., & Sengoku, A. (2001). Frontal midline theta rhythm is correlated with cardiac autonomic activities during the performance of an attention demanding meditation procedure. *Cognitive Brain Research, 11*(2), 281–287. https://doi.org/10.1016/S0926-6410(00)00086-0

Lumma, A. L., Kok, B. E., & Singer, T. (2015). Is meditation always relaxing? Investigating heart rate, heart rate variability, experienced effort and likeability during training of three types of meditation. *International Journal of Psychophysiology, 97*(1), 38–45. https://doi.org/10.1016/j.ijpsycho.2015.04.017

Lutz, A., Slagter, H. A., Dunne, J. D., & Davidson, R. J. (2008). Attention regulation and monitoring in meditation. *Trends in Cognitive Sciences, 12*(4), 163–169. https://doi.org/10.1016/j.tics.2008.01.005

Ma, K., Deng, N., & Hommel, B. (2021). Meditation-induced cognitive-control states regulate working memory task performance. *Quarterly Journal of Experimental Psychology, 74*(8), 1465–1476. https://doi.org/10.1177/1747021821997826

Mackworth, N. H. (1948). The breakdown of vigilance during prolonged visual search. *Quarterly Journal of Experimental Psychology, 1*(1), 6–21.

Malinowski, P. (2013). Neural mechanisms of attentional control in mindfulness meditation. *Frontiers in Neuroscience, 7*, 8. https://doi.org/10.3389/fnins.2013.00008

Mantzios, M., & Giannou, K. (2019). A real-world application of short mindfulness-based practices: A review and reflection of the literature and a practical proposition for an effortless mindful lifestyle. *American Journal of Lifestyle Medicine, 13*(6), 520–525. https://doi.org/10.1177/1559827618772036

Mercer-Lynn, K. B., Bar, R. J., & Eastwood, J. D. (2014). Causes of boredom: The person, the situation, or both? *Personality and Individual Differences, 56*(1), 122–126. https://doi.org/10.1016/j.paid.2013.08.034

Milyavskaya, M., Inzlicht, M., Johnson, T., & Larson, M. J. (2019). Reward sensitivity following boredom and cognitive effort: A high-powered neurophysiological investigation. *Neuropsychologia, 123*, 159–168. https://doi.org/10.1016/j.neuropsychologia.2018.03.033

Milz, P., Faber, P. L., Lehmann, D., Kochi, K., & Pascual-marqui, R. D. (2014). sLORETA intracortical lagged coherence during breath counting in meditation-naïve participants. *Frontiers in Human Neuroscience, 8*, 303. https://doi.org/10.3389/fnhum.2014.00303

Mizuno, K., Tanaka, M., Yamaguti, K., Kajimoto, O., Kuratsune, H., & Watanabe, Y. (2011). Mental fatigue caused by prolonged cognitive load associated with sympathetic hyperactivity. *Behavioral and Brain Functions*, *7*, 1–7. https://doi.org/10.1186/1744-9081-7-17

NHK ENTERPRISES, INC. (2013). *Sekai hureai machi aruki DVD-BOXX [World Strollers]*. https://www.nhk-ep.com/products/detail/h19015AA

Noone, C., & Hogan, M. J. (2018). Improvements in critical thinking performance following mindfulness meditation depend on thinking dispositions. *Mindfulness, 9*(2), 461–473. https://doi.org/10.1007/s12671-017-0789-8

R Core Team. (2018). *R: A language and environment for statistical computing*. http://www.R-project.org/

Sakairi, Y., Nakatsuka, K., & Shimizu, T. (2013). Development of the Two-Dimensional Mood Scale for self-monitoring and self-regulation of momentary mood states. *Japanese Psychological Research, 55*(4), 338–349. https://doi.org/10.1111/jpr.12021

Sakairi, Y., Soya, H., & Kizuka, T. (2009). *TDMS (Two-dimensional Mood Scale) tebiki-Nijigen kibun syakudo [Guidance-Two dimensional mood scale]*. IMF CORP.

Smith, M. R., Chai, R., Nguyen, H. T., Marcora, S. M., & Coutts, A. J. (2019). Comparing the effects of three cognitive tasks on indicators of mental fatigue. *The Journal of Psychology, 153*(8), 759–783. https://doi.org/10.1080/00223980.2019.1611530

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

Tanaka, M., Nakashima, R., Hiromitsu, K., & Imamizu, H. (2021). Individual differences in the change of attentional functions with brief one-time focused attention and open monitoring meditations. *Frontiers in Psychology, 12*, 716138. https://doi.org/10.3389/FPSYG.2021.716138/FULL

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

Tang, Y. Y., & Posner, M. I. (2009). Attention training and attention state training. *Trends in Cognitive Sciences, 13*(5), 222–227. https://doi.org/10.1016/j.tics.2009.01.009

Tang, Y. Y., Rothbart, M. K., & Posner, M. I. (2012). Neural correlates of establishing, maintaining, and switching brain states. *Trends in Cognitive Sciences, 16*(6), 330–337. https://doi.org/10.1016/j.tics.2012.05.001

Tang, Y. Y., & Tang, R. (2020). *The neuroscience of meditation: Understanding individual differences*. Academic Press.

Thomson, D. R., Besner, D., & Smilek, D. (2015). A resource-control account of sustained attention: evidence from mind-wandering and vigilance paradigms. *Perspectives on Psychological Science, 10*(1), 82–96. https://doi.org/10.1177/1745691614556681

Tsukamoto, H., Suga, T., Ishibashi, A., Takenaka, S., Tanaka, D., Hirano, Y., Hamaoka, T., Goto, K., Ebi, K., Isaka, T., & Hashimoto, T. (2018). Flavanol-rich cocoa consumption enhances exercise-induced executive function improvements in humans. *Nutrition, 46*, 90–96. https://doi.org/10.1016/j.nut.2017.08.017

Unsworth, N., & Robison, M. K. (2020). Working memory capacity and sustained attention: A cognitive-energetic perspective. *Journal of Experimental Psychology: Learning Memory and Cognition, 46*(1), 77–103. https://doi.org/10.1037/xlm0000712

Wenk-Sormaz, H. (2005). Meditation can reduce habitual responding. *Alternative Therapies in Health and Medicine, 11*(2), 42–59.

Westgate, E. C. (2020). Why boredom is interesting. *Current Directions in Psychological Science, 29*(1), 33–40. https://doi.org/10.1177/0963721419884309

Yamamoto, R., & Nomura, S. (2010). Nyuminji sentakuteki chui ga nyuminkonnan ni oyobosu eikyou —Susokukan ni yoru chui no tousei wo mochiita kentou— [The influence of pre-sleep selective attention on sleep onset insomnia —A study of attention control by the breath counting exercise—]. *Koudou Igaku Kenkyu, 15*(1), 22–32.

Yamaya, N., Tsuchiya, K., Takizawa, I., Shimoda, K., Kitazawa, K., & Tozato, F. (2021). Effect of one-session focused attention meditation on the working memory capacity of meditation novices: A functional near-infrared spectroscopy study. *Brain and Behavior, 11*(8), 1–11. https://doi.org/10.1002/brb3.2288

Zeidan, F., Johnson, S. K., Gordon, N. S., & Goolkasian, P. (2010). Effects of brief and sham mindfulness meditation on mood and cardiovascular variables. *The Journal of Alternative and Complementary Medicine, 16*(8), 867–873. https://doi.org/10.1089/acm.2009.0321

Zheng, Y. L., Wang, D. X., Zhang, Y. R., & Tang, Y. Y. (2019). Enhancing attention by synchronizing respiration and fingertip pressure: A pilot study using functional near-infrared spectroscopy. *Frontiers in Neuroscience, 13*, 1209. https://doi.org/10.3389/fnins.2019.01209