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Domain-Specific Enhancement of Metacognitive Ability Following Meditation Training

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Contemplative mental practices aim to enable individuals to develop greater awareness of their own cognitive and affective states through repeated examination of first-person experience. Recent cross-sectional studies of long-term meditation practitioners suggest that the subjective reports of such individuals are better calibrated with objective indices; however, the impact of mental training on metacognitive ability has not yet been examined in a randomized controlled investigation. The present study evaluated the impact of a 2-week meditation-training program on introspective accuracy in the domains of perception and memory. Compared with an active control group that elicited no change, we found that a 2-week meditation program significantly enhanced introspective accuracy, quantified by metacognitive judgments of cognition on a trial-by-trial basis, in a memory but not a perception domain. Together, these data suggest that, in at least some domains, the human capacity to introspect is plastic and can be enhanced through training.

Keywords: metacognition, meditation, introspection, training, cognitive ability

Through systematic examination of first-person experience, meditative practices across a variety of cultures and traditions aim to develop greater introspective awareness of cognitive, affective, and experiential states (e.g., Lutz, Dunne, & Davidson, 2007; Thompson, 2006; Wallace, 2006). Whereas modern scientific discourse has largely focused on the limitations of introspection (Nisbett & Wilson, 1977; Schooler & Schreiber, 2004), meditative traditions characterize introspection as a skill that can be improved through training (Lutz & Thompson, 2003). This perspective invites the empirical question of whether it is indeed possible to enhance introspective ability or whether an individual's introspective capacity is relatively invariant.

Preliminary evidence appears broadly supportive of a connection between meditation practice and introspective skill. Although a direct link between mental training and enhanced introspective ability remains to be established, cross-sectional studies comparing long-term meditation practitioners with control populations suggest that individuals with training in meditation can give more accurate reports of their visceral sensations, affective states, and ongoing performance on tasks. For example, experienced meditators show enhanced correspondence between introspective reports of the vividness of tactile stimulation at different points on the body and objective cortical and psychophysical measures of sensitivity (Fox et al., 2012). Furthermore, the reports of long-term meditators regarding their moment-to-moment emotional state have been shown to have better correspondence with objective measures of autonomic arousal (heart period) while watching emotionally engaging films (Sze, Gyurak, Yuan, & Levenson, 2010). Another study revealed no differences between experienced meditators and controls on a heartbeat detection task at rest, but the subjective accuracy ratings of advanced meditators were better calibrated with objective accuracy on the interoceptive task. Although the size of this effect was small, it provides preliminary evidence for the suggestion that individuals with experience in meditation practice may have more accurate metacognitive awareness of their own performance (Khalsa et al., 2008).

Together these studies lend support to the hypothesis that meditation training can lead to improvements in introspective skills; however, because all studies examining this question have used cross-sectional designs, it remains unclear whether the observed differences in introspective accuracy are directly attributable to meditation training rather than preexisting differences between groups (Davidson, 2010). It also remains unclear whether meditation training directly influences introspective mechanisms or whether it merely improves lower level perceptual or affective sensitivity. Specifically, an alternative account of the above findings is that meditation instead impacted sensitivity on the primary task, resulting in increased accessibility of visceral, emotional, or tactile information to higher level mechanisms. According to this hypothesis, meditation practice may not have influenced the capacity to reflect on experiential states, but rather boosted the signal

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available to those mechanisms. It is particularly important to consider this alternative hypothesis given that other studies have revealed that meditation training can increase perceptual and tactile acuity (Brown, Forte, & Dysart, 1984; Kerr et al., 2008; MacLean et al., 2010).

Recent computational advances allow introspective ability to be measured independently of an individual's sensitivity or accuracy on the primary task, enabling it to be objectively quantified across a range of cognitive contexts in a way that isolates it from these potential confounding influences (Barrett, Dienes, & Seth, 2013; Fleming, Weil, Nagy, Dolan, & Rees, 2010; Maniscalco & Lau, 2012). This approach uses psychophysical measures to quantify an individual's "metacognitive sensitivity," or their ability to discriminate between their own correct and incorrect judgments or behavior on a trial-by-trial basis (see Fleming & Dolan, 2012, for a review). Variance in performance can be controlled in this approach through either experimental design or computation (Barrett et al., 2013; Fleming et al., 2010; Maniscalco & Lau, 2012).

Studies using this method have revealed substantial variance in metacognitive ability among healthy adults and have linked this variance to individual differences in brain anatomy and connectivity (Baird, Smallwood, Gorgolewski, & Margulies, 2013; Fleming et al., 2010; McCurdy et al., 2013). Across this emerging literature, a convergence of evidence indicates that the anterior prefrontal cortex (aPFC/BA10) is a critical part of the neuroanatomical basis of introspective or metacognitive processes (e.g., Baird et al., 2013; Fleming & Dolan, 2012; Fleming, Huijgen, & Dolan, 2012; Fleming et al., 2010; McCurdy et al., 2013). This insight is important because structural changes in frontopolar cortices have also been linked to meditation training. Although morphometric studies of the effects of meditation practice have produced mixed and inconsistent results (e.g., Hölzel et al., 2011; Luders, Toga, Lepore, & Gaser, 2009), in part likely due to the diversity of practices under study and small sample sizes, a number of investigations have noted increased cortical thickness or gray matter density in aPFC/BA10 in meditation practitioners from a variety of traditions, including Insight (Vipassana) (Lazar et al., 2005), Zen (Grant, Courtemanche, Duerden, Duncan, & Rainville, 2010), Brain Wave Vibration (Kang et al., 2013), and the Dzogchen tradition of Tibetan Buddhism (Vestergaard-Poulsen et al., 2009) compared with control populations. Long-term meditation practitioners have also shown increased functional and structural connectivity of anterior prefrontal regions (Hasenkamp & Barsalou, 2012; Jang et al., 2011; Kang et al., 2013; Taylor et al., 2013). Additionally, a recent real-time functional magnetic resonance imaging neurofeedback training study indicates that individuals can learn to voluntarily modulate activity in aPFC through a metacognitive awareness strategy bearing strong similarities to some types of meditation practice (McCaig, Dixon, Keramatian, Liu, & Christoff, 2011). Together this evidence suggests that the functional and structural plasticity induced by some types of meditation training practices occurs in the brain regions involved in metacognitive function, providing a plausible neural basis for training-induced improvements in introspective ability.

The primary aim of the present study was to directly evaluate the impact of meditation training on metacognitive ability. Using a randomized controlled design coupled with psychophysical measures of introspective accuracy, we evaluated the impact of a 2-week meditation-training program on the accuracy of metacognitive reports in the domains of perception and memory. Our hypothesis was that meditation training would enhance the capacity to accurately reflect on one's own cognitive and experiential states, resulting in significant improvements in metacognitive ability from baseline.

Materials and Method

Participants

Fifty undergraduate students (17 men; mean age = 20.5 years, *SD* = 1.37) were randomly assigned to either a meditation class ($n = 26$) or a nutrition class ($n = 24$) using a mixed factorial pretest-posttest design. Several participants who completed the pretesting did not attend the courses (Meditation: $n = 1$; Nutrition: $n = 5$). Data from two participants on the memory task were excluded due to abnormal performance, with scores > 5 *SD*s from the group mean (d' near 0 of 0.06 and 0.08, respectively), and data from one participant on the perceptual task was excluded because she never stabilized the staircase (Levitt, 1971). Signed informed consent was obtained from all participants prior to completing the study, and ethical approval for the study was obtained from the University of California, Santa Barbara, Institutional Review Board. All participants had normal or corrected-to-normal vision and no history of neurological or psychiatric disease.

Nutrition and Meditation Courses

Following a training procedure reported previously (Mrazek, Franklin, Phillips, Baird, & Schooler, 2013), classes met for 45 min four times per week for 2 weeks and were taught by professionals with extensive teaching experience in their respective fields. The nutrition course was taught by an expert nutrition consultant and educator with a master's of science in Nutrition and additional specialty certifications. The meditation course was taught by D.T.P., a classically trained master meditation teacher and mindfulness expert with multiyear retreat experience who is the executive director of TICA, an organization dedicated to offering secular meditation training programs.

The meditation class emphasized the physical posture and mental strategies of focused attention (*śamatha*) meditation (Lutz, Slagter, Dunne, & Davidson, 2008; Wallace, 1999). During class, participants sat on cushions in a circle. Each class included 10–20 min of meditation exercises requiring focused attention to some aspect of sensory experience (e.g., sensations of breathing). Following the meditation exercises, participants shared their experiences with the class and received personalized feedback from the instructor. Class content was designed to provide a clear set of strategies for practicing meditation as well as a conceptual understanding of the practice. Classes focused on (a) sitting in an upright posture with legs crossed and gaze lowered, (b) using the breath as an anchor for attention during meditation, (c) repeatedly counting up to 21 consecutive exhalations, (d) distinguishing between naturally arising thoughts and elaborated thinking, (e) learning to recognize the occurrence of distracting thoughts and monitoring one's ongoing attentional state, and (f) allowing the mind to rest naturally rather than trying to suppress the occurrence of thoughts. Participants also completed 10–15 min of daily meditation outside of class. In order to gauge adherence to this requirement, participants submitted daily journals to the instructor in which they logged the start time and end time of their meditation session, rated their affective and attentional state during the practice, and noted their thoughts and reflections on the meditation session.

The control nutrition program covered fundamental topics in nutrition science and applied strategies for healthy eating. To match the time commitment of the daily meditation requirement, participants logged their daily food intake but were not required to make specific dietary changes. Participants submitted their food journals to the instructor at the start of each class.

Several aspects of the methodological design, particularly the control group, allow for confidence that any observed improvements in metacognitive ability were a direct result of the meditation training rather than a confounding element of the program or research design. First, participants understood that they would be randomly assigned to a training program, eliminating self-selection effects between conditions. Second, both classes were taught by expert instructors, were composed of similar numbers of students, were held in comparable classrooms during the late afternoon, and used a similar class format, including both lectures and group discussions. Third, all participants were recruited under the pretense that the study was a direct comparison of two equally viable programs for improving cognitive performance, which minimized motivation and placebo effects (Boot, Simons, Stothart, & Stutts, 2013). Finally, we minimized experimenter expectancy effects by testing participants in mixed-condition groups in which nearly all task instructions were provided by computers.

Participants completed a questionnaire at the beginning of the program that assessed their course preferences and at the end of the program that assessed their experience with the program and the instructor. Course preferences were assessed with the following two questions: “I have a strong interest in learning about meditation” and “I have a strong interest in learning about nutrition,” to which participants responded using a 6-point Likert scale that ranging from 1 (*strongly disagree*) to 6 (*strongly agree*). The program assessment questionnaire consisted of 12 items (e.g., “The program was beneficial,” “The program motivated me to change my behavior,” “The information in this program was useful,” “I would recommend this program to others”), to which participants responded using a 6-point Likert scale ranging from 1 (*strongly disagree*) to 6 (*strongly agree*). The instructor assessment questionnaire consisted of 15 items (e.g., “I found the instructor effective in communicating key concepts,” “The instructor appeared to have extensive knowledge of the subject matter,” “The instructor appeared to be well prepared,” “The instructor responded effectively to participants comments and questions”), and answer choices again consisted of those on a 6-point Likert scale ranging from 1 (*strongly disagree*) to 6 (*strongly agree*). Composite scores were computed by averaging across all items for each questionnaire.

Metacognitive Tasks

Tasks were programmed in MATLAB Version 7.9 using the Psychophysics Toolbox Version 3.0 (Brainard, 1997; Kleiner et al., 2007). A schematic outline of the tasks is shown in Figure 1. Task order was counterbalanced across participants, and tasks were completed in the same order during pretesting and posttesting.

The perceptual task was adapted from Fleming et al. (2010) and Song et al. (2011). Each trial presented a visual display of six Gabor gratings in a circle around central fixation (eccentricity of 6.5 visual degrees), followed by an interstimulus interval during which only the fixation cross remained on screen, followed by a second display of six Gabors arranged around fixation (see Figure 1A). Each grating subtended 2.8° and consisted of vertical alternating light and dark bars modulated at a spatial frequency of 2.2 cycles per visual degree at a contrast of 20%. Stimuli were presented in a darkened room at a viewing distance of approximately 60 cm. In one of the two displays, the orientation of one of the Gabors was tilted slightly from the vertical axis. The display interval in which this “pop-out” Gabor occurred as well as its spatial location varied randomly across trials. The orientation of the pop-out Gabor was adjusted using a 2-up 1-down adaptive staircase procedure (Levitt, 1971) designed to result in a convergence on 70% accuracy for individual performance. Two consecutive correct responses resulted in a reduction of the orientation parameter by one step (0.25 degree), whereas one incorrect response resulted in an increase of the orientation parameter by one step. Following the offset of the second stimulus presentation, participants made unspeeded two-choice discriminations as to whether the pop-out Gabor occurred in either the first or the second stimulus display. Participants then rated their confidence in the accuracy of their response on a scale ranging from 1 (*low confidence*) to 6 (*high confidence*) (Fleming et al., 2010).

The memory task consisted of two phases: encoding and recognition. Before beginning the encoding phase, participants were informed that a recognition phase would follow in which their memory for the presented words would be tested. During encoding, participants viewed 160 words randomly selected from the full set of 320 words presented sequentially in the center of the screen. Word stimuli consisted of neutral-valence noncomposite nouns selected from the Medical Research Council Psycholinguistic database (Wilson, 1988). All stimuli were five characters in length and had a word frequency between one and 800 per million. During recognition, participants were presented with each word from the full list of stimuli in a random order (half of which were presented during encoding and half of which were new) and were asked to make unspeeded two-choice discriminations as to whether the stimulus was old or new. Participants then rated their confidence in the accuracy of their response on a scale ranging from 1 (*low confidence*) to 6 (*high confidence*).

Quantification of metacognitive ability. Signal detection theory (SDT; Green & Swets, 1966) was used to compute estimates of metacognitive accuracy, here quantified as the ability of an individual to discriminate between their own correct and incorrect perceptual decisions or memorial judgments with confidence ratings on a trial-by-trial basis. A primary concern in any metacognitive (“Type II”) analysis is to separate estimates of Type II sensitivity from the potential confounding influence of sensitivity on the primary (“Type I”) task (e.g., Galvin, Podd, Drga, & Whitmore, 2003). *Type II sensitivity* refers to an individual’s ability to discriminate between their own correct and incorrect responses, whereas *Type I sensitivity* refers to an individual’s ability to discriminate between stimulus alternatives (i.e., their capacity to distinguish old items from new items in a recognition memory task) (Clarke, Birdsall, & Tanner, 1959; Higham, Perfect, & Bruno, 2009). SDT approaches can quantify metacognitive

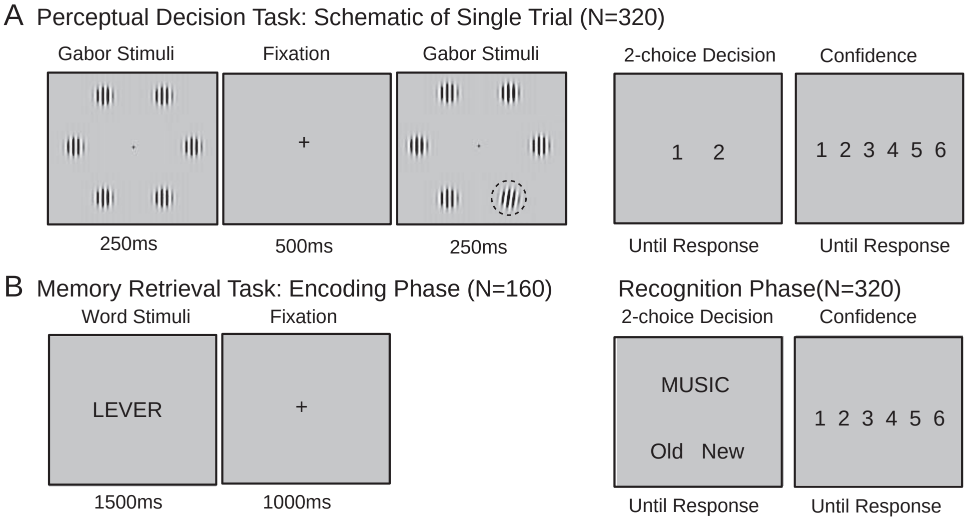

Figure 1. Experimental paradigm. Participants completed two tasks in a counterbalanced order during pre- and posttesting sessions. A: Perceptual discrimination task. Each trial ($N = 320$) consisted of a visual display of six Gabor gratings, followed by an interstimulus interval of 50 0ms, followed by a second visual display of six Gabor gratings. In one of the two displays, the orientation of one randomly selected Gabor patch was tilted slightly from the vertical axis (indicated here with a dashed circle that was not present in the actual display). The orientation angle of this pop-out Gabor was adjusted using a 2-up 1-down adaptive staircase procedure. Participants made unspeeded two-choice discrimination judgments as to whether the "pop-out" Gabor occurred in either the first or second stimulus display, then rated their confidence in the accuracy of their response on a scale ranging from 1 (*low confidence*) to 6 (*high confidence*). B: Memory retrieval task. The memory task consisted of a classic verbal recognition memory paradigm. During encoding, participants viewed 160 words randomly selected from a set of 320 words. During recognition, participants were presented with each word from the full list of stimuli in a random order (half of which were presented during encoding and half of which were new), and were asked to make unspeeded two-choice discrimination judgments as to whether the stimulus was old or new, and then rated their confidence in their response.

accuracy independently of an observer's decision strategy or cognitive ability on the primary task, which have been shown to confound other methods of estimating metacognitive ability (Maniscalco & Lau, 2012).

Metacognitive accuracy on the perceptual task was quantified using the computational methods outlined in Fleming et al. (2010). Because performance on the perceptual task is held constant with an online thresholding procedure, it is possible to compute a measure of metacognitive accuracy that is unconfounded by Type I performance directly from the empirical Type II receiver operating characteristic (ROC) curve. The Type II ROC curve reflects the relationship between the accuracy of visual discriminations and an observer's confidence ratings. To plot the ROC, p(confidence $= i \mid$ correct) and p(confidence $= i \mid$ incorrect) were calculated for each level of confidence i, transformed into cumulative probabilities and used to construct each x,y point on the empirical ROC curve (Fleming et al., 2010; Galvin et al., 2003). ROC curves were anchored at [0,0] and [1,1]. The Type II ROC curve thus reflects the probability of being correct for each level of confidence. An ROC curve that rises steeply off the diagonal axis indicates that the likelihood of being correct increases with increasing confidence level, whereas a flat ROC along the major diagonal indicates a weak relationship between confidence and accuracy. When several points on the Type II ROC are available, an empirical estimate of the area under the ROC may be obtained, yielding a nonparametric measure of Type II sensitivity (Kornbrot, 2006). The area under the Type II ROC curve (A_{roc}) when performance is held constant provides a robust estimate of metacognitive discrimination that is independent of bias and sensitivity. Type I sensitivity (d') was calculated as $d' = \mathrm{z(H)} - \mathrm{z(FA)}$, where z represents the inverse of the cumulative normal distribution and $\mathrm{H} = \mathrm{p(response} = 1 \mid \mathrm{interval} = 1)$ and $\mathrm{FA} = \mathrm{p(response} = 1 \mid \mathrm{interval} = 2)$.

Quantification of metacognitive accuracy in the memory task required a computational approach that explicitly accounts for Type I performance. A model-based SDT approach to account for variance in primary task performance in the computation of Type II sensitivity has recently been described and validated (Maniscalco & Lau, 2012; McCurdy et al., 2013). This method has been discussed at length elsewhere (Maniscalco & Lau, 2012). Briefly, the approach exploits the link between Type I and Type II SDT models to express observed Type II sensitivity at the level of the Type I SDT model (termed *meta* d'). Maximum likelihood estimation is used to determine the parameter values of the Type I SDT model that provide the best fit to the observed Type II data. A measure of metacognitive ability that controls for differences in Type I sensitivity is then calculated by taking the ratio of *meta* d' and the Type I sensitivity parameter d': $M_{\mathrm{ratio}} = meta\ d'/d'$. The most straightforward approach to computing M_{ratio} involves an equal variance SDT model in which the variances of internal distributions of evidence for categorizing an item as "old" or "new" in the Type I model are assumed to be equal. However, this assumption is violated for two-choice old/new recognition memory tasks (Mickes, Wixted, & Wais, 2007; Swets, 1986). We therefore computed M_{ratio} under an unequal variance SDT model, which uses the slope of the Type I zROC to infer the ratio of the standard deviations of the Type I distributions (s) underlying the two response categories and then holds this parameter constant in the estimation M_{ratio}. Type I sensitivity (d') was calculated as $d' = \text{z(H)} - \text{z(FA)}$, where z represents the inverse of the cumulative normal distribution, and H = p(response = old|stimulus = old) and FA = p(response = old|stimulus = new).

Results

Compliance with outside assignments in both programs was assessed with daily journals that were submitted to the instructor at the beginning of each class. Compliance for both groups was high: Of the 10 required assignments, participants in the meditation course submitted an average of 9.32 assignments, and participants in the nutrition course submitted an average of 9.53 assignments. No difference in compliance rate was observed between groups, $t(42) = 0.59$, $p = .56$.

The perceptual task was performed at an individually determined threshold using a 2-up 1-down adaptive staircase procedure that results in a convergence on 70% accuracy at the limit for individual performance (Levitt, 1971). Analysis revealed that performance accuracy was well controlled by the staircase for all participants at both pretesting ($M = 0.71$, $SD = 0.01$, range = 0.68–0.74) and posttesting ($M = 0.71$, $SD = 0.01$, range = 0.68–0.74). Performance on the memory task had similar mean accuracy (pretest: $M = 0.72$, $SD = 0.10$, range = 0.56–0.94; posttest: $M = 0.73$, $SD = 0.10$, range = 0.57–0.96).

Analysis confirmed that metacognitive ability in both the perceptual decision task (A_{roc}) and recognition memory task (M_{ratio}) were uncorrelated with Type I performance at both pretesting (A_{roc}: $r = .07$, $p = .67$; M_{ratio}: $r = -.21$, $p = .19$) and posttesting (A_{roc}: $r = .22$, $p = .16$; M_{ratio}: $r = -.29$, $p = .07$). Additionally, orientation discrimination threshold in the perceptual task was uncorrelated with perceptual A_{roc} (pretest: $r = -.03$, $p = .84$; posttest: $r = -.13$, $p = .41$). These results confirm that estimates of metacognitive ability were not confounded with either Type I sensitivity or variance in perceptual acuity.

We analyzed the effects of training on metacognitive ability using a mixed model analysis of variance, with condition (meditation vs. nutrition) entered as a between-subjects factor and testing session (pretesting vs. posttesting) entered as a within-subjects factor. We first evaluated how meditation training impacted metacognitive ability for memory (M_{ratio}) relative to the control group. We observed no main effect of pre–post performance when collapsing across training condition, $F(1, 40) = 0.25$, $p = .62$. More importantly, we observed a significant Condition × Session interaction for metacognitive ability for memory, $F(1, 40) = 4.98$, $p < .05$. Follow-up t tests indicated that meditation training led to increased metacognitive accuracy for memory ($p < .05$), whereas nutrition training had no effect ($p = .24$) (see Figure 2). Although our computational methods (see the Quantification of metacognitive ability section) and above results indicate that our measure of metacognitive ability was not confounded with Type I performance, in order to ensure that this effect was not driven by differences in Type I performance, we first tested the Condition × Session interaction for d' on the memory task. No significant interaction was observed, $F(1, 40) = 0.18$, $p = .67$, and no effect of training on memory d' was observed for either the meditation course ($p = .87$; pretest: $M = 1.38$, $SD = .67$; posttest: $M = 1.36$, $SD = .83$) or nutrition course ($p = .68$; pretest: $M = 1.25$, $SD = .68$; posttest: $M = 1.30$, $SD = .62$). Additionally, we compared the within-group correlations between changes in M_{ratio} (posttesting vs. pretesting) and changes in Type I performance (posttesting vs. pretesting) across training condition to ensure that they did not significantly differ between groups. No difference between within-group correlations was observed ($z = -0.77$, $p = .44$), and no relationship was observed between change in M_{ratio} and change in Type I performance for either training group (all ps > .05).

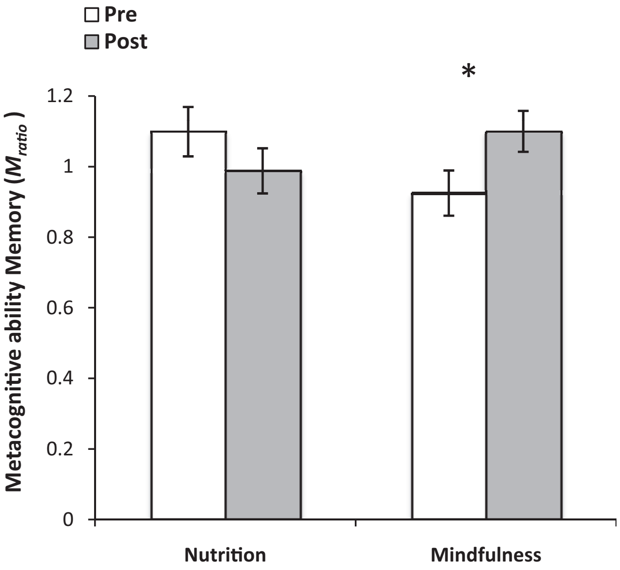

Figure 2. Meditation training enhanced metacognitive accuracy for memory, as revealed by a significant Condition × Session interaction, $F(1, 40) = 4.98$, $p < .05$. Error bars represent standard errors of the mean. Asterisk indicates significant differences between pre- and posttesting sessions ($p < .05$).

We next evaluated the impact of training condition on metacognitive ability on the perceptual task (A_{roc}). No main effect was observed, $F(1, 41) = 2.29$, $p = .14$, and no Condition × Session interaction was observed for metacognitive ability for perception, $F(1, 41) = 0.10$, $p = .75$. Not surprisingly, given that it was controlled by the adaptive staircase procedure, no main effect, $F(1, 41) = 0.05$, $p = .82$, and no interaction, $F(1, 41) = 0.23$, $p = .63$, was observed for d' for perceptual discriminations. Finally, no significant differences in baseline performance between training conditions for either A_{roc} or M_{ratio} were observed (all ps > .05).

Consistent with previous investigations (Brown et al., 1984; MacLean et al., 2010), we observed a trend toward an interaction between training program and perceptual threshold, $F(1, 41) = 2.91$, $p = .095$. Follow-up t tests indicated that meditation training led to a marginal decrease in perceptual threshold for orientation discrimination ($p = .097$; pretest: $M = 3.76$, $SD = 1.52$; posttest: $M = 3.34$, $SD = 1.24$), whereas no difference was observed for nutrition training ($p = .39$; pretest: $M = 3.67$, $SD = 1.43$; posttest: $M = 4.06$, $SD = 2.49$). We also found a significant main effect of confidence on the perceptual decision task, $F(1, 41) = 5.05$, $p = .03$, indicating a significant increase in confidence between pretesting and posttesting, but no significant interaction was observed with training condition, $F(1, 41) = 0.004$, $p = .95$. No main effect of mean confidence was found on the memory task or a significant interaction (all ps $> .05$).

Replicating our prior study (Baird et al., 2013), we also found that metacognitive ability for perception and memory were uncorrelated across individuals at both pretesting ($r = .01$, $p = .93$) and posttesting ($r = .04$, $p = .81$), indicating an intraindividual dissociation in metacognitive ability across process domains.

One limitation of the present study is that a higher number of participants who were assigned to the nutrition program did not participate in the classes. In all cases, these participants completed the pretesting and were randomly assigned to a course, but then either never showed up to the first class or attended the first class only and then stopped attending. We analyzed participant's post-participation assessment of the classes to determine whether this discrepancy was attributable to differences in how either the course or the instructor was perceived, but we found no differences in course ratings, $F(1, 44) = 0.91$, $p = .35$, or instructor ratings, $F(1, 44) = 0.20$, $p = .66$. This difference is therefore unlikely to be attributed to differences in class content, difficulty, or other similar variables pertaining to the quality of the training programs. Our data also indicate that it is unlikely to be attributable to differences in course preference. We observed no difference in course preference overall, $t(51) = 0.36$, $p = .72$, and analysis of course preferences for the group of participants who dropped out of the nutrition course or the mindfulness course also revealed no numerical or statistical differences (all ps $> .05$). Finally, our previous study (Mrazek et al., 2013) used a highly similar training program, and we did not observe any differences in participation rate between groups. Our data therefore suggest that the discrepancy in dropout rate is not attributable to motivation effects, differences in course preference between groups, or inconsistencies in class format or content.

Discussion

The present study is the first to demonstrate that meditation training, long hypothesized to develop an increased capacity to reflect on experience and thought (e.g., Lutz et al., 2007; Schooler & Mauss, 2010; Wallace, 2006), can objectively enhance metacognitive ability. Using a randomized controlled design, we found that a 2-week meditation program lead to significantly enhanced metacognitive ability for memory, whereas an active control group (nutrition training) showed no improvement. In contrast, there were no significant improvements in metacognitive ability for perceptual decisions for either training group. These results suggest that although meditation training can improve introspective accuracy in a domain that is outside of the training context, such improvements may not translate equally to all cognitive domains.

Our findings are consistent with several recent cross-sectional studies of long-term meditation practitioners, which revealed that individuals with advanced training in such practices were able to give introspective reports that showed a greater calibration with objective neural and physiological measures (Fox et al., 2012; Sze et al., 2010). Our results are also consistent with the strong overlap between the brain regions and networks that support metacognitive ability for memory and those influenced by meditation training. Specifically, metacognitive ability for memory is linked to enhanced functional connectivity in a network of regions including the medial aPFC, inferior parietal lobule (IPL), precuneus, and parahippocampal gyrus (Baird et al., 2013). As noted above, a number of studies have linked structural plasticity in anterior prefrontal regions to meditation training (Grant et al., 2010; Kang et al., 2013; Lazar et al., 2005; Vestergaard-Poulsen et al., 2009). Long-term meditation practitioners have also shown increased functional and structural connectivity of medial aPFC (Jang et al., 2011; Kang et al., 2013) and enhanced functional connectivity between medial aPFC and IPL specifically (Hasenkamp & Barsalou, 2012; Taylor et al., 2013). Furthermore, volume in the hippocampus, IPL, and posterior cingulate cortex (PCC) has been found to increase following an 8-week meditation course (Hölzel et al., 2011), and experienced meditators have larger hippocampal volume (Hölzel et al., 2008; Luders et al., 2009).

An intriguing possibility is that training-induced neuroplasticity in these regions may underlie the observed improvements in metacognition. However, at the present time, such an assertion remains highly speculative given that no study has evaluated how changes in introspective ability induced by meditation practice relate to changes in brain structure. From this perspective, it is also puzzling that we did not observe improvements in metacognitive ability on the perceptual task. Metacognitive ability in the perceptual domain is linked to activation and connectivity of the anterior cingulate cortex (ACC; Baird et al., 2013; Fleming & Dolan, 2012; Fleming et al., 2012), and the ACC is active during meditation practice (Hölzel et al., 2007); in addition, meditation experience has been associated with increased connectivity of the ACC (Brewer et al., 2011; Tang et al., 2010; Xue, Tang, & Posner, 2011). One possibility is that metacognitive accuracy in the perceptual domain may simply require more intensive training for enhancement. Another possibility is that even intensive meditation training influences introspective accuracy in a domain-specific fashion, which would provide evidence against the claim that meditation practice results in a generalizable increase in introspective awareness across process domains (see Fox et al., 2012, for discussion). Although the precise reasons for the disparate effects of meditation on perceptual and memory-based metacognitive skill are unknown, such differences are not particularly surprising given that the two abilities are uncorrelated and have distinct neural substrates (Baird et al., 2013; McCurdy et al., 2013). Future research might profitably explore whether more intensive interventions influence metacognitive ability in the perceptual domain, the reasons why it affects some domains more than others, as well as the mechanisms underpinning the beneficial effects of meditation on metacognitive processes.

In summary, we found that a 2-week meditation program enhanced introspective accuracy, quantified by metacognitive judgments of performance on a trial-by-trial basis, in a memory but not a perception domain. These results suggest that although enhancements of introspective ability derived from meditation are generalizable, they may not extend equally to all cognitive or experiential domains. Extending previous cross-sectional studies documenting improved introspective accuracy in long-term meditators (Fox et al., 2012; Sze et al., 2010), these findings provide the first evidence from a randomized controlled investigation that meditation training can directly influence the capacity to accurately reflect on cognitive states. Altogether, our results lend qualified support to the view that the human capacity to introspect, though imperfect, can nevertheless be trained.

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