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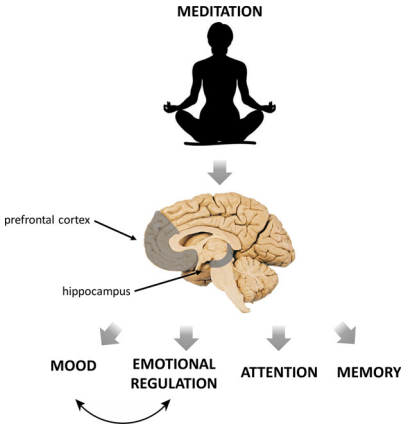
Research report

# Brief, daily meditation enhances attention, memory, mood, and emotional regulation in non-experienced meditators

Julia C. Basso[a,b,*], Alexandra McHale[a], Victoria Ende[a], Douglas J. Oberlin[a], Wendy A. Suzuki[a,*]

[a] New York University, Center for Neural Science, 4 Washington Place, Room 809, New York, NY 10003, United States
[b] Virginia Tech Carilion Research Institute, Center for Transformative Research on Health Behaviors, 1 Riverside Circle, Suite 104G, Roanoke, VA 24016, United States

## GRAPHICAL ABSTRACT

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## ABSTRACT

Meditation is an ancient practice that cultivates a calm yet focused mind; however, little is known about how short, practical meditation practices affect cognitive functioning in meditation-naïve populations. To address this question, we randomized subjects (ages of 18–45) who were non-experienced meditators into either a 13-min daily guided meditation session or a 13-min daily podcast listening session (control group) for a total duration of 8 weeks. We examined the effects of the daily meditation practice relative to podcast listening on mood, prefrontal and hippocampal functioning, baseline cortisol levels, and emotional regulation using the Trier Social Stress Test (TSST). Compared to our control group, we found that 8 but not 4 weeks of brief, daily meditation decreased negative mood state and enhanced attention, working memory, and recognition memory as well as decreased state anxiety scores on the TSST. Furthermore, we report that meditation-induced changes in emotional regulation are more strongly linked to improved affective state than improved cognition. This study not only suggests a lower limit for the duration of brief daily meditation needed to see significant benefits in non-experienced meditators, but suggests that even relatively short daily meditation practice can have similar behavioral effects as longer duration and higher-intensity mediation practices.

* Corresponding authors at: New York University, Center for Neural Science, 4 Washington Place, Room 809, New York, NY 10003, United States.
*E-mail addresses:* jbasso@vt.edu (J.C. Basso), ws21@nyu.edu (W.A. Suzuki).

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## 1. Introduction

Meditation is an ancient mindfulness practice that stems from Buddhist and Hindu cultures, where the practitioner intentionally engages the mind by bringing an increased awareness to thought and feeling. Many different types of meditation practices exist. For example, focused attention meditation encourages concentration on a single object such as the breath, a part of the body, or an external object, while open monitoring mediation encourages a non-judgmental and non-attached monitoring of all things coming into our conscious awareness. In parallel with the growing popularity of meditation, a growing body of studies on the behavioral and neurophysiological effects of meditation has begun to explore whether meditation can be used to improve mood, decrease stress, and affect various cognitive functions in both normal [1] and patient population groups [2].

While prominent early studies of the effects of meditation focused on patterns of electroencephalography (EEG) signals in the brains of highly experienced Tibetan Buddhist monks relative to inexperienced meditators [3], many meditation studies to date have taken either a cross-sectional approach in individuals completing intensive meditation retreats [4,5], or performed randomized controlled experiments using either experienced meditators or non-experienced meditators with various mental health issues. These studies report a range of mind/body benefits with the most common being enhanced emotional regulation, attention, and self-awareness [1]. In patients with mental health issues, meditation has shown to be affective at decreasing levels of depression, anxiety, pain, psychological stress, and substance abuse [2,6]. Other benefits reported include decreased blood pressure and inflammation, improved immune function and glucose and insulin resistance, and increased telomerase activity [7–9]. Less information is available on the effects of meditation practices that are both shorter in overall duration and shorter in terms of individual meditation sessions, though the data thus far suggests that shorter practices may offer some of the same cognitive and functional benefits as longer, intense meditation practices [10,11]. Here we explore a range of cognitive and physiological changes associated with brief, daily mediation practice as well as the time course of these effects.

Scientists have theorized that meditation may produce these beneficial effects by enhancing emotional regulation or the ability to control our emotional state. For example, meditation is associated with a decreased physiological response during the viewing of a stressful film [12], decreased emotional interference during the Emotional Interference Task [13], and decreased self-reported difficulty in regulating the emotional state [14]. In addition, meditation programs have been shown to reduce symptoms of anxiety, panic, and depression in patients with anxiety disorders, with these effects lasting for up to 3 years after the initial meditation intervention [15,16].

The hypothalamic-pituitary-adrenal (HPA) axis is a major component of the endocrine system that controls our reaction to stress and is connected to a circuit of brain regions including the amygdala, hippocampus, and prefrontal cortex, all of which work in tandem to regulate our behavioral and physiological response to stress [17]. Research indicates that the beneficial effects of meditation may be due to changes in this stress circuitry. For example, meditation has been shown to increase the volume of both the hippocampal and prefrontal cortical regions [18]. Moreover, mediators show decreased activation of the amygdala while viewing emotional images [19,20]. While many previous studies have reported improved functions associated with the prefrontal cortex with increased meditation (e.g., attention and working memory), many fewer studies have examined the effects on meditation of the memory functions of the hippocampus/medial temporal lobe [21]. We hypothesize that meditation will improve 1) affective state, 2) executive functions such as attention, working memory, response inhibition, and cognitive flexibility, that have been linked with the prefrontal cortex, and 3) recognition memory and behavioral pattern separation, functions that have been linked with the hippocampus. Furthermore, we predict that compared to controls, meditators will demonstrate enhanced emotional regulation in response to an acute psychosocial stressor. Importantly, and as a new addition to the literature, we examined the relationship between meditation-induced changes in the stress response and changes in both psychological state and cognitive function. We predicted that those individuals who show the greatest reductions in stress responsivity would show the largest gains in mood and cognition.

To address these questions, we randomly assigned healthy adults between the ages of 18 and 45 who did not have previous experience with mediation to either a 13-min daily guided meditation program or a 13-min daily podcast listening session for a total duration of eight weeks. Before, at the 4-week time point, and after this training, we assessed cognitive functioning via a battery of neuropsychological tasks and mood state via a battery of self-reported questionnaires. To determine how meditation affected stress level at the physiological level, baseline saliva cortisol samples were taken before the intervention, at the 4-week time point, and after the intervention. In addition, to determine how meditation affected the acute response to stress, after the eight-week program, subjects were subjected to the Trier Social Stress Test (TSST), and both behavioral measures of anxiety and cortisol levels were assessed before and after this test. We asked if and when brief daily meditation would have an effect on these cognitive and physiological functions. We discuss how the effects of our brief daily meditation intervention compare with the effects of more intense meditation regimes examined in previous studies.

## 2. Methods

### 2.1. Recruitment and participants

For this study, we recruited healthy, non-smoking subjects between the ages of 18 to 45 who were not experienced meditators. Subjects were disqualified if they had a mediation practice of more than once per week for the past three months or if they had a current or prior diagnosis of any neurological or mental health issue (e.g., depression, anxiety, schizophrenia, epilepsy, traumatic brain injury, etc.). Prior to the start of the study, all subjects gave their informed consent. All procedures were approved by the New York University Committee on Activities Involving Human Subjects and were performed in accordance with the relevant guidelines and regulations. Using these criteria, a total of 76 subjects were recruited from the New York City area via flyer advertisements and online postings. Throughout the course of the study, 34 subjects dropped out (n = 14) or were excluded (n = 20), for a total subject number of 42 (15 males, 27 females).

High attrition rates are common amongst longitudinal studies, which may lead to problems of research bias [22–24]. In this study, we report an attrition rate of 44.7% (dropout rate of 18.4%), similar to other longitudinal studies [22]. Dropout or exclusion from the study generally occurred prior to or early in the data collection period, and subjects dropped out for a variety of reasons including 1) lack of correspondence to emails; 2) logistical issues scheduling visits; 3) non-completion of mood questionnaires within one week of visiting the laboratory; 4) non-compliance listening to meditation or pod-cast sessions; and 5) life responsibilities too demanding to continue with the study. A Fisher's Exact Test was conducted in order to determine whether dropout/exclusion subjects differed from subjects who completed the study in terms of sex, race, ethnicity, education level, marital status, number of children, and household income. Dropout/exclusion subjects did not differ from study participants in any of these areas ($p > 0.05$).

Sample size for a repeated-measures analysis of variance (ANOVA) was determined using an *a priori* power analysis via G*Power 3.1 [25,26]. The power analysis was conducted using two groups with three measurements, an alpha level of 0.05, a power of 0.80, a small to medium effect size (f = 0.2), a correlation among repeated measures of

0.5, and a nonsphericity correction ε of 1. Using these criteria, the desired total sample size was 42 subjects.

### 2.2. Interventions

#### 2.2.1. Meditation (experimental group)

This eight-week study consisted of three visits to the laboratory: pre-intervention, mid-intervention (conducted at the four-week time point), and post-intervention. All procedures conducted at each of these visits were similar and as described below (see mood and neuropsychological assessment). Prior to the start of the intervention, subjects were randomly assigned to a meditation group or a podcast listening group. Once the pre-intervention laboratory session was complete, subjects were instructed to listen to thirteen minutes of either a meditation recording or a podcast every day for eight weeks. While listening to the meditation or podcast recordings, subjects were required to log into an audio/video hosting website (https://wistia.com/) that allowed us to track when subjects completed their daily sessions. Subjects were disqualified if they listened to the guided meditations or podcasts less than five times per week for two consecutive weeks.

All subjects were financially compensated a total of $60 for their participation in the study. Additionally, in order to promote subject retention, participants had the opportunity to receive small prizes if they adhered to meditation or podcast listening at least six times per week for two consecutive weeks.

Meditation subjects were given a 13-min recording of a guided meditation called Journey Meditation. Journey meditation, developed by Stephen Sokoler (http://www.journeymeditation.com/), is a simple, step-by-step, guided meditation through a variety of breathing exercises and full-body scans currently being used in corporate situations. The meditation recording also included an intermittent time of silence where subjects were able to breathe at their own pace. This length of meditation is in accordance with other brief meditation practices that have shown positive outcomes in a variety of variables including pain, anxiety, attentional resources, and alcohol consumption using meditation sessions from 10 to 20 min [27–30]. Subjects listened to the same meditation recording daily for eight consecutive weeks. During their first laboratory session, meditation subjects listened to a 17-min introductory meditation recording provided by Journey Meditation.

#### 2.2.2. Podcast listening (control group)

Podcast listening was used as a control for this study. All podcasts were taken from www.radiolab.org and segmented into approximately 13-min sections in order to mimic the same time-duration of the meditation recording. Radio Lab is a podcast series that promotes scientific understanding for the general public and discusses research and stories in science and philosophy. Topics included narratives from biology, sociology, astronomy, cultural trends, and economics, and were screened to ensure that they did not discuss meditation practices. Subjects listened to a different podcast daily for eight consecutive weeks. During their first laboratory session, control subjects listened to a 15-min sample recording of a Radio Lab podcast.

Podcast listening was explicitly chosen as an appropriate intervention for our control group because of the following reasons: (1) podcast listening was intended to be an active, learning experience similar to the active engagement of meditation; (2) both meditation and podcast listening could take place online and be conducted in the privacy of the home setting; (3) podcast listening sessions could be structured to mimic the exact time frame of the meditation sessions; (4) direct participation in podcast listening and meditation could be monitored via the same online system (i.e., wistia); and (5) podcast sessions did not include mindfulness or mindfulness-related topics. Other active learning control groups, such as the Health Enhancement Program, have been validated for when meditation was used as the experimental group [31]. In addition, other studies have successfully used podcast listening as a control to demonstrate differences in brain state signals between meditators and controls [32,33].

### 2.3. Affective, cognitive, and physiological assessments

#### 2.3.1. Mood assessment

Within 24 h after their visit to the laboratory, subjects completed a variety of standardized, online questionnaires to assess mood, emotion, and affective states. Subjects completed these questionnaires at home. These included the Mindful Attention Awareness Scale, Profile of Mood States, Quality of Life Scale, Subjective Happiness Scale, Rosenberg Self-Esteem Scale, Pittsburgh Sleep Quality Index, Mindful Eating Questionnaire, Fatigue Severity Scale, Rumination Scale, Perceived Stress Scale, Beck Anxiety Inventory, Beck Depression Inventory, and State-Trait Anxiety Inventory.

#### 2.3.2. Neuropsychological assessment

Subjects completed a series of six tests that assessed functioning of the prefrontal cortex and hippocampus. All methodological task details were taken directly from previously published manuscripts. Tasks were recreated in house using Unity, a cross-platform game engine and were administered on a computer. These included tests of executive functioning as well as recognition memory and pattern separation. Because of study timing, all tasks needed to be completed in one visit to the laboratory. To account for fatigue and/or interference effects, task order was randomized between subjects; however, task order was preserved for each subject at pre-, mid-, and post-intervention visits. All tasks included embedded rest periods. In addition, subjects were allowed to take breaks as needed. To account for learning effects, task stimuli were changed between visits.

*2.3.2.1. N-Back Task.* This prefrontal cortex-dependent task tests the capacity for short-term memory [34]. Subjects were serially presented with letters and asked to determine via button press whether each letter was a match or not for the letter presented n-items prior. Twelve sets of 0-, 1-, 2- and 3-back trials were presented randomly. Subjects were shown 30 + n random letters, each for 500 ms, and then had an additional 2500 ms to respond. Subjects were given 30 s of rest in between each trial and 2 min of rest in between each set. This task was adapted for the computer from [35].

*2.3.2.2. Reading Span Task.* This dual-processing test, dependent on the prefrontal cortex, assesses short-term memory [36,37]. Subjects were presented with a series of three sets of sentences; each set consisted of 2-, 3-, 4-, 5-, and 6-sentence trials presented randomly. Each sentence was followed by an unrelated word. Subjects were allowed to read the sentence and word at their own pace and move on at their own discretion. After each trial, subjects were asked to recall, in order, as many words as they could. To test for task adherence, subjects were also asked a comprehension question about the sentences. Subjects were given 30 s of rest in between each set, except for the middle of the task (i.e., in between sets 3 and 4) when subjects were given 2 min of rest. This task was adapted for the computer from [38,39].

*2.3.2.3. Wisconsin Card Sorting Task.* This task, a traditional task that has been shown to assess prefrontal cortex functioning and newly other areas including the parietal lobe and even subcortical structures like the basal ganglia, tests the capacity for cognitive flexibility [40–42]. Subjects were presented with a deck of 128 cards that varied in the dimensions of color, shape, and number. They were then asked to sort the deck by matching the cards to one of four "stimulus cards"; there was no set time limit to respond. Subjects were then informed whether their response was correct or incorrect. Once the subject matched 10 cards correctly, the sorting principle changed without notice. This process continued until either the subject successfully sorted the cards under the six different classification principles or all 128 trials completed. This task was adapted from [43].

*2.3.2.4. Stroop Color and Word Task*. This test, which assesses both attention and the inhibition of cognitive interference, is dependent on the prefrontal cortex [44,45]. Subjects were serially presented with the words "RED", "BLUE," "GREEN" or "YELLOW" in either their congruent (same) or incongruent (different) colors. Subjects were then asked to indicate via button press the color, rather than the meaning, of the word. Three sets of 48 trials were presented. A fixation cross was first presented for 500 ms, followed by a colored word for 1500 ms, followed by an inter-stimulus interval of 850–1100 ms. Subjects were given 30 s of rest in between each set. This task was adapted from [29].

*2.3.2.5. Eriksen Flanker Task*. This prefrontal cortex task tests attention and response inhibition abilities [46,47]. Subjects were presented with a string of seven letters comprised of a target stimulus in the center and six flankers (i.e., three of the same letter on either side). The target stimuli were associated with either a left or right button press. Subjects were instructed to pay attention to the center letter and indicate whether that letter was associated with a left or right direction. Three sets of 144 trails were presented, with a response time of 1500 ms. Subjects were allowed time to rest in between each set, but could move on at their own discretion. This task was adapted from [48].

*2.3.2.6. Mnemonic Similarity Task*. This is a hippocampal-dependent task that tests both recognition memory and pattern separation abilities [49]. Subjects viewed 128 images and were asked to classify them as indoor or outdoor items via button press. Subjects were given 30 s of rest after the first 64 images and 2 min of rest after the second 64 images. Later, in a surprise trial, subjects viewed another 192 images and were asked whether they were old, similar, or new in comparison to the previously presented objects. 64 of these images the subjects saw previously (old/target), 64 were similar to images seen previously (similar/lures), and 64 the subjects had not seen previously (new/foils). Subjects were given 30 s of rest after every 64 images. Sets C and D were utilized and all images were presented for 2000 ms followed by an inter-stimulus interval of 500 ms. This task was adapted from [50].

*2.3.3. Behavioral and physiological response to an acute stressor*

To determine how meditation affected the behavioral and physiological response to an acute stressor, the TSST was performed at the end of the post-intervention testing session. Both behavioral and physiological measurements were taken immediately prior to the TSST, immediately after the TSST, and 10, 20, and 30 min after the TSST.

*2.3.3.1. Trier social stress test (TSST)*. The TSST was used to assess the effects of meditation on social stress responsiveness. For this task, subjects were given five minutes to prepare for a five-minute interview for their "dream job". In front of two expressionless observers, they were then asked to present a case for why they should receive the job. They were misleadingly instructed that their responses would be recorded and that a panel of judges trained in public speaking would review their video-taped performance. After the interview, participants were instructed to sequentially subtract 13 from 1,022 for five minutes. If a mistake was made, they were asked to start from the beginning. To determine the behavioral response to the TSST, the state anxiety portion of the State-Trait Anxiety Inventory (STAI) was administered immediately before the TSST, immediately after the TSST, and 10, 20, and 30 min after the TSST. After this 30-min period, participants were given a debriefing form explaining the true goal and nature of the test [51].

*2.3.3.2. Salivary cortisol collection and analysis*. Salivary cortisol was collected using Sarstedt's salivette with the blue cap, which contains a biocompatible synthetic swab without preparation. Subjects were instructed to place the swab in their mouths and gently chew for one minute. To assess the effect of meditation on baseline cortisol levels, saliva samples were taken at the beginning of the pre-, mid- and post-intervention visits. Additionally, to assess the effects of meditation on the physiological response to acute stress, saliva samples were taken immediately before the TSST, immediately after the TSST, and 10, 20, and 30 min after the TSST. All baseline saliva samples were taken at approximately the same time of day (between 1:00 to 5:00 pm). This protocol was followed in order to account for variability in the diurnal cortisol level cycle [52]. Immediately after collection, all salivary cortisol samples were frozen in a −20 °C freezer until later analysis.

Once all samples were collected, they were sent to the University of Trier in Germany for analysis. Cortisol levels were measured using a competitive solid phase time-resolved fluorescence immunoassay with flouromeric end point detection (DELFIA). After thawing, saliva samples were centrifuged at 2000 *g* for 10 min; 100 µl of saliva were used for duplicate analysis. 96-well-Maxisorb microtiterplates were coated with polyclonal swine anti-rabbit immunoglobulin. After an incubation period of 24 h at 4 °C, plates were washed three times with washbuffer (pH = 7.4). The plates were then coated with a rabbit anti-cortisol antibody and incubated for 48 h at 4 °C. Synthetic saliva mixed with cortisol in a range from 0 to 100 nmol/l served as standards. Standards, controls (saliva pools), and samples were given in duplicate wells. 50 µl of biotin-conjugated cortisol was added and after 30 min of incubation, the non-binding cortisol/biotin-conjugated cortisol was removed by washing (3x). 200 µl europium-streptavidin (Perkin Elmerc, Liefe science Turku, Finnland) was added to each well and after 30 min and 6 times of washing, 200 µl enhancement solution was added (Pharmacia, Freiburg, Germany). Within 15 min on a shaker, the enhancement solution induced the fluorescence, which can be detected with VICTOR™ *X*4 Multilabel Plate Reader (Perkin Elmer, Massachusetts, USA). With a computer-controlled program, a standard curve was generated and the cortisol concentration of the samples was calculated. The intra-assay coefficient of variation was between 4.0% and 6.7%, and the corresponding inter-assay coefficients of variation were between 7.1% and 9.0%.

### 2.4. Statistical analyses

To analyze differences in a variety of demographic variables between our drop out versus our study subjects, we utilized a Fisher's exact test. An independent-samples t-tests was used to assess differences in baseline measures for all mood questionnaires, cognitive tasks, and cortisol levels. To account for the large number of dependent variables within the experimental setup, a full omnibus model was conducted prior to the individual statistical tests. A repeated measures multivariate analysis of variance (MANOVA) was run as an omnibus test to account for possible co-variance among variables within the study, while allowing for the inclusion of several cognitive and mood measurements. The repeated measures MANOVA used group and time points as the main effects (as well as an interaction) for 7 behavioral measures. After the repeated measures MANOVA showed significant findings, repeated measures analysis of variance (ANOVAs) were used to examine the changes within the different test measures over time. Additionally, an Analysis of Covariance (ANCOVA) using Pittsburgh Sleep Quality Index (PSQI) change score was used when mentioned (see Results section). Additionally, an ANCOVA was used to determine whether the intervention affected acute stress response. In this case, the within-subjects factor included two time points (i.e., immediately before and immediately or 10 min after the TSST), intervention type served as the between-subjects factor, and the PSQI change score served as the co-variate. When a significant interaction effect was found, paired-samples t-tests were conducted to determine the precise nature of the statistical change. If the original test was performed using a covariate, post-hoc analyses were also conducted using the same covariate. To assess the relationship between the changes in mood, cognition, and the response to acute stress, we tested whether a differences existed in mood (z score) or cognition (z score) between meditation and control groups given differences in the change in 1) cortisol after the

stress test, and 3) STAI score after the stress test using an ANCOVA (mood = Group | TSST-induced cortisol change, and TSST-induced STAI score change). To assess differences in whether the groups listened to the sessions at different times of day, we examined the significance of the difference between two independent proportions. An alpha level of 0.05 was used to determine statistical significance.

No outliers were present in the data, all data was normally distributed and met sphericity, and there was homogeneity of variances and covariances for pre-, mid- and post-intervention values. In instances where we evaluated more than two time points and sphericity was not met, a Greenhouse-Geisser correction was made.

Two subjects did not complete the mid-intervention mood questionnaire and so statistical analyses for these results were conducted on a total of 40 individuals (20 per group). For data analyses regarding the Stroop and N-Back Tasks, one subject was removed because of non-compliance with the tasks. For analyses regarding baseline cortisol levels, one subject was removed from analysis because the data were found to be outliers as assessed by inspection of boxplots (greater than or equal to 1.5 times the interquartile range). For analyses regarding the TSST data, four subjects were removed because their behavioral and/or physiological data were found to be outliers. All data reported are unadjusted mean values ± standard error of the mean (SEM).

## 3. Results

Baseline values for all mood questionnaires, cognitive tasks, and cortisol measurements were equal across groups (all $p > 0.05$). On average, the experimental group listened to the guided meditations 5.5 (± 0.16) times per week, whereas controls listened to their podcasts 6.4 (± 0.15) times per week, which was significantly different ($t(40) = 4.289$, $p < 0.001$).

### 3.1. The effects of 4 weeks of meditation (midpoint assessment)

None of the measures examined at the midpoint assessment of 4 weeks were significant, suggesting that 4 weeks of daily meditation does not affect mood, cognitive function, or cortisol levels.

### 3.2. The effects of 8 weeks of meditation on affect and cognition

#### 3.2.1. The overall model

The repeated measures MANOVA showed significant effects within our model ($\Lambda = 0.554$, $F = 4.558$, $p = 0.002$) for group * time * test (described in Section 3.2.).

#### 3.2.2. The effect of meditation on sleep quality

*3.2.2.1. Pittsburgh sleep quality index (PSQI).* A significant interaction was found in overall sleep quality (time * group $F(1,40) = 8.729$, $p = 0.005$, partial $\eta^2 = 0.179$) as measured by the PSQI (Fig. 1A; Meditation 4.905 ± 0.497 / 5.619 ± 0.741; Control 5.000 ± 0.473 / 3.619 ± 0.455. This effect was in the opposite direction as expected, with controls showing a significant improvement in sleep quality ($t(20) = 3.408$, $p = 0.003$) and meditators showing no change over time ($t(20) = -1.227$, $p = 0.234$). This effect was driven by poorer sleep efficiency (time * group $F(1,40) = 7.191$, $p = 0.011$, partial $\eta^2 = 0.152$; Meditation 0.095 ± 0.066 / 1.000 ± 0.293; Control 0.238 ± 0.118 / 0.238 ± 0.153), with meditators showing worse sleep efficiency ($t(20) = -3.189$, $p = 0.005$) and controls showing no change between the two time points ($t(20) = 0.000$, $p = 1.000$). At post-intervention, controls had a total PSQI score of 3.60 (± 0.46) whereas meditators had a total PSQI score of 5.62 (± 0.74), which qualifies on the PSQI as an index of poor sleep quality. We hypothesize that this effect may be due to the timing of meditation versus podcast listening. Compared to controls (42.4%), meditators listened to significantly more sessions (48.8%) before bedtime (defined as the hours of 8 P.M. to 3 A.M.) (Fig. 1B; $z = 2.632$, $p = 0.009$). As we hypothesized that this effect might influence the outcome of meditation on a variety of mood, stress, and cognitive variables, all proceeding statistics were assessed both with and without the use of the PSQI change score (total PSQI post-intervention minus total PSQI pre-intervention) as a co-variate.

#### 3.2.3. The effect of meditation on mood

*3.2.3.1. Profile of mood states (POMS).* The POMS is a scale that measures overall total mood disturbance, which is comprised of several subscales including tension/anxiety, depression/dejection, anger/hostility, fatigue/inertia, confusion/bewilderment, and vigor/activity (subtracted from the total of other combined scales). After adjusting for PSQI change score, a significant interaction effect was seen for the total mood disturbance score on the POMS (time * group $F(1,39) = 4.822$, $p = 0.034$, partial $\eta^2 = 0.110$) (Fig. 2A; Meditation 33.333 ± 5.795 / 19.095 ± 8.719; Control 23.238 ± 6.530 / 22.190 ± 6.169). Meditators showed a significant decrease (time $F(1,19) = 5.324$, $p = 0.032$, partial $\eta^2 = 0.219$) for total mood disturbance score whereas controls showed no change (time $F(1,19) = 2.11$, $p = 0.651$, partial $\eta^2 = 0.011$). This effect was driven by both anger/hostility (time * group $F(1,39) = 4.529$, $p = 0.040$, partial $\eta^2 = 0.104$; Meditation 7.190 ± 1.808 / 5.381 ± 2.097; Control 5.000 ± 1.366 / 6.667 ± 1.482) and confusion/bewilderment (time * group $F(1,39) = 4.458$, $p = 0.041$, partial $\eta^2 = 0.103$; Meditation 8.238 ± 1.040 / 5.905 ±

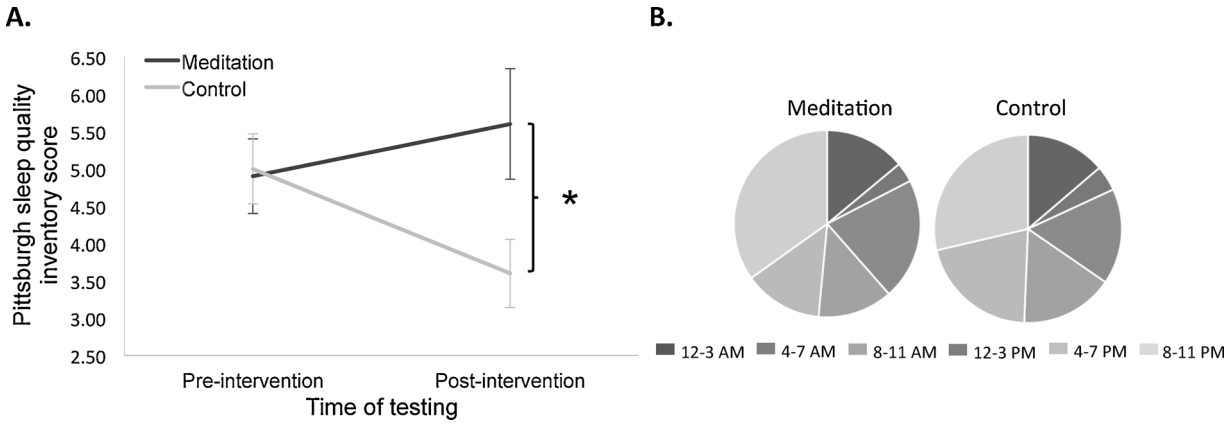


**Fig. 1.** (A) Data are presented as averages (± SEM) for the meditation and control groups both before and after the intervention. Eight weeks of meditation significantly impaired sleep quality as assessed by the Pittsburgh Sleep Quality Inventory (* represents a significant time x group interaction, $F(1,40) = 8.729$, $p = 0.005$, partial $\eta^2 = 0.179$). (B) Percentage of time spent listening to meditation or podcast sessions between the hours of 12–3 AM, 4–7 AM, 8–11 AM, 12–3 PM, 4–7 PM, and 8–11 PM. Compared to controls, meditators listened to significantly more sessions during the before bedtime hours (8 PM to 3 AM) ($z = 2.632$, $p = 0.009$).

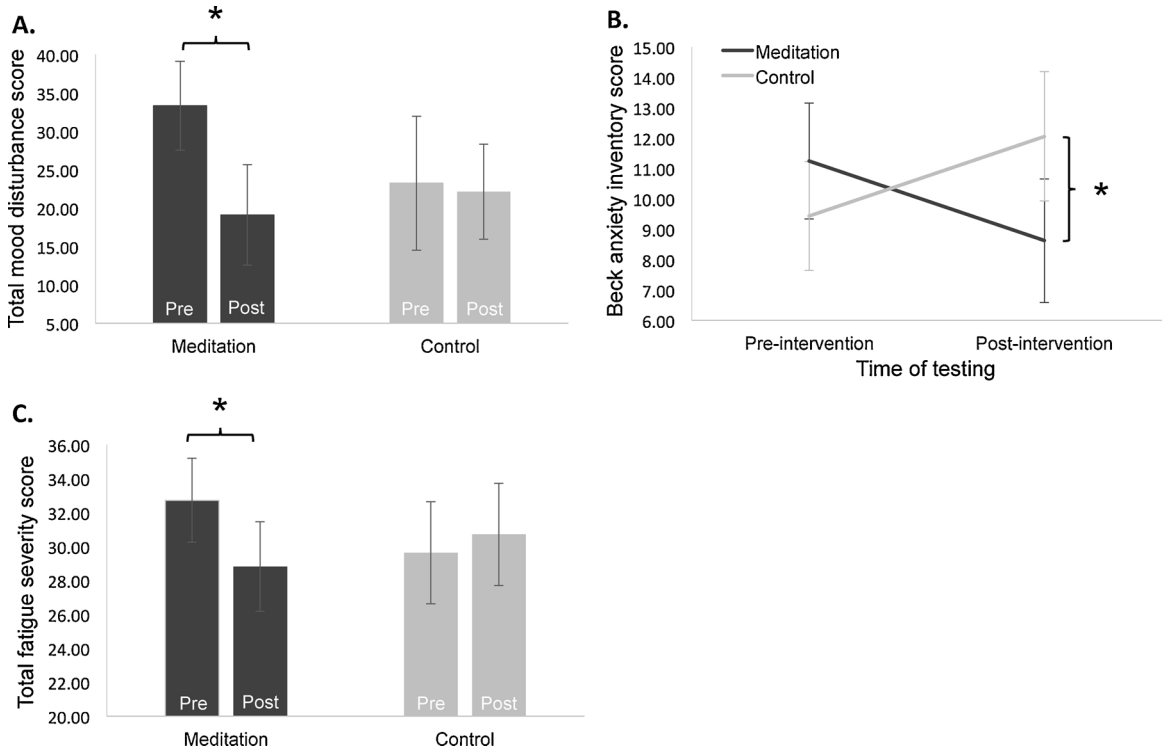


**Fig. 2.** Data are presented as averages ( ± SEM) for the meditation and control groups both before and after the intervention. Eight weeks of meditation (A) significantly decreased total mood disturbance as assessed by the Profile of Mood States (* represents a significant time effect, $F(1,19) = 5.324$, $p = 0.032$, partial $\eta^2 = 0.219$), (B) significantly decreased anxiety as measured by the Beck Anxiety Inventory (* represents a significant time x group interaction, $F(1,40) = 4.584$, $p = 0.038$, partial $\eta^2 = 0.103$), and (C) significantly decreased fatigue as measured by the Fatigue Severity Scale (* represents a significant time effect, $F(1,19) = 7.460$, $p = 0.013$, partial $\eta^2 = 0.282$).

1.108; Control 7.095 ± 1.019 / 7.000 ± 0.831) measurements.

*3.2.3.2. Beck anxiety inventory (BAI).* On this measure of anxiety, a significant interaction effect was seen for the BAI score (time * group $F(1,40) = 4.584$, $p = 0.038$, partial $\eta^2 = 0.103$) (Fig. 2B; Meditation 11.238 ± 1.906 / 8.619 ± 2.028; Control 9.429 ± 1.788 / 12.048 ± 2.128). Meditators showed a non-significant decrease in anxiety ($t(20) = 1.633$, $p = 0.118$) whereas controls showed a non-significant increase in anxiety ($t(20) = -1.418$, $p = 0.172$).

*3.2.3.3. Fatigue severity scale (FSS).* After adjusting for PSQI change score, a significant interaction effect was seen for scores on the FSS (time * group $F(1,39) = 7.023$, $p = 0.012$, partial $\eta^2 = 0.153$) (Fig. 2C; Meditation 32.714 ± 2.468 / 28.810 ± 2.640; Control 29.619 ± 2.996 / 30.714 ± 3.022). Eight weeks of meditation caused a significant decrease in total fatigue severity (time $F(1,19) = 7.460$, $p = 0.013$, partial $\eta^2 = 0.282$); however, no change was found for the control group (time $F(1,19) = 1.480$, $p = 0.239$, partial $\eta^2 = 0.072$).

No significant effects were found for any of the other mood questionnaires utilized.

*3.2.4. The effect of meditation on cognitive functioning*

*3.2.4.1. Stroop Color and Word Task.* Compared to podcast listening, meditation improved performance on this task. Specifically, a significant interaction effect was found for the percentage of congruent trials answered correctly (time * group $F(1,39) = 5.449$, $p = 0.025$, partial $\eta^2 = 0.123$) (Fig. 3; Meditation 97.23 ± 0.76 / 98.55 ± 0.36; Control 98.08 ± 0.48 / 97.41 ± 0.65). Meditators showed a near significant improvement ($t(20) = -2.024$, $p = 0.057$) whereas controls showed no change ($t(19) = 1.218$, $p = 0.238$). No significant interactions were found for percentage of incongruent trials answered correctly, reaction times on congruent or incongruent trials, or the interference score (reaction times on incongruent minus congruent trials).

*3.2.4.2. N-Back Task.* Compared to podcast listening, meditation improved performance on this test of short-term memory. Specifically, a significant interaction effect was found for the average percentage of trials answered correctly for all trials combined (0-, 1-, 2- and 3-back) (time * group $F(1,39) = 4.943$, $p = 0.032$, partial $\eta^2 = 0.112$) (Fig. 4; Meditation 62.35 ± 3.56 / 73.47 ± 3.70; Control 71.63 ± 2.53 / 73.49 ± 4.31). Eight weeks of meditation significantly improved short-term memory performance ($t(20) = -3.602$, $p = 0.002$), whereas controls showed no change over time ($t(19) = -0.604$, $p = 0.553$).

*3.2.4.3. Mnemonic Similarity Task.* Compared to podcast listening, meditation improved performance on traditional recognition memory, a process linked to the medial temporal lobe along with other regions of the frontal and parietal cortex [53]. Specifically, an interaction effect was found for the recognition memory score (time * group $F(1,40) = 4.261$, $p = 0.046$, partial $\eta^2 = 0.096$) (Fig. 5; Meditation 0.622 ± 0.050 / 0.661 ± 0.047; Control 0.655 ± 0.069 / 0.580 ± 0.059). Meditators showed a non-significant improvement in recognition memory ($t(20) = -1.227$, $p = 0.234$) whereas controls showed a non-significant detriment in recognition memory ($t(20) = 1.661$, $p = 0.112$). Primarily, this effect was driven by an increased capacity to identify previously viewed images (i.e., targets) as old (time * group $F(1,40) = 7.558$, $p = 0.009$, partial $\eta^2 = 0.159$; Meditation 42.095 ± 2.844 / 44.857 ± 2.785; Control 47.857 ± 2.618 / 42.857 ± 3.247). No significant interactions were found for the behavioral pattern separation score or for measures identifying similar images (i.e., lures) as similar or new images (i.e., foils) as new.

No significant effects were found for the Reading Span Task, Wisconsin Card Sorting Task, or Eriksen Flanker Task.

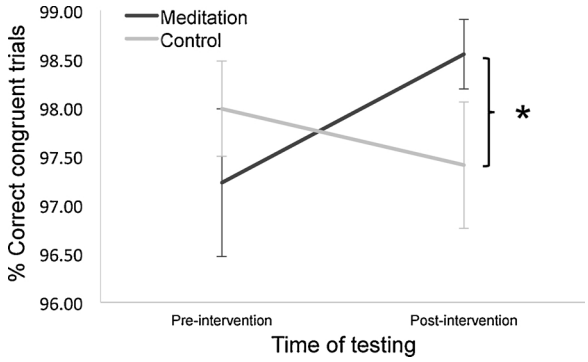


**Fig. 3.** Data are presented as averages ( ± SEM) for the meditation and control groups both before and after the intervention. Eight weeks of meditation significantly enhanced attention as assessed by accuracy (percent correct) on congruent trials of the Stroop Color and Word Task (* represents a significant time x group interaction, $F(1,39) = 5.449$, $p = 0.025$, partial $\eta^2 = 0.123$).

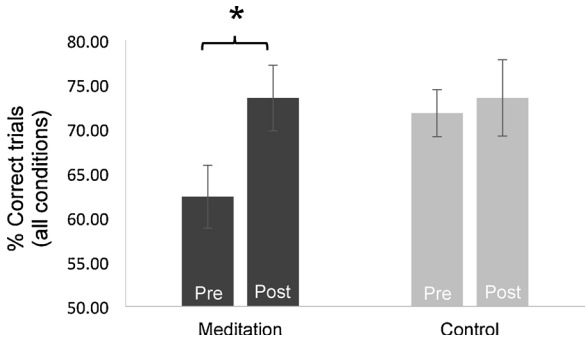


**Fig. 4.** Data are presented as averages ( ± SEM) for the meditation and control groups both before and after the intervention. Eight weeks of meditation significantly enhanced working memory as assessed by accuracy (percent correct) on 0-, 1-, 2-, and 3-back trials of the N-Back Task (* represents a significant difference using a paired samples t test, $t(20) = -3.602$, $p = 0.002$).

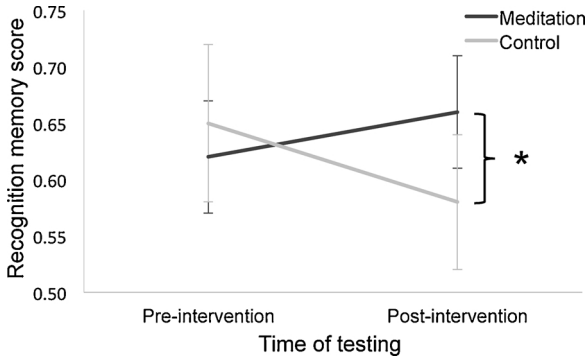


**Fig. 5.** Data are presented as averages ( ± SEM) for the meditation and control groups both before and after the intervention. Eight weeks of meditation significantly enhanced recognition memory as assessed by the Mnemonic Similarity Task (* represents a significant time x group interaction, $F(1,40) = 4.261$, $p = 0.046$, partial $\eta^2 = 0.096$).

### 3.3. The effect of meditation on baseline measures of stress and the response to acute stress

#### 3.3.1. Baseline cortisol measures

No significant interaction effect was found for baseline cortisol values (time*group $F(1,39) = 0.194$, $p = 0.662$, partial $\eta^2 = 0.005$; Meditation 4.457 ± 0.686 / 3.924 ± 0.504; Control 4.493 ± 0.646 / 4.305 ± 0.523), indicating no change in baseline cortisol values over time.

#### 3.3.2. Acute stress response

All TSST-related analyses were conducted using the PSQI change score as a co-variate. The TSST, a laboratory test that serves as a psychosocial stressor, increased state anxiety levels (state component score of the STAI) as measured from immediately before to immediately after the test (time $F(1,35) = 33.439$, $p < 0.001$, partial $\eta^2 = 0.489$). Additionally, a significant interaction effect was found for the state anxiety score between these two time points (time*group $F(1,35) = 4.128$, $p = 0.050$, partial $\eta^2 = 0.105$; Meditation 33.550 ± 2.271 / 39.200 ± 2.973; Control 35.444 ± 2.058 / 46.222 ± 3.190), with eight weeks of meditation significantly reducing the behavioral stress response to the TSST (Fig. 6A). State anxiety levels then continued to decrease for both groups through the final time point of testing (i.e., 30 min after the TSST). The TSST also increased saliva cortisol levels, with peak cortisol levels occurring at 10 min after completion of the TSST (time $F(1,35) = 16.589$, $p < 0.000$, partial $\eta^2 = 0.322$). Despite behavioral differences, no significant interaction effect was found for cortisol levels between time points immediately before the test to immediately after (time*group $F(1,35) = 2.323$, $p = 0.144$, partial $\eta^2 = 0.060$; Meditation 2.248 ± 0.265 / 2.273 ± 0.318; Control 2.912 ± 0.340 / 3.176 ± 0.360) or 10 min after the TSST (time*group $F(1,35) = 2.835$, $p = 0.101$, partial $\eta^2 = 0.075$; Meditation 2.248 ± 0.265 / 4.198 ± 0.619; Control 2.912 ± 0.340 / 3.944 ± 0.413) (Fig. 6B). Cortisol levels then continued to decrease for both groups through the final time point of testing.

### 3.4. The relationship between meditation-induced changes in the acute stress response, mood, and cognition

After determining that meditation enhanced mood (i.e., total mood disturbance, anxiety, and fatigue), cognition (i.e., attention, working memory, and recognition memory), and the response to acute stress, we sought to determine the relationship between these meditation-induced changes. To do this, we tested whether a differences existed in mood (z score) between meditation and control groups given differences in both the behavioral (i.e., TSST-induced changes in STAI score) and physiological (i.e., TSST-induced changes in saliva cortisol) measure of acute stress. The model (adj. $R^2 = 0.27$) showed a significant difference in mood change between meditators and control subjects ($F = 5.24$, $p = 0.028$). However, no significant relationship existed between the change in STAI score and mood ($F = 2.39$, $p = 0.131$), nor was the change in cortisol significantly associated with mood ($F = 2.41$, $p = 0.130$). Because this finding was surprising, the relationships of STAI and cortisol were further explored by regressing mood on STAI score and cortisol using the enter method. A significant overall correlation was found (adj. $R^2 = 0.181$, $F = 5.09$, $p = 0.011$), but only STAI score was a significantly correlated coefficient ($\beta = -0.33$, $t = -2.080$, $p = 0.045$) with mood, compared to cortisol ($\beta = 0.248$, $t = 1.565$, $p = 0.127$) (Fig. 7A). Therefore, the ANCOVA model was reduced to group given STAI score, which was significant (adj. R2 = 0.24) with a significant group difference ($F = 5.37$, $p = 0.026$), and a significant effect of STAI score ($F = 4.44$, $p = 0.042$).

In addition to testing mood differences, cognition (z score) was assessed using the same original ANCOVA model (cognition = group|ΔSTAI*ΔCortisol). This model (adj. $R^2 = 0.114$) showed significant differences between groups ($F = 7.42$, $p = 0.010$); however, no significant effects were found for either STAI ($F = 0.99$, $p = 0.326$) or cortisol change ($F = 0.33$, $p = 0.568$). When cognition was regressed on STAI score and cortisol, no significant effect was found for the overall model (adj. $R^2 = -0.053$, $F = 0.09$, $p = 0.911$), and no significant effects were found for either STAI score ($\beta = 0.048$, $t = 0.267$, $p = 0.791$) or cortisol ($\beta = -0.042$, $t = -0.234$, $p = 0.816$) (Fig. 7B). Therefore, we removed the covariates, and the one-way ANOVA for the change in cognition demonstrated statistical significance ($F = 8.44$, $p = 0.006$). In addition, no correlation existed between mood (z-score) and cognition (z-score).

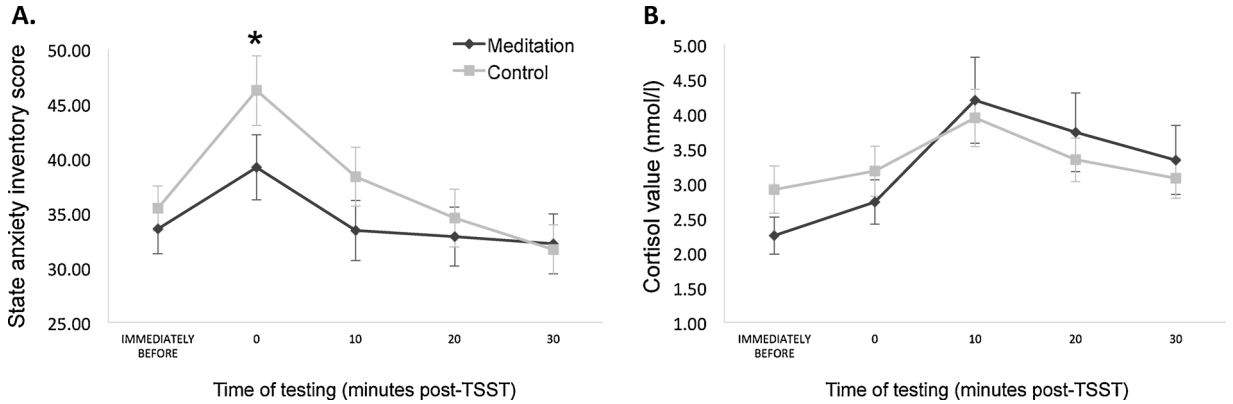


**Fig. 6.** Data are presented as averages ( ± SEM) for the time points immediately before, immediately after (0), and 10-, 20-, and 30-min after the Trier Social Stress Test, which served as a psychosocial stressor. Eight weeks of meditation (A) significantly decreased the behavioral response (as measured by the state component of the State-Trait Anxiety Inventory) to the TSST (* represents a significant time x group interaction, $F(1,35) = 4.128$, $p = 0.050$, partial $\eta^2 = 0.105$). (B) Cortisol values (nmol/l) in response to the TSST were similar between the two groups.

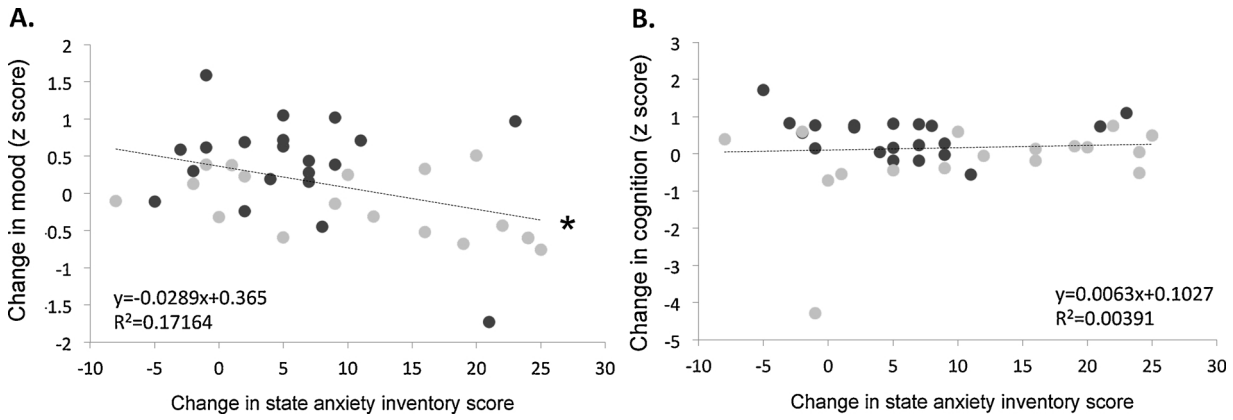


**Fig. 7.** These data graphs represent the relationship between changes in (A) mood state (z score including total mood disturbance, anxiety, and fatigue) or (B) cognition (z score including attention, working memory, and recognition memory) over the eight weeks of the intervention (post-intervention minus pre-intervention) and the behavioral response to the TSST (immediately after minus immediately before) for both meditation and control groups. Meditation-related changes in emotional regulation are more strongly related to benefits in mood than cognition. Those individuals who showed the largest improvements in mood displayed the lowest levels of anxiety in response to the TSST (* represents a significant correlation, (A) $r(38) = -0.414$, $p = 0.010$, (B) $r(38) = 0.062$, $p = 0.716$).

## 4. Discussion

Here we report that relative to a podcast-listening control group, 8 but not 4 weeks of a daily 13-min meditation resulted in decreased negative mood states including decreases in mood disturbance, anxiety, and fatigue scores, enhanced attention (as measured by the Stroop Task), working memory (as measured by the N-Back Task) and recognition memory (as measured by the recognition component of the Mnemonic Similarity Task), a decrease in the behavioral anxiety response to the TSST and surprisingly, a reduction in overall sleep quality. We also showed that those individuals who were best able to emotionally regulate in response to an acute stressor showed the largest decreases in negative mood states from the intervention. Finally, we found that meditation-related emotional regulation is more strongly linked to the benefits in affective state than cognitive function. These results add to the growing body of studies (e.g., [10,11,30,54]) showing that even short duration meditation sessions in naïve meditators exhibit a similar range of cognitive benefits as the effects previously reported following longer duration, more intense meditation training in both normal and clinical populations.

### 4.1. Meditation-induced changes in mood

Our finding that 8 weeks of brief daily meditation relieves feelings of negativity by decreasing levels of mood disturbance and anxiety are consistent with other studies showing that similar duration meditation programs provide decreased negative affect [4,55] and increased positive affect [5]. Similar findings have been reported for intense month-long meditation retreats [56], as well as in individuals with years of meditation experience [57], suggesting that a wide range of meditation intensity and durations have an overall positive effect on mood.

### 4.2. Meditation-induced changes in the stress response

We also showed that brief daily meditation enhanced emotional regulation by decreasing the behavioral response to an acute psychosocial stressor. While previous studies reported similar findings in experienced meditators [58] as well as with intensive long-term meditation programs [59] or intense, acute meditation interventions (3 days) [60,61], ours is the first to show these effects with a brief daily mediation practice. Furthermore, this is the first study to identify a significant correlation between the behavioral response to acute stress and changes in mood. Other studies have shown that meditation enhances emotional regulation by decreasing self-reported difficulty in emotional regulation [14], reducing emotional interference while viewing unpleasant pictures [13], and decreasing physiological reactivity while viewing a stressful film [1,62].

Previous studies have suggested that meditation may induce beneficial effects on emotional regulation through circuit-level changes involving the amygdala and prefrontal cortex. Using fMRI, researchers

found that while viewing emotionally charged images, novice meditators show a decrease in activation in the amygdala but an increase in activation of the prefrontal cortex [19]. This increase in prefrontal cortex activation was also shown in novice meditators during an affective Stroop Task [63]. This indicates that novice meditators may engage both bottom-up and top-down processes simultaneously to actively control stress and regulate their emotional state. On the other hand, expert meditators viewing emotional images show a decreased activation across a range of default mode network nodes including the medial prefrontal and posterior cingulate cortices [20]. This suggests that long-term meditative practices may lead to a state of emotional stability, whichis regulated by higher-order cognitive regions.

### 4.3. Meditation-induced changes in cognitive function

In addition to changes in mood and the stress response, eight weeks of brief daily mediation also improved performance on a range of cognitive tasks including accuracy on the congruent trials of the Stroop Task. That is, meditation enhances the ability to identify the color name when the color of the word matches the word presented, referred to as the Stroop facilitation effect. Researchers have hypothesized that this occurs because when the brain processes congruent (rather than incongruent) color and word information simultaneously, it can do so at a faster speed [64,65]. Facilitation is considered to be a measure of attention distinct from the Stroop interference effect [64], and like interference, is a process that relies on the anterior cingulate cortex [66]. Research has shown that individuals with better inhibitory control (as measured by reaction time on the stop-signal task) perform better on the congruent trials of the Stroop Task [67]. Though other studies have found that meditation enhances the Stroop interference effect [63,68], this is the first study to find that a brief meditation practice enhances facilitation. One other study found that meditation did not enhance the Stroop facilitation effect, but changes were assessed after only one 20 min-bout of meditation [69]. Other studies are consistent with our finding by showing that meditation enhances attentional awareness, especially in the area of conflict monitoring, through tasks such as the attention network test and the attentional blink test [10,70]. Electrophysiological studies suggest that meditation may be enhancing attention through neural mechanisms involving the error-related negativity signal, an event related potential that signals error detection and is associated with the anterior cingulate cortex and dorsolateral prefrontal cortex [71]. Future studies will need to assess the neural correlates underlying the meditation-induced improvements in facilitation.

Eight weeks of daily meditation also enhanced both working memory (as measured by the N-Back Task) and recognition memory (as measured by the recognition component of the Mnemonic Similarity Task). Consistent with our findings, previous studies have reported that meditation enhances performance on the N-Back Task [30] as well as the digit and operation span tasks, other tasks of working memory [4,30,72–74]. One previous study showed that increased meditation practice resulted in increased levels of grey matter volume in the frontal cortex, especially in the areas of the anterior cingulate cortex and medial frontal gyrus, suggesting a possible morphological correlate of these working memory improvements [75]. Fewer studies have investigated the effects of meditation on recognition memory. One study reported that approximately 10 min of meditation done both before encoding and before retrieval of a Remember-Know Task increased the ability to recognize previously seen images [21]. This study also showed that 10 min of meditation prior to reading a passage of text increased free recall memory of this text [21]. However, to our knowledge, ours is the only study to report that 8 weeks of brief daily meditation results in improved recognition memory. Previous studies have reported that meditators show greater gray matter concentration in the hippocampus and parahippocampal cortex as well as white matter tracts between the hippocampus and other brain regions [76–80]; however, these studies were conducted on long-term meditation practitioners (5 years or more of experience).

Other studies suggest that the improvements in attention, working memory and recognition memory performance observed here may be mediated at least in part by changes in resting state brain activity. For example, a number of studies have reported that a long-term meditation practice enhances resting state alpha and theta power [81,82]. These oscillatory brain states have been linked to both relaxation as well as cognitive functions, including attention, information processing, and learning and memory; collectively, enhancements in alpha and theta may lead to the “relaxed alertness” experienced after a meditation practice. Additionally, a resting state fMRI study showed that 5 h of meditation training over a period of 2 weeks enhanced resting state functional connectivity in a diffuse network of brain regions including the bilateral superior/middle occipital gyrus, bilateral frontal operculum, bilateral superior temporal gyrus, right superior temporal pole, bilateral insula, caudate, and cerebellum [11].

### 4.4. Meditation-related emotional regulation is more strongly linked to benefits in affective state than cognitive function

Though previous studies have found that brief mindfulness training enhances mood, cognition, and the response to acute stress, few studies have explored the interconnected nature behind these phenomena [30,83–86]. We found that meditation-induced changes in the response to acute stress are related to changes in affective state. That is, a heightened capacity for emotional regulation predicts the mood benefits from meditation. Furthermore, regardless of equivalent stress-induced increases in cortisol between the groups, meditators reported lower levels of anxiety in response to the TSST. This suggests that meditation may cause specific changes in the brain that modulate how we interpret and respond to physiological stress signals. One could imagine that the consistent positive behavioral responses to real life acute stressors conferred by meditation may help lead to overall more positive mood states. The relationship described above was not true for cognition, nor was the meditation-induced improvements in mood related to the improvements in cognition. These additional findings suggest that the cognitive benefits from meditation may have a different underlying mechanism than the mood benefits.

Previous research in this area has shown an association between self-reported mindfulness and affective state [87]. Specifically, high levels of mindfulness are associated with high levels of positive affect and low levels of negative affect, perceived stress, and depressive symptom severity [88]. Additionally, one randomized controlled trial study found that 8 weeks of Mindfulness-Based Stress Reduction training reduced perceived stress and vital exhaustion while enhancing positive affect, quality of life, and mindfulness [89]. Further, they found that mindfulness partially mediated the beneficial effects of meditation [89]. Our study adds to this research by showing that the larger the meditation-induced gains in the ability to cope with acute stress, the larger the benefits in affective state.

### 4.5. The neural correlates of meditation

Our behavioral findings, along with other functional, physiological, and morphological studies noted here, suggest that the practice of meditation may change brain regions that regulate mood, stress, and cognitive processes. One meta-analysis provided insight into the brain areas active during meditation [90]. Using activation likelihood estimation (ALE), the authors concluded that three key brain regions subserve the meditative state; namely, the basal ganglia (caudate), the entorhinal cortex (parahippocampal region), and the medial prefrontal cortex. These regions play a role in a variety of cognitive processes that are relevant for the meditative state including attentional awareness, response inhibition, emotional regulation, learning and memory, imagination, monitoring of thoughts, and self-referential thinking. These authors suggested that during the meditative state, the basal ganglia

contributes to the inhibition of irrelevant thoughts, the entorhinal cortex contributes to the control of the mental state, and the mPFC contributes to the enhanced sense of self-awareness [90]. It would be of interest to image these brain areas both before and after our 8 weeks of brief daily meditation to see if the specific brain regions or activation patterns change with improved performance.

### 4.6. Meditation and sleep quality

A surprising finding reported here was that brief daily meditation impairs sleep quality relative to control subjects. By contrast, other studies have reported that meditation improves sleep quality, especially in individuals with sleep disturbance issues [91–93]. This finding could be due to the fact that many of our study subjects completed their meditation sessions before bedtime. This may have caused them difficulty in falling asleep and affected their sleep efficiency, calculating by dividing the total number of hours slept by the total number of hours spent in bed. Many external factors influence sleep including stress, sleep environment, light (e.g., using the computer or watching television), medication intake, and food, caffeine, or alcohol consumption [94,95]. The majority of subjects completed their meditation sessions from 8 to 11 p.m., with some individuals completing their sessions from 12 to 3 a.m. Considering that subjects completed their sessions so late in the day and prior to bedtime, we hypothesize that they may have been performing other tasks late at night including completing homework, watching television, eating, drinking, or consuming alcohol, which may have affected their overall sleep quality. Despite our finding that meditators reported worse sleep quality, 8 weeks of meditation decreased levels of fatigue. Other studies of similar design have found beneficial effects of meditation on feelings of fatigue, but these have been primarily in patient populations [92,96–98]. This is one of the first studies to report that brief meditation training results in lower fatigue levels in non-patient populations.

### 4.7. Negative findings

Though our findings reveal a variety of meditation-induced improvements (i.e., decreased mood disturbance, anxiety, fatigue, and emotional response to a psychosocial stressor, as well as improved attention, working memory, and recognition memory), some of the neuropsychological tasks we assessed revealed no meditation-induced effect.

For example, meditation did not alter baseline levels of cortisol. Others have found that meditation significantly decreases baseline levels of cortisol [99–101]. Reasons for this may be methodological in nature. Cortisol levels are notoriously difficult to measure because of their circadian rhythm. Cortisol levels peak after waking and wane throughout the day until the onset of sleep, and then slowly rise again throughout the night. Because of the lengthy laboratory sessions and the varying subject schedules, cortisol collection times ranged from 11:00 A.M. to 8:00 P.M. For each individual subject, cortisol was collected at approximately the same time at each visit; however, in some instances collection time was not consistent. Because of this, SEMs were large and overlapped between the groups. Future studies should ensure a more constrained cortisol collection time period.

In addition, meditation did not alter the cortisol response to a psychosocial stressor, though self-reported measures of anxiety were decreased in the meditation compared to the control group. The TSST is a known psychosocial stressor that has been shown to reliably increase levels of saliva cortisol two to four times above baseline levels, with peak cortisol levels occurring from 15 to 20 min post-test [51,102]. Studies have shown that meditation has varying effects on the cortisol response to the TSST, ranging from a decrease [103], no change [103], or even an increase [61]; these differences appear to be dependent on the type of meditation and have been shown to occur in spite of a decrease in the perceived stress level, similar to the results of our study. Another possible reason for lack of between group differences may be due to the range of inter-individual differences to psychosocial stress [104], which again may have led to large SEMs and overlap between the groups. A few variables mediating these inter-individual differences include age, sex, sex steroid levels, genetic factors, diet, and caffeine and alcohol consumption [104]. In regards to the lack of relationship between the psychosocial stressor-induced changes in cortisol and changes in anxiety, a meta-analysis revealed that significant positive correlations between cortisol responses and perceived emotional stress was only found in 25% of studies [105]. They report that a variety of factors influence the relationship between the physiological and emotional outcomes of psychosocial response including sex, menstrual phase, brain morphology, hypothalamic-pituitary-adrenal axis and autonomic nervous system baseline characteristics, and personality traits such as social desirability, motivation for task engagement, emotion regulation and processing, and appraisal processes [105]. Others suggest that assessing levels of cortisol and self-reported measures of emotion during the TSST may be a more accurate or informative marker of the stress response than measures taken before or after the test [106]. The present study did not obtain measures during the test and future studies should think about incorporating an additional measurement during the test.

Finally, not all cognitive tasks showed an improvement with meditation. Specifically, meditation did not improve performance on the Reading Span Task, Wisconsin Card Sorting Task, Eriksen Flanker Task, or pattern separation component of the Mnemonic Similarity Task. In contrast to the tasks that show meditation-induced improvements (i.e., N-Back Task, Stroop Task, and recognition memory component of the Mnemonic Similarity Task), this highlights the idea that some neuropsychological tasks may be more sensitive than others in identifying cognitive improvements as they relate to meditation. A meta-analysis of 163 meditation studies revealed that the beneficial effects of meditation are strongest in areas of emotion (medium to large effect size), weaker in measures of attention (medium effect size), and weakest in other areas of cognitive functioning (small to medium effect size) [107]. Other reviews have noted that the most sensitive areas of cognitive function affected by meditation include attention, memory, verbal fluency, and cognitive flexibility, and suggest that meditation may be a good intervention for prevention of cognitive decline in the elderly [108]. A lack of effect may be seen in the above tasks for several reasons. First, the impact of meditation on these cognitive areas varies with the type of meditation practice (e.g., transcendental meditation or mindfulness meditation) along with the practitioner's previous meditation experience [107]. Second, some of our tasks such as the Eriksen Flanker Task were being performed at ceiling level (~95% percent correct); task difficulty may need to be increased in order to see an effect. Third, a longer, more intensive meditation period may be needed to see a functional change in specific tasks; that is, some tasks may be more sensitive at revealing meditation-induced cognitive changes than others. Finally, and specifically when we look at the Mnemonic Similarity Task, the finding that meditation improved recognition memory but not behavioral pattern separation may indicate that meditation may effect the brain in a region-specific manner (i.e., meditation may benefit a diverse network of brain regions supporting recognition memory such as the medial temporal, frontal, and parietal lobes along with the hippocampus [53], but not others such as the dentate gyrus subregion of the hippocampus that supports behavioral pattern separation [109].

### 4.8. Limitations

Mindfulness and meditation research is still in its infancy, only having begun in the 1970s; researchers in this field have suggested that this body of work suffers from methodological issues [110]. The current study is not without its limitations. First, individuals who choose to participate in meditation studies may be fundamentally different from those who do not choose to participate in these types of mindfulness

practices. Second, the high dropout rate may have biased the study results; however, analyses revealed that subjects in both groups did not differ on a variety of demographic variables including sex, race, ethnicity, education level, marital status, number of children, and household income. Third, the small sample size was not ideal, though an *a priori* power analysis confirmed that a sample size of 42 subjects was sufficient to find a statistically significant difference if one existed. A fourth limitation regards the self-reported measures collected to assess affective state; self-reported measures may not fully capture multifaceted psychological phenomenon and often do not align with information derived from implicit measures [111]. To limit this, we performed these self-reported measures in collaboration with neuropsychological assessment, psychosocial stress testing, and physiological measures (i.e., cortisol). Fifth, the fact that subjects logged into wistia to register their completion of the meditation or podcast listening sessions does not guarantee that they actually adhered to the protocol and engaged with the material. However, home training sessions are common in mindfulness research, and a recent meta-analysis across 43 studies (N = 1,427) revealed that on average, subjects completed 64% of their meditation sessions [112]. In our study, adherence for the meditation group was 78.6%, whereas adherence for the control group was 91.4%; values that are much higher than those in [112]. We predict that adherence would have been much lower if we required subjects to come into the laboratory to listen to their daily meditation or podcast sessions. Finally, this work utilizes one type of meditative practice, which is in the broader context of a range of mindfulness practices. Future research will be needed to expand and highlight the types of meditative practices that are most beneficial for enhancing psychological processes such as mood, stress regulation, and cognitive functioning.

### 4.9. Conclusions

Taken together, our results contribute to the establishment of the "minimum dose" of meditation that results in significant mood and cognitive benefits. Namely, we show that 8, but not 4, weeks of brief daily meditation is beneficial not only for decreasing negative mood state but for stress reduction, as well as the ability to pay attention to and remember information in the environment. Importantly, our study shows that 8 weeks of brief daily mediation in healthy adults can have a similar range of cognitive and mood benefits as has been seen in other studies using longer and/or more intense meditation training in naïve meditators, experienced meditators, or patient populations with depression or anxiety [113,114]. Moreover, these findings and others suggest a major target for the effects of meditation on the brain areas associated with and strongly influenced by the HPA axis, though the specific mechanisms by which meditation is working remain to be elucidated.

## Competing interests

The authors declare that there is no potential conflict of interest.

## Declaration of interest

None.

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