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Combining Behavior and EEG to Study the Effects of Mindfulness Meditation on Episodic Memory

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Abstract

Although there has been recent interest in how mindfulness meditation can affect episodic memory as well as brain structure and function, no study has examined the behavioral and neural effects of mindfulness meditation on episodic memory. Here we present a protocol that combines mindfulness meditation training, an episodic memory task, and EEG to examine how mindfulness meditation changes behavioral performance and the neural correlates of episodic memory. Subjects in a mindfulness meditation experimental group were compared to a waitlist control group. Subjects in the mindfulness meditation experimental group spent four weeks training and practicing mindfulness meditation. Mindfulness was measured before and after training using the Five Facet Mindfulness Questionnaire (FFMQ). Episodic memory was measured before and after training using a source recognition task. During the retrieval phase of the source recognition task, EEG was recorded. The results showed that mindfulness, source recognition behavioral performance, and EEG theta power in right frontal and left parietal channels increased following mindfulness meditation training. In addition, increases in mindfulness correlated with increases in theta power in right frontal channels. Therefore, results obtained from combining mindfulness meditation training, an episodic memory task, and EEG reveal the behavioral and neural effects of mindfulness meditation on episodic memory.

Introduction

There has been recent interest in mindfulness meditation to treat symptoms of mental illness and to enhance cognition, but there is still much research to be done to understand the effects of mindfulness meditation on cognitive function. Previous research has shown that mindfulness meditation can reduce symptoms of stress, depression, generalized anxiety disorder, addictions, attention deficit disorder, and pain disorders[1,2,3,4,5,6,7,8,9], as well as increase attention and executive function[2,3,4,5,6,7,10,11,12,13,14,15,16].

Despite interest in the effects of mindfulness meditation on cognition, little research has been done on the effects of mindfulness meditation on episodic memory[17]. Given the contribution of attention and executive function to episodic encoding and retrieval, mindfulness meditation should also increase episodic memory. A few recent behavioral studies have shown that mindfulness training increases recognition memory recollection[18,19] and free recall[20].

In addition to behavioral effects of mindfulness meditation on cognition, previous research has examined the effects of mindfulness meditation on the brain. Mindfulness meditation has been shown to change both the structure and function of the brain. Importantly, mindfulness meditation has been shown to change brain structure and function in networks related to episodic memory[21,22,23]; specifically increasing grey matter volume and activity in the prefrontal cortex[1,24,25,26,27,28,29,30,31,32] and hippocampus[25,27,28,33,34,35,36,37] as well as increasing theta (4–8 Hz) power and coherence[1,36,38,39,40,41,42,43,44,45].

Therefore, previous research has separately examined the behavioral effects of mindfulness meditation on episodic memory[17,18,19,20] and the neural effects of mindfulness meditation[1,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45]. In order to understand the effects of mindfulness meditation on episodic memory and its neural correlates it is important to measure both behavior and brain activity during episodic memory. One method for studying the neural correlates of episodic memory is with electroencephalography (EEG). Here we describe a method for combining mindfulness meditation training with an episodic memory task while measuring EEG. By combining training in mindfulness meditation with behavioral and neural measures of episodic memory we can better understand the effects of mindfulness meditation on cognitive function.

Protocol

All procedures were approved by the Institutional Review Board of Bowdoin College, in accord with federal guidelines for the protection of human subjects.

1. Subject recruitment and preparation for the experiment

1. Recruit 40 18-29 year old subjects who are meditation naïve, right-handed, fluent English speakers, with normal or corrected to normal vision, with no neurological conditions.
   NOTE: Studying younger children and older adults would require a separate age-specific study. The development of the frontal and parietal lobes is important for performing the episodic memory task. And there is variability in the EEG across age. Studying younger children and older adults requires age specific cognitive tasks and specialized EEG recording and data analysis protocols that are not accommodated in the present protocol. Recruit only right-handed subjects to reduce variability in EEG activity.
2. Randomly assign 40 subjects to a mindfulness meditation experimental or waitlist control group for a total of 20 subjects in each group.
3. Schedule the experimental sessions and mindfulness meditation training such that the delay between pre-training and post-training experimental sessions are equal for the mindfulness meditation experimental and waitlist control groups (see **Figure 1** for a visual depiction of the sessions).

Figure 1: Visual depiction of the sessions. Subjects completed the Five Facet Mindfulness Questionnaire (FFMQ)[46] and performed the episodic memory task while EEG was recorded during the pre-training and post-training experimental sessions. Subjects were randomly assigned to either train in mindfulness meditation for four weeks or remain on a waitlist to be trained in mindfulness meditation. Please click here to view a larger version of this figure.

4. Inform subjects about the procedures involved in the behavioral testing, the EEG recording, and the mindfulness meditation training. Ensure that subjects refrain from practicing meditation outside those conducted for the research study.

2. Mindfulness questionnaire

1. For each experimental session, have subjects complete the Five Facet Mindfulness Questionnaire (FFMQ)[46] (see **Supplementary File 1**).
2. Analyze the mindfulness data.
    1. Measure each subject's mindfulness by calculating scores for FFMQ Total as well as Observe, Describe, Awareness, Nonjudge, and Nonreactive scales by summing up the scores for each subscale (note that for some items the scoring must be reversed (i.e., change 1 to 5, 2 to 4, 4 to 2, and 5 to 1) according to the instructions in the FFMQ[46] (see scoring instructions in **Supplementary File 1**).
    2. Compare subjects' FFMQ Total as well as Observe, Describe, Awareness, Nonjudge, and Nonreactive scores for the mindfulness meditation experimental and waitlist control group across pre-training and post-training experimental sessions.

3. Episodic memory task

1. Prepare a list of 800 adjectives that are equated for word frequency according to the Kucera and Francis[47] word norms (see **Supplementary File 2**).
2. For each experimental session, have subjects practice the encoding phase by presenting 10 words and performing the encoding task as described below.
3. For each experimental session, have subjects perform the encoding phase.
    1. Have subjects study a list of 200 adjectives and either create a mental image of a spatial scene described by the adjective (place task) or think about the meaning of the word and rate its pleasantness (pleasant task).
    2. After presentation of each word, ask subjects to rate how well they performed the encoding task (see **Figure 2** for a visual depiction of the encoding procedure).

4. For each experimental session, have subjects practice the source retrieval phase by presenting the 10 words that were shown at encoding practice and five new words, and perform the source retrieval task as described below.
5. For each experimental session, have subjects perform the source retrieval phase while recording EEG.
    1. Present the 200 words that were shown at encoding randomly intermixed with 200 new words. Send time stamps that correspond to each behavioral condition to the EEG recording. Words should be presented in 20 blocks to give subjects rest breaks to rest their eyes.
    2. During the presentation of each word, ask subjects to indicate if the word was new or if they recognized it as being studied in the encoding phase. For recognized words, ask subjects to indicate the source, whether the word was studied in the place task or the pleasant task (see **Figure 2** for a visual depiction of the source retrieval procedure).
    NOTE: The episodic memory task can be designed using any software designed for behavioral research such as EPrime which can send time stamps to the EEG recording using Task Events (see **Table of Materials**). Tutorials and example experiments are available online (e.g., https://pstnet.com, https://step.talkbank.org[48]).

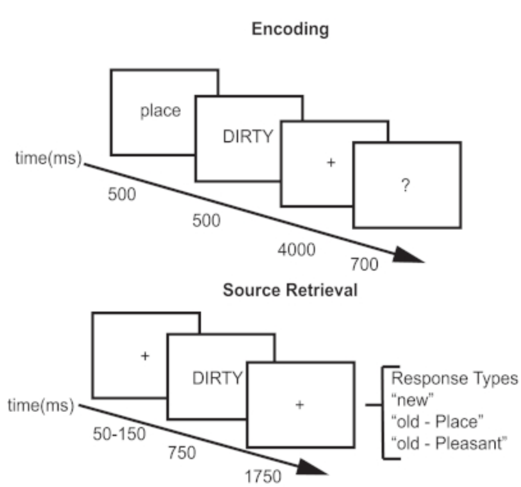

Figure 2: Visual depiction of the experimental paradigm. During the episodic memory task, subjects studied adjectives and either imagined a scene (place task) or judged its pleasantness (pleasant task). During the source retrieval phase subjects decided which task was performed with each word ("Old Place Task" or "Old Pleasant Task") or "New". This figure has been modified from Nyhus et al.[60]. Please click here to view a larger version of this figure.

6. Mark each trial based on the behavioral condition and the subject's response (see **Figure 3** and **Figure 4**) and analyze the episodic memory behavioral data.
    1. Measure subjects' ability to remember source information by calculating item discrimination (item *d'*, see **Figure 3**):

Z(hit rate) – Z(false alarm rate)

2. Measure subjects' ability to remember source information by calculating source discrimination (source *d'*, see **Figure 4**).

Z(correct source rate) – Z(incorrect source rate)

3. Compare subjects' item and source discrimination (item and source *d'*) for the mindfulness meditation experimental and waitlist control group across pre-training and post-training experimental sessions.

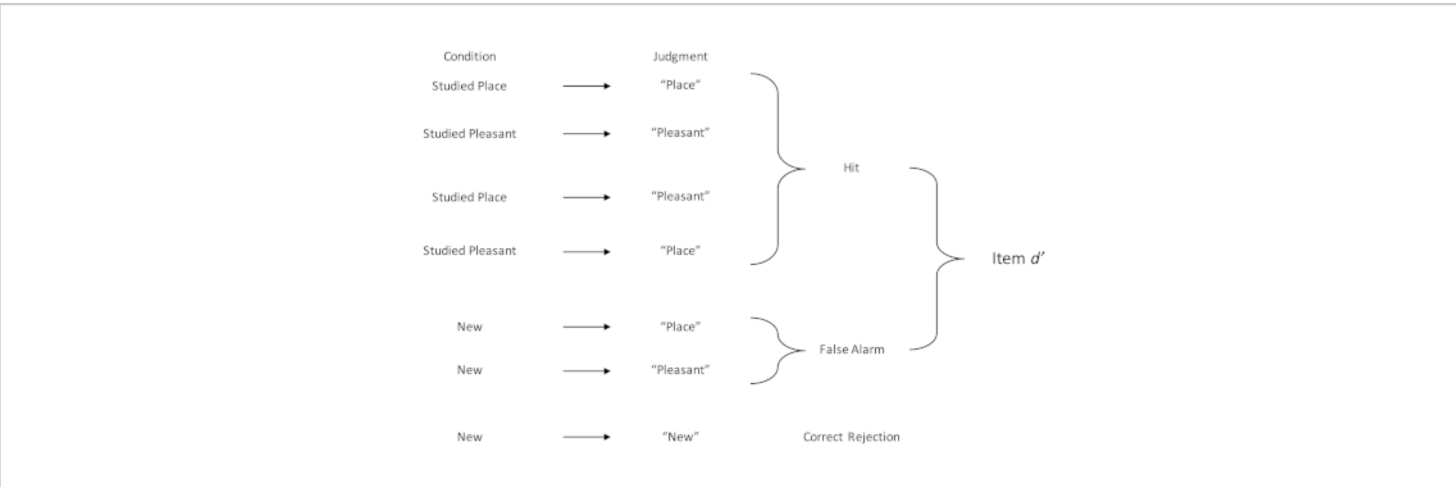

Figure 3: Data categories included in the measurement of word memory. Trials were marked based on the behavioral condition and the subject's response and used to calculate item discrimination (item *d'*). Please click here to view a larger version of this figure.

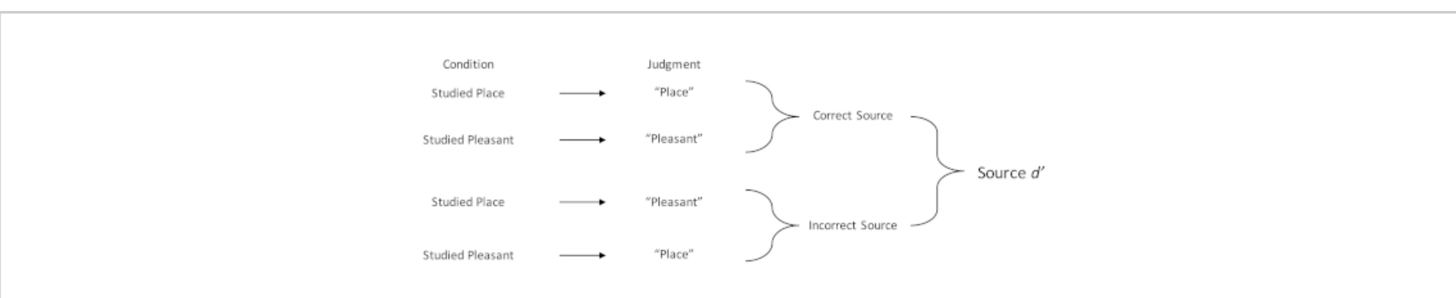

Figure 4: Data categories included in the measurement of source memory. Trials were marked based on the behavioral condition and the subject's response and used to calculate source discrimination (source *d'*). Please click here to view a larger version of this figure.

4. EEG recording and analysis

1. Set up the EEG cap (see **Table of Materials**).

NOTE: An EEG capping tutorial and other useful information is available through online resources (e.g., https://pursue.richmond.edu[49]).

1. Measure the subject's head and put all the electrodes on the correct size EEG cap according to the extended international 10-20 system.
2. Clean the subject's forehead with an alcohol wipe.
3. Apply the EEG cap to the subject's head by parting their hair then inserting conductive gel with a Luer-lock syringe with a blunted needle.
4. Using the EEG recording software, click on impedances and make sure they are under the resistance level recommended by the specific EEG system chosen for use by the researchers.
5. Ask the subject to remain as still as possible during the experiment. Show the subject the EEG signal when they are still and when they blink or make jaw or facial movement.

2. Record the EEG.
   1. Set the EEG amplifier with the EEG recording software by clicking on edit workspace and set to acquire signal with a .1–100 Hz bandpass filter and 500 Hz sampling rate for all subjects.
   2. Start the EEG recording.
   3. Start the source retrieval phase and ensure that the time stamps from the source retrieval task are showing up in the EEG recording.
3. Once the subject has completed the source retrieval task, clean the EEG cap and electrodes with deionized water and disinfectant.
4. Process and analyze the EEG data.
   1. High-pass filter the data at 1 Hz and low-pass filter the data at 100 Hz.
   2. Identify and interpolate bad channels using surrounding channels[50].
   3. Re-refence the data to an average reference[51].
   4. Segment the data relative to the onset of each time stamp from the source retrieval task and subtract a pre-stimulus baseline period.
   5. Identify and remove artifacts in the EEG data such as eye-blink and eye-movement artifacts. Detect and reject trials with large artifacts (voltage fluctuations of over 1,000 µV or data 5 standard deviations beyond the norm). Reconstruct the EEG after running independent component analysis (ICA)[52] and identifying and removing noise components[53].
   6. Convert the EEG data to the time-frequency domain across 100 log-spaced frequencies from 3 Hz to 125 Hz using a Morlet wavelet transformation with the wavelet increasing from 3 cycles at 3 Hz to 25 cycles at 125 Hz.
   7. Compare theta power relative to pre-stimulus baseline in the mindfulness meditation experimental and waitlist control groups across pre-training and post-training experimental sessions in right frontal and left parietal channels which show effects during source retrieval[54,55,56,57]. All analyses should control for multiple comparisons.

      NOTE: The EEG data can be processed and analyzed using publicly available software designed for signal processing such as EEGLab[58]. EEGLab training workshops and tutorials are available through the Swartz

Center for Computational Neuroscience (https://sccn.ucsd.edu/eeglab/index.php).

5. Mindfulness meditation training

1. Hire a mindfulness meditation instructor trained in the Mindfulness Based Stress Reduction (MBSR) technique[59].
   NOTE: Instructors trained in the MBSR technique can be found online (e.g. https://www.brown.edu/public-health/mindfulness/programs/mbsr-teacher-recognition).
2. Have the 20 subjects in the mindfulness meditation experimental group meet as a group for one hour each week for four weeks with the mindfulness meditation instructor.
   NOTE: The standard MBSR course is eight weeks and includes breath awareness, sitting meditation, yoga, and relaxation techniques. The mindfulness meditation training should include aspects of the standard MBSR course such as breath awareness and sitting meditation (see **Supplementary File 3**). These practices, which relate to focusing attention and executive function are most likely to contribute to episodic memory.
3. Have subjects practice mindfulness meditation for at least 20 min each day using a guided breath awareness meditation recording provided by the mindfulness meditation instructor.
4. Track daily mindfulness meditation practice by asking subjects how many minutes they practiced mindfulness meditation, what they did during their meditation, and how the practice was going for them through daily emailed surveys (see **Table of Materials**).
   NOTE: Researchers should consider excluding subjects who do not spend a substantial amount of time practicing mindfulness meditation.
5. Schedule the post-training experimental session as soon as possible after completion of the mindfulness meditation training.
   NOTE: Researchers should consider excluding subjects who are unable to complete the post-training experimental session soon after the completion of the mindfulness meditation training. Please reach out to experts in cognitive neuroscience who use the EEG technique for randomized controlled experiments for further information.

Representative Results

Representative results are reported for 40 meditation naïve, right-handed, fluent English-speaking subjects (10 male and 10 female subjects ranging from 18 to 22 years old in the mindfulness meditation experimental group and 7 male and 13 female subjects ranging from 18 to 22 years old in the waitlist control group). Behavioral and EEG data were analyzed using mixed analysis of variance (ANOVA) comparing mindfulness meditation experimental and waitlist control groups (experimental, control) across time (pre-training, post-training). All post-hoc tests corrected for multiple comparisons.

Mindfulness questionnaires

First, analysis assessed whether the mindfulness meditation training was successful. Subjects spent a substantial amount of time practicing mindfulness meditation and their mindfulness increased as measured by the FFMQ. Specifically, there was an interaction between group and time for FFMQ Total (F(1,38) = 11.15, MSE = 67.67, p < .01) and a marginal interaction between group and time for

FFMQ Describe ($F(1,38) = 3.35$, $MSE = 12.26$, $p = .08$) and Nonjudge ($F(1,38) = 3.87$, $MSE = 15.37$, $p = .06$) scales. Scores increased from pre-training to post-training for FFMQ Total ($F(1,19) = 15.60$, $MSE = 63.34$, $p < .01$), Describe ($F(1,19) = 6.36$, $MSE = 8.44$, $p = .02$), and Nonjudge ($F(1,19) = 10.12$, $MSE = 8.60$, $p < .01$) scales for the mindfulness meditation experimental group, whereas the waitlist control group did not change (see **Table 1**).

	Experimental		Control	
	Pre-training	**Post-training**	**Pre-training**	**Post-training**
Total	128.13 (2.38)	138.07 (3.24)	123.59 (4.19)	121.25 (4.77)
Observe	26.98 (1.16)	28.70 (1.00)	23.83 (1.14)	23.70 (1.26)
Describe	29.5 (1.36)	31.82 (.99)	27.10 (1.25)	26.55 (1.26)
Awareness	25.25 (1.06)	26.95 (1.12)	25.27 (.94)	24.05 (1.28)
Nonjudge	24.65 (1.26)	27.60 (1.40)	27.50 (1.42)	27.00 (2.05)
Nonreacitve	21.75 (.99)	23.00 (1.08)	19.90 (1.09)	19.95 (1.16)

Table 1: Five Facet Mindfulness Questionnaire data. FFMQ Total as well as Observe, Describe, Awareness, Nonjudge, and Nonreactive scores for the mindfulness meditation experimental and the waitlist control group for the pre-training compared to the post-training experimental session. Means with standard errors in parentheses are shown. This table has been modified from Nyhus et al.[60].

Episodic memory

Second, analysis examined the effect of mindfulness meditation on behavioral performance of the episodic memory task. The mindfulness meditation training led to increases in source memory as measured by source discrimination (source *d'*). Although there was no interaction between group and time ($F(1,38) = 1.16$, $MSE = .12$, $p = .29$), pairwise comparisons showed that source discrimination increased from pre-training to post-training for the mindfulness meditation experimental group ($F(1,19)=10.53$, $MSE=.12$, $p<.01$), but not the waitlist control group (see **Table 2**).

		Experimental		Control	
	Condition	**Pre-training**	**Post-training**	**Pre-training**	**Post-training**
Hit	Place correct source	.66 (.02)	.67 (.03)	.71 (.03)	.69 (.02)
	Pleasantness correct source	.61 (.03)	.72 (.03)	.64 (.05)	.74 (.03)

FA	Place incorrect source	.34 (.02)	.33 (.03)	.29 (.03	.31 (.02)
	Pleasantness incorrect source	.39 (.03)	.28 (.03)	.36 (.05)	.26 (.03)
Source *d'*		.70 (.11)	1.06 (.12)	1.04 (.17)	1.23 (.14)
Source *c*		-.06 (.05)	.07 (.05)	-.12 (.12)	.10 (.07)

Table 2: Source behavioral data. Hit rate, false alarm rate, source discrimination (source *d'*) and response bias (source *c*) for the mindfulness meditation experimental and the waitlist control group for the pre-training compared to the post-training experimental session. Means with standard errors in parentheses are shown. This table has been modified from Nyhus et al.[60].

EEG Results

Third, EEG analysis examined the effect of mindfulness meditation on a neural correlate of episodic memory. Specifically, theta power was examined in right frontal and left parietal channels from 1000 to 1500 ms as these effects have been found in multiple source retrieval tasks[54,55,56,57]. For the left parietal channels, group interacted with time ($F(1,37) = 9.52$, $MSE = .92$, $p < .01$). Theta power increased from pre-training to post-training for the mindfulness meditation experimental group ($F(1,19) = 17.37$, $MSE = .23$, $p < .01$), but not the waitlist control group (see **Figure 5**).

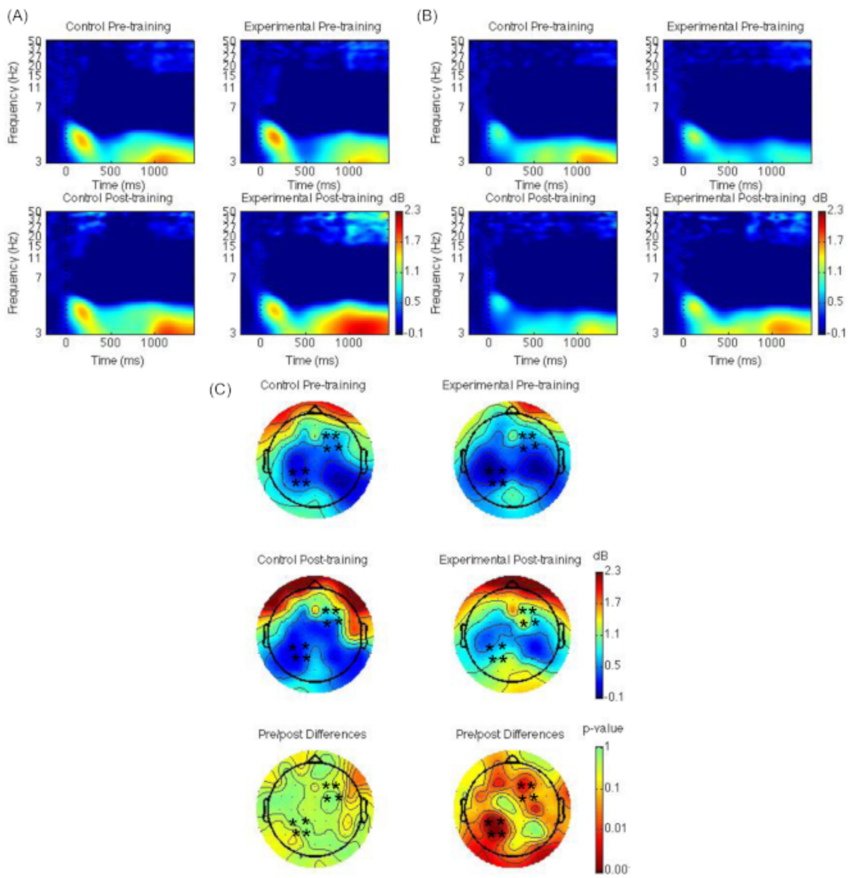

Figure 5: Effect of mindfulness meditation on theta power. Theta power for the mindfulness meditation experimental and the waitlist control group for the pre-training compared to the post-training experimental session. (**A**) Time-frequency spectrograms across times and frequencies in a right frontal channel. (**B**) Time-frequency spectrograms across times and frequencies in a left parietal channel. (**C**) Theta power across all channels from 1000–1500 ms and differences from pre-training to post-training. (**C**) Black * marks analyzed channels in right frontal and left parietal regions. Color scale: decibel change from pre-stimulus baseline and *p*-value of pre-training to post-training differences. This figure has been modified from Nyhus et al.[60]. Please click here to view a larger version of this figure.

Finally, the correlation between changes in mindfulness and changes in episodic memory behavioral performance and EEG was examined in the mindfulness meditation experimental group. There was a positive correlation between increases in FFMQ Describe scores from pre-training to post-training and EEG theta power increases from pre-training to post-training in right frontal channels ($r = .72$, $n = 20$, $p < .01$, two-tailed, Bonferrroni corrected; see **Figure 6**).

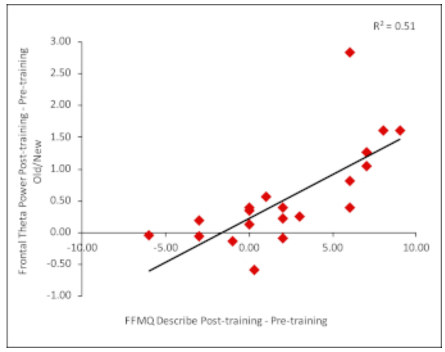

Figure 6: Correlation between changes in FFMQ and theta power. Correlation between the average difference in theta power between pre-training and post-training for hits and correct rejections in right frontal channels and the difference in FFMQ Describe scores between pre-training and post-training. This figure has been modified from Nyhus et al.[60]. Please click here to view a larger version of this figure.

Supplemental File 1. Please click here to download this file.

Supplemental File 2. Please click here to download this file.

Supplemental File 3. Please click here to download this file.

Discussion

The current protocol provided the first evidence that mindfulness meditation can increase source memory and theta oscillations. By combining training in mindfulness meditation with behavioral and neural measures we are better able to understand the effects of mindfulness meditation on episodic memory and its neural correlates.

Although previous research has separately examined the behavioral effects of mindfulness meditation on episodic memory[17,18,19,20] and the neural effects of mindfulness meditation[1,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45] no study has combined behavior and EEG during episodic memory. In addition, previous research on mindfulness meditation has often studied expert meditators[1,17,21,22,23,24,25,26,27,28,29,30,32,33,35,36,37,38,3 and therefore risks self-selection bias. By using a longitudinal design with randomly assigned mindfulness meditation and waitlist control groups we were better able to control for group differences. Finally, previous research on mindfulness meditation has often used the full 8-week MBSR course, but the current study showed significant effects with only 4-weeks of mindfulness meditation training.

There were a number of key steps in successfully implementing these methods. First, random assignment to the mindfulness meditation experimental or waitlist control group was critical for ensuring that the groups were roughly equal. Second, it was important to focus the mindfulness meditation training on aspects of the MBSR course that relate to focusing attention and executive function (e.g., breath awareness) as these are most likely to contribute to episodic memory. Third, it was important to have subjects spend a substantial amount of time practicing mindfulness meditation and to accurately report the time they spent meditating each day. Fourth, it was important to equate the time between pre-training and post-training experimental sessions between the mindfulness meditation experimental and waitlist control groups to control for timing and to schedule the post-training experimental session as soon as possible following the mindfulness meditation training so that the effects of mindfulness meditation training did not dissipate prior to testing. Fifth, it is likely that mindfulness meditation affects episodic memory by increasing attention and executive function. Therefore, it was important to use an episodic memory task that requires executive function such as source memory. Finally, it is important to obtain high quality EEG data that is free of artifacts.

Although there were advantages to this method over existing methods, a few limitations should be noted. The effect of mindfulness meditation on source memory was weak. This could have resulted from using subjects who were healthy young adults with good memory performance or the limited amount of time that subjects spent practicing mindfulness meditation. The 4-week mindfulness meditation training was shorter than the standard 8-week MBSR course and, on average, subjects did not report spending the full 20 min practicing mindfulness meditation each day. In addition, there was no active control group, so it is unclear how mindfulness meditation compares to other treatments in boosting source memory or theta oscillations. Finally, the EEG analysis methods used here do not separate out the contribution of periodic oscillatory power from aperiodic 1/f non-oscillatory power which may affect the interpretation of the results. Therefore, future research should consider using subjects with weaker memory ability, implementing the full 8-week MBSR course, employing an active control condition, and using newly developed analysis methods that separate out oscillatory and 1/f non-oscillatory activity[61].

Therefore, the current methods were successful in combining behavior and EEG to study the effects of mindfulness meditation on episodic memory. Future research should use these methods to compare mindfulness meditation with other treatments that have been shown to improve episodic memory and change the structure and function of the brain. In addition, future research should combine behavior and neural measures to examine the effects of mindfulness meditation on other facets of cognition. By combining behavioral and neural measures and comparing mindfulness meditation to alternative treatments we will be better able to determine the most promising treatments for cognitive enhancement.

Disclosures

The authors have nothing to disclose.

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