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Multimodal Sustained Attention Superiority in Concentrative Meditators Compared to Nonmeditators

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Abstract Attention regulation plays a central role in both Buddhist and secular forms of meditation. One of the most common meditative practices is a concentrative meditation technique aimed at developing sustained focused attention. Despite a growing body of research showing meditation practice enhances various attention abilities, evidence of sustained attention benefits from meditation has been inconsistent. Also, most studies that tested meditators' sustained attention abilities used visual tasks. The extent to which the putative superior sustained attention in meditators might generalize to other stimulus modalities (e.g., auditory), and thus, whether meditation is associated with general attentional enhancement, is still unclear. Here, we compared regular meditators' sustained attention performance to nonmeditator controls using the response switching task (RST) in unimodal visual and auditory conditions (Exp 1) as well as bimodal visual-auditory conditions (Exp 2). The RST involves continuous responding to frequent stimuli and switching button-responses with an infrequent target stimulus. Errors in responding to the target signify difficulties in sustaining attention. Our main results showed that meditators made significantly fewer errors, indicating fewer attentional lapses in sustained attention, than nonmeditators across all unimodal and bimodal RST conditions, a finding that has not been reported before in previous studies. These findings provide further evidence of a positive association between meditators and enhanced sustained attention and new evidence that suggest that meditation is associated with general, modality nonspecific, enhancement of attentional control.

Keywords Meditation · Sustained attention · Visual stimuli · Auditory stimuli · Multimodal attention

The study of meditation has become increasingly popular in cognitive neuroscience in recent years, particularly within the field of attention (for reviews, see Lutz et al. 2008; Malinowski 2013; Raffone and Srinivasan 2010). Buddhist meditation practices, and secular meditative techniques drawn from Buddhism, focus on training attention regulation skills, which is believed to promote positive emotional control and well-being (Wadlinger and Isaacowitz 2011; Walsh and Shapiro 2006). In the research literature, meditation has been broadly categorized into two main types with different attention training regimes: focused attention (FA) meditation and open-monitoring (OM) meditation (Goleman 1996; Lippelt et al. 2014; Lutz et al. 2008).

FA meditation involves maintaining focused attention on a stimulus (such as an image, sound, or one's own breath) for an extended amount of time while suppressing mind wandering and distraction from competing stimuli. The aim of FA meditation is to cultivate calm and concentration. In contrast, OM meditation involves attentiveness to any thoughts or sensations that might arise moment to moment. The aim of OM meditation is to develop nonreactive, nonjudgmental open awareness of the content of experience. A major distinction between these two meditative practices is that FA meditation is essentially a sustained attention task given its highly concentrative nature involving a narrow attentional focus, whereas OM meditation involves monitoring any mental events without explicitly focusing on anything in particular.

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Although some meditators may only practice one meditation style, either FA or OM, meditators often incorporate both in their practice (Lutz et al. 2008; Malinowski 2013).

A growing body of research has shown a positive relationship between meditation and enhanced performance on various attention tasks. Compared to nonmeditator controls, regular meditators show better executive attentional control (Jha et al. 2007; Kozasa et al. 2012), less attentional blink (van Leeuwen et al. 2009), less change blindness (Hodgins and Adair 2010), and faster attentional orienting (Hodgins and Adair 2010; van Leeuwen et al. 2012). Previous research has also shown changes in attentional performance after meditation training (Slagter et al. 2007; Tang et al. 2007). For instance, Tang et al. (2007) found that novice meditators showed better executive attention performance in a conflict-monitoring task after practicing meditation 20 minutes per day for five days. Similarly, Slagter et al. (2007) found reduced attentional blink effects in novice meditators after they completed a three-month meditation training program.

Behavioral findings of enhanced attentional performance in meditators dovetail with evidence from several neuroimaging studies showing that meditation experience is associated with changes in neuronal activity (Brefczynski-Lewis et al. 2007; Hauswald et al. 2015; Hölzel et al. 2007; Jo et al. 2016; Lutz et al. 2004, 2009; Manna et al. 2010; Moore et al. 2012; Short et al. 2010; Slagter et al. 2007; Tang et al. 2009) and increased functional connectivity (Brewer et al. 2011; Hasenkamp and Barsalou 2012; Tang et al. 2010, 2012) among attention-related brain regions (for in-depth reviews of neuroimaging research on meditation, see Marchand 2014 and Tang et al. 2015). Taken together, these psychophysical and neuroimaging findings provide evidence that meditation, even with short-term practice (e.g., Tang et al. 2007, 2010), can alter behavioral performance and neural processes related to attention.

Interestingly, research on meditation and sustained attention, the ability to maintain focus of attention on a selected stimulus for prolonged periods of time (Sarter et al. 2001), has produced mixed results. Some studies show that meditation training is positively associated with enhanced sustained attention (Chambers et al. 2008; Lutz et al. 2009; MacLean et al. 2010; Morrison et al. 2014; Mrazek et al. 2012; Valentine and Sweet 1999; Zeidan et al. 2010). For example, Mrazek et al. (2012) found that subjects who completed only eight minutes of FA meditation (involving focused attention on breathing) before performing a sustained attention task outperformed subjects who spent the same time either reading or relaxing. However, other studies have failed to find an advantage for meditators in sustained attention compared to controls (Anderson et al. 2007; Cusen et al. 2010; Josefsson and Broberg 2011; Lykins et al. 2012).

These inconsistent findings warrant further investigation to establish a more complete understanding of how meditation impacts attentional processing, in particular sustained attention. Moreover, the study of sustained attention capacity of meditators has been dominated by the use of visual tasks. To date, only two studies have used auditory sustained attention tasks, and both found that meditators performed better than controls (Lutz et al. 2009 and Valentine and Sweet 1999). Together, these visual and auditory studies might suggest that meditation is associated with general, modality nonspecific, superior sustained attention. However, such a conclusion has not been directly established in an individual study. To our knowledge, no study has tested meditators' sustained attention to both visual and auditory stimuli, either in separate unimodal or crossmodal conditions. In sum, the questions of whether meditators show better sustained attention than nonmeditators and the extent to which meditators' putative superior sustained attention generalizes across sensory modalities are still unresolved.

The present study had two main goals. First, we sought further evidence of superior sustained attention in meditators compared to nonmeditators. Second, we extend this research to examine for the first time meditators' sustained attention performance in visual, auditory, and bimodal visual-auditory conditions. We conducted two experiments where we tested regular FA meditators' and nonmeditators' sustained attention to visual and auditory stimuli in separate unimodal conditions (experiment 1) and in bimodal visual-auditory conditions (experiment 2) using the response switching task (RST; Cheyne et al. 2009). No previous study assessing meditators' sustained attention has used the RST or examined meditators' sustained attention to stimuli across sensory modalities. It is important to note that we acknowledge that our study here is a correlational study. Thus, we cannot infer any causal relationship between meditation practice and sustained attention performance from our results.

Experiment 1

Method

Participants

Our meditation group consisted of 20 regular meditators (10 females) with a mean age of 37.6 years (SD 12.7) and an age range of 20–69 years. On average, these meditators had 6.6 years of meditative practice, practiced 5.8 times per week, and for 30.7 min per session. Only meditators who practice focused attention meditation were included in this study. The control group consisted of 20 subjects (13 females) with no prior experience with any meditation practice with a mean age of 38.3 years (SD 15.2) and an age range of 22–65 years. The control subjects were gender-, education-, and age-matched with the meditators as closely as possible (see Table 1).

Table 1 Demographic characteristics of participants

	Experiment 1			Experiment 2		
	Meditators	Controls	t or χ^2	Meditators	Controls	t or χ^2
N	20	20		18	18	
Mean age in years (range)	37.6 (20–69)	38.3 (22–65)	$t = 0.167$ ns	35.1 (20–55)	32 (20–52)	$t = 0.87$ ns
Females/males	10/10	13/7	$\chi^2 = 0.39$ ns	9/9	11/7	$\chi^2 = 0.2$ ns
Education (SD)*	2.65 (0.75)	2.45 (0.88)	$t = 0.77$ ns	2.61 (0.69)	2.72 (0.67)	$t = 0.49$ ns
Mean years meditation practice (SD)	6.6 (7.3)	–	–	4.3 (3.6)	–	–
Mean meditation sessions/week (SD)	5.8 (3.8)	–	–	6.5 (4.4)	–	–
Mean minutes/meditation session (SD)	30.7 (13.03)	–	–	32.8 (21.4)	–	–

Between-group statistical tests (t test and χ^2) showed no significant differences between meditators and controls for any of the demographic characteristics in both experiments

*Education level was scored on the following scale (similar to MacLean et al. 2010): 1 = high school diploma; 2 = some postsecondary; 3 = university degree

However, previous evidence has shown that gender, age, and education have a minimal effect on sustained attention performance assessed by the Sustained Attention to Response Task (SART; Chan 2001). Note that the RST is a nearly identical variant of the SART, with the only major difference being that subjects switch their response to press a different button in the RST rather than withhold their response as in the SART when the target is presented. The majority of controls and meditators were age-matched to within four years of each other, which is similar to age matching in other meditation and attention studies (e.g., Lykins et al. 2012). All subjects self-reported normal or correct-to-normal vision and normal hearing.

Procedure

Meditators were recruited from meditation centers across the Wellington city region via visits to some meditation centers and posting recruitment flyers at others. Nonmeditators that made up the control group were a mixture of students and nonstudents recruited via recruitment flyers posted around Victoria University of Wellington campus and local businesses around Wellington as well as advertisements in local newspapers. Subjects received a movie voucher for their participation.

Sustained attention performance was assessed using the RST. The RST is an attentionally demanding monotonous, repetitive task designed to assess transient lapses in sustained attention. Subjects make continuous button-press responses to a rapid stream of stimuli (e.g., numbers on a computer screen), but switching response to a different button whenever an infrequent target appears (e.g., the number 3). Response error rate is the main measure of lapses in sustained attention. Due to the immediate demands of the task, the RST provides information on the moment-to-moment fluctuations in sustained attention because even extremely brief attention lapses rapidly lead to an increased likelihood of errors. Thus, the RST is more sensitive to brief attention lapses than conventional vigilance tasks where subjects only respond to an infrequent stimuli presented at random intervals, like the tasks used in most of the previously cited studies that assessed meditators' sustained attention (e.g., Anderson et al. 2007; Lutz et al. 2009; MacLean et al. 2010).

Other studies testing meditators' sustained attention (Cusen et al. 2010; Josefsson and Broberg 2011; Morrison et al. 2014; Mrazek et al. 2012) have used the SART (Robertson et al. 1997). The RST is a variant of the SART; the major difference between the two tasks is that the SART is essentially a GO/NOGO task where subjects withhold their response when the target stimulus is presented. We preferred the RST because, as noted by Seli et al. (2012b), the SART is susceptible to the possibility of misidentifying a lack of a response during a NOGO trial as a correctly inhibited response—and therefore as no failure in sustained attention—when a subject momentarily has an attentional failure and ceases responding to all stimulus occurrences around the time of the NOGO trial. We avoid this possibility by using the RST because subjects are required to respond to all stimuli, but switch their button-press response to target stimulus.

Figure 1 shows the general experimental paradigm of the visual RST, which was similar to Cheyne et al. (2009, 2012). Subjects were required to make rapid button responses to a pseudorandom stream of single digits ('1' to '9') presented on a computer screen. Each digit was presented for 250 ms and followed by a 900-ms mask ('&' symbol) until the next digit for a 1150-ms digit-to-digit SOA. Subjects were instructed to press the same computer key (the 'default' button) in response after every digit presentation except for the digit 3. When the digit 3 (the switch target) was presented, subjects had to switch their response to press a different key (the 'switch' button). The left and right arrow keys were used as the default and switch buttons, counterbalanced between subjects. Cheyne et al. (2012) found that there was no

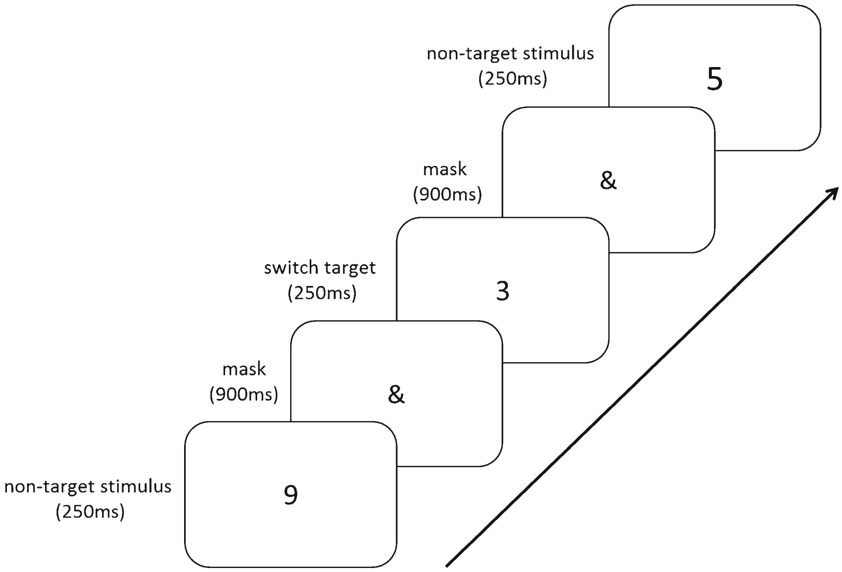

Fig. 1 General experimental paradigm of the visual response switch task in experiment 1. A pseudorandom stream of single digits ('1' to '9') was presented on a computer screen. Digits were presented for 250 ms and followed by a mask (an '&' symbol) for 900 ms. Digit font size was randomly varied and is not shown to scale here. Subjects responded to all nontarget stimuli (all digits except '3') by pressing either the left or right arrow key (counterbalanced between subjects) and responded to the switch target ('3') by pressing the opposite arrow key. The switch target had a 20% probability of occurring

difference in RST performance between responding using two fingers from only one hand and responding with one finger from each hand. Therefore, subjects were permitted to use either ways of pressing the response buttons in a manner they found most comfortable.

There were a total of 1000 digit presentations, 200 of which were the switch target, resulting in a 20% probability of the occurrence of the switch target. The switch target was pseudorandomly presented so that there was an equal probability of 1, 3, 5, or 7 nontarget stimuli between every presentation of the switch target. Targets were never presented immediately after another target. Stimuli were presented in Times New Roman font and in one of four randomized font sizes to ensure subjects did not identify stimuli based on their familiar features (similar to Robertson et al. 1997).

The auditory RST was similar to visual RST except that the target and nontargets were auditory stimuli presented over headphones. The nontarget stimuli consisted of eight different pure tones ranging between 350 and 950 Hz in intervals of 75 Hz with the exception of the 650-Hz tone. The switch target was a white noise burst. We chose a white noise burst as our target because we wanted the target to be more distinct and easier to identify than another pure tone. All auditory stimuli were presented for 250 ms with a 1150-ms SOA, same as in the visual RST. Subjects responded to the nontargets (the pure tones) by pressing the default response button and to the switch target (the white noise burst) by pressing the switch response button. To avoid visual distractions with items in the testing room, subjects were asked to maintain their gaze on a fixation-cross presented centrally on the computer screen throughout the task. The total number of stimuli and probabilities of the switch target's occurrence was the same as in the visual RST.

The experiment was run on a Dell Precision T1650 3.30-GHz personal computer. Stimulus presentation and data recording were controlled by the Psychopy experiment builder software package (Peirce 2007). Visual stimuli were presented on a 23-in 120-Hz Samsung LCD monitor. Auditory stimuli were presented over headphones. Subjects' heads were stabilized using a chin and forehead rest mounted 60 cm from the computer screen. Subjects performed a practice block of trials to get acquainted with the task. Meditators and controls performed both the visual and auditory RSTs, and the order of the tasks was counterbalanced between subjects. All subjects were run in a dimly lit private room. Subjects were not given an opportunity to practice meditation immediately prior to testing after they arrived at the laboratory.

Measures

Before testing, all meditators completed a short questionnaire to assess their meditative history and classify their meditative practice, which was a combination of questionnaires used in other previous meditation studies (Grant et al. 2010; Valentine and Sweet 1999). The questionnaire asked them about the number of years practicing, frequency of meditative practice per week, and length of individual sessions in minutes (Grant et al. 2010). The questionnaire also included the same questions from Valentine and Sweet (1999) to classify meditators as either focused-attention meditators (those that agree with the statements ‘I focus my attention as far as possible to a single point—a mental image, a perceptual object, breath, sound, or thought’ and, ‘I try and concentrate solely on this one item to the exclusion of everything else’) or open-monitoring meditators (those that agree with the statements ‘I expand my attention/awareness to as many possible events as possible. I consider nothing to be a distraction. Any new event physical or mental is considered by me to be part of my meditation’). Only meditators that agreed to the first set of questions indicating focus-attention meditation practice and disagreed with the second set of questions indicating open-monitoring mediation practice were included in this study.

Our main measure of RST performance was error rate, which were identified as default button responses when the switch target (the digit 3 in the visual RST and white noise burst in the auditory RST) was presented. We also measured reaction time (RT) to ensure any differences in error rate between the meditators and controls were not due to potential speed-accuracy trade-off effects and ensure performance was comparable to other RST studies (e.g., Cheyne et al. 2009, 2012). Consistent with these previously cited RST studies, RT was measured for all possible responses subjects could make: *default RT* for correct responses to nontarget stimuli, *switch RT* for correct responses to the switch target, *error RT* when pressing the default button when the target was presented, and *false alarm RT* when pressing the switch response button when a nontarget was presented.

Data Analyses

Our main analysis of interest was comparing the error rates between the meditators and nonmeditator controls in each task. Error rate was the percentage of times subjects pressed the default response button when the switch target was presented. For each task, an independent t test analysis was conducted to compare error rates between meditators and controls. To evaluate the extent to which visual and auditory RST performance was related, correlation analyses (Pearson r) were conducted on the error rates between the visual RST and the auditory RST separately for both meditators and controls.

To evaluate potential differences in RT between the groups and response types, RTs were analyzed using a mixed design analysis of variance (ANOVA) with *group* (meditator versus controls) as the between-group factor and *response type* (default, error, and switch) as the within-group factor. Consistent with previous RST studies (Cheyne et al. 2009, 2012), the frequency of false alarms was very rare for both meditators (visual RST: $M = 5$, SD = 7.03; auditory RST: $M = 2.72$, SD = 2.82) and controls (visual RST: $M = 4.23$, SD = 7.28; auditory RST: $M = 3.42$, SD = 3.15). Thus, as in these previously cited RST studies, false alarms were not included in the RT data analyses. For all analyses, a p value of 0.05 was adopted for significance.

Results

The overall results of the error rates of meditators and controls in both the visual RST and auditory RST are summarized in Table 2. Our main results show that meditators had lower error rates than controls, indicating meditators had fewer lapses in sustained attention. In the visual RST, meditators’ mean error rate ($M = 15.7\%$, SD = 12.1) was significantly less than controls’ ($M = 26.6\%$, SD = 16.1), $t_{(38)} = -2.42$; $p = 0.02$, $d = 0.79$. Interestingly, our control group’s error rate was remarkably similar to Cheyne et al. (2012); their subjects’ mean error percentage was about 29%. Similarly, in the auditory RST, meditators’ mean error rate ($M = 7.6\%$, SD = 6.7) was significantly less than controls’ ($M = 14.6\%$ SD = 9.9), $t_{(38)} = -2.63$; $p = 0.012$, $d = 0.85$. Correlation analyses on error rates across tasks for each group revealed significant correlations for meditators ($r = 0.51$, $p = 0.02$) and controls ($r = 0.72$, $p < 0.01$), indicating consistent performance across modality conditions.

Table 3 summarizes each group’s mean RTs for each response type (default RT, error RT, and switch RT) in both the visual RST and auditory RST. A visual inspection of the RT data for the visual RST in Table 3 shows meditators and controls appear to have similar RTs with the switch RT as the slowest. These observations were confirmed by a mixed design ANOVA with group as the between-group factor and response type (default, error, and switch) as the within-group factor. The ANOVA results are summarized in Table 4. No significance was found for the group factor ($F_{(1,\ 38)} = 0.002$; $p = 0.97$) and the group × response type interaction ($F_{(2,\ 76)} = 0.34$; $p = 0.71$), indicating that the groups’ RTs were statistically the same. The main effect of response type was significant ($F_{(2,\ 76)} = 15.23$; $p < 0.01$, $\eta_p^2 = 0.29$). Tukey’s post hoc tests revealed that switch RT was significantly longer than both default RT and error RT (both comparisons $p < 0.01$), consistent with Cheyne et al. (2012).

We conducted the same mixed design ANOVA (group × response type) for the RT data in the auditory RST. Similar to the visual RT results, the response type main effect was significant ($F_{(2,\ 76)} = 8.63$; $p < 0.01$, $\eta_p^2 = 0.19$); Tukey’s post hoc tests revealed that switch RT was significantly longer than both default and error RT (both comparisons $p < 0.01$). The group × response type interaction was not significant ($F_{(2,\ 76)} = 0.36$; $p = 0.69$). Unlike the visual RST results, the main effect of group was significant ($F_{(1,\ 38)} = 5.93$; $p = 0.02$, $\eta_p^2 = 0.13$), indicating that controls were overall faster than meditators.

The group differences in error rate and overall RT in the auditory RST could indicate a speed-accuracy trade-off. To investigate this issue, we first conducted three separate t tests

Table 2 Summary of error rates and *t* tests comparing meditators and controls in Exp 1 and Exp 2

	Meditators		Controls		*df*	*t*	*p*	Cohen's *d*
	M	SD	*M*	SD				
Experiment 1								
Visual RST	15.7	12.1	26.6	16.1	38	− 2.42	0.02	0.79
Auditory RST	7.6	6.7	14.6	9.9	38	− 2.63	0.012	0.85
Experiment 2								
Bimodal 1 RST	4.3	7.9	13.9	11.7	34	− 2.87	< 0.01	0.96
Bimodal 2 RST	14.8	15.1	29.7	16.8	34	− 2.79	< 0.01	0.93

to directly compare the RTs between meditators and controls for each response type. All of the *t* tests were not significant: for default RT ($t_{(38)} = 1.51$; $p = 0.14$), error RT ($t_{(38)} = 1.67$; $p = 0.1$), and switch RT ($t_{(38)} = 1.6$; $p = 0.12$), indicating that meditators' and controls' RTs were statistically the same when each response type was analyzed separately.

Despite these nonsignificant *t* test results, we still calculated the effect sizes (Cohen's *d*) in RT between meditators and controls for each response type and compared these Cohen's *d* values to the auditory RST error rate effect size ($d = 0.85$). This method of comparing RT and accuracy effect sizes to determine potential speed-accuracy trade-off effects is similar to previous studies (e.g., Lykins et al. 2012). It has been shown that when accuracy is high, as it was for both groups in the auditory RST, speed-accuracy trade-off effects are typically characterized as relatively larger changes in RT to produce small differences in error (McCormick and Francis 2005; Wickelgren 1977), which is not the case here as supported by the smaller Cohen's *d* for the RTs, in default responses ($d = 0.47$), in error responses ($d = 0.53$), and in switch responses ($d = 0.51$), compared to the error rate effect size ($d = 0.85$).

Table 3 Reaction times (ms) for each response type in Exp 1 and Exp 2

	Meditators		Controls	
	M	SD	*M*	SD
Experiment 1				
Visual RST				
Default	401	60	386	76
Error	377	142	395	155
Switch	492	66	486	104
Auditory RST				
Default	523	108	483	46
Error	528	189	449	110
Switch	607	90	557	108
Experiment 2				
Bimodal 1 RST				
Default	457	103	418	75
Error	401	205	394	244
Switch	459	78	446	113
Bimodal 2 RST				
Default	388	64	333	34
Error	419	175	390	207
Switch	542	96	477	55

Moreover, as previous researchers have pointed out (Cheyne et al. 2011; Seli et al. 2012b), although continuous perceptual-motor tasks like the RST we used here are susceptible to speed-accuracy trade-off strategies, lapses in attention can still occur during such strategic responding. Taken together, although we acknowledge that we cannot completely rule out the possibility of a speed-accuracy trade-off in the auditory RST results, we argue that there is no clear evidence of a speed-accuracy trade-off and that any potential speed-accuracy trade-off was at most minimal such that it does not jeopardize our main results that meditators' sustained attention performance was better than nonmeditators.

In sum, the main results of experiment 1 show that regular meditators made significantly fewer errors than nonmeditators in both unimodal visual and auditory versions of the RST. These findings are consistent with previous studies showing superior sustained attention performance in meditators (Chambers et al. 2008; Lutz et al. 2009; MacLean et al. 2010; Morrison et al. 2014; Mrazek et al. 2012; Valentine and Sweet 1999; Zeidan et al. 2010). More importantly, our results extend these cited studies by also showing evidence that superior sustained attention associated with meditation practice is not limited to stimuli from one modality.

Experiment 2

Method

Participants

As in experiment 1, we compared regular FA meditators to nonmeditator controls. The participants consisted of eighteen regular meditators (9 females) with a mean age of 35.1 years (SD 11.3) and an age range of 20–55 years. On average, meditators had 4.3 years of meditative practice, practiced 6.5 times

Table 4 Summary of ANOVA results of group and response type for reaction times in Exp 1 and Exp 2

	Source	SS	*df**	*F*	*p*	η_p^2
Experiment 1						
Visual RST	Group	28.1	1, 38	0.0016	0.97	0.000
	Response type	262,546	2, 76	15.23	< 0.001	0.29
	Group × Response type	5896	2, 76	0.34	0.71	0.009
Auditory RST	Group	95,768	1, 38	5.93	0.02	0.13
	Response type	201,537	2, 76	8.63	< 0.001	0.19
	Group × Response type	8470	2, 76	0.36	0.69	0.009
Experiment 2						
Bimodal 1 RST	Group	10,726	1, 34	0.37	0.54	0.011
	Response type	58,535	2, 68	1.87	0.16	0.052
	Group × Response type	5511	2, 68	0.18	0.84	0.005
Bimodal 2 RST	Group	68,038	1, 34	3.59	0.08	0.093
	Response type	418,176	2, 68	15.76	< 0.001	0.32
	Group × Response type	6635	2, 68	0.25	0.78	0.007

Group: between-group factor between meditators versus controls. Response type: within-group factor of default, error, and switch responses. **df* = (factor, error)

per week, and 32.8 min per session. Only meditators who practice focused attention meditation were included in this study. There were eighteen control subjects with no prior experience with any meditation practice (11 females) with a mean age of 32 years (SD 11.2) and an age range of 20–52 years. As in experiment 1, the control subjects were gender-, education-, and age-matched with the meditators as closely as possible (see Table 1). All subjects self-reported normal or correct-to-normal vision and normal hearing.

Procedure

Here, we further assessed the extent of superior sustained attention in meditators under crossmodal conditions. The procedure for recruiting meditators and nonmeditators was the same as experiment 1. Subject received a movie voucher for their time. Meditators and nonmeditators were tested in two bimodal versions of the RST where the target and nontargets were in different modalities. The *bimodal 1 RST* consisted of visual targets and auditory nontargets. The *bimodal 2 RST* consisted of auditory targets and visual nontargets. To perform these bimodal RST conditions accurately, subjects had to continuously respond to the rapid stream of nontargets from one modality while simultaneously attending to the other modality for the infrequent occurrence of the switch target. That is, subjects had to maintain sustained attention to both modalities concurrently. We included two bimodal RSTs where the modalities of the targets and nontargets were swapped to determine the extent to which sustained attention performance might depend on the crossmodal relationship between the target and nontarget modalities.

In the bimodal 1 RST, subjects made default button responses to the auditory nontargets presented over headphones and a switch button response to an infrequent visual switch target presented on the computer screen. The auditory nontargets (pure tones), visual switch target (digit 3), stimulus duration (250 ms), SOA (1150 ms), and the probability of the occurrence of the switch target (20% probability pseudorandomly presented with an equal probability of 1, 3, 5, or 7 nontargets between every switch target) were identical to those used in the unimodal RST versions in experiment 1. Similar to the auditory RST in experiment 1, subjects maintained eye fixation on a cross presented centrally on the computer screen throughout the experiment. When the switch target was presented, the digit 3 replaced the fixation-cross for 250 ms and then the fixation-cross reappeared.

In the bimodal 2 RST, the modality of the nontargets and targets was reversed. Subjects made default button responses to visual nontargets (digits ‘1’ to ‘9’ except ‘3’) and a switch button response to an infrequent auditory switch target (white noise burst) presented over headphones. Visual nontargets were separated by a 900-ms mask (‘&’ symbol). The bimodal 2 RST was the same as the bimodal 1 RST in all other respects.

The experiment was run on a Dell Precision T1650 3.30-GHz personal computer. Stimulus presentation and data recording were controlled by the Psychopy experiment builder software package (Peirce 2007). Visual stimuli were presented on a 23-in 120-Hz Samsung LCD monitor. Auditory stimuli were presented over headphones. Subjects’ heads were stabilized using a chin and forehead rest mounted 60 cm from the computer screen. Subjects performed a practice block of trials to get acquainted with the task. Meditators and controls performed both tasks and the order of task performance was counterbalanced between subjects. All subjects were run in a dimly lit private room. Subjects were not given an opportunity to practice meditation immediately prior to testing after they arrived at the laboratory.

Measures

Meditators completed the same meditation experience questionnaire used in experiment 1 before testing. Only meditators that agreed to the first set of questions indicating focus-attention meditation practice and disagreed with the second set of questions indicating open-monitoring mediation practice were included in this study. Measures of interest in experiment 2 were the same as experiment 1. Our main interest was error rate. Error rate was based on the percentage of times subjects pressed the default response button when the switch target was presented. As in experiment 1, RT was measured for three possible responses subjects could make: *default RT* for correct responses to nontarget stimuli, *switch RT* for correct responses to the switch target, and *error RT* when pressing the default button when the target was presented.

Data Analyses

We conducted the same analyses as in experiment 1 for comparing error rates between the meditators and nonmeditator controls and evaluating potential group and response type differences in RT. For each task, an independent t test analysis was conducted to compare error rates between meditators and controls. As in experiment 1, we conducted correlation analyses (Pearson r) on the error rates between tasks separately for meditators and controls to evaluate the extent to which bimodal 1 and bimodal 2 RST performance was related.

To evaluate potential differences in RT between the groups and response types, RTs were analyzed using a mixed design ANOVA with *group* (meditator versus controls) as the between-group factor and *response type* (default, error, and switch) as the within-group factor. As in experiment 1, the frequency of false alarms (pressing the switch response button when a non-target was presented) was very low for both meditators (bimodal 1 RST: $M = 1.6$, SD = 2.22; bimodal 2 RST: $M = 4.7$, SD = 7.23) and controls (bimodal 1 RST: $M = 3$, SD = 3.83; bimodal 2 RST: $M = 4.2$, SD = 5.55), and consistent with previous RST studies (e.g., Cheyne et al. 2012), false alarms were not included in the data analyses. For all analyses, a p value of 0.05 was adopted for significance.

Results

The overall results of the error rates of meditators and controls in both the bimodal 1 RST and bimodal 2 RST are summarized in Table 2. As in experiment 1, our main results show that meditators had lower error rates than controls, indicating fewer lapses of sustained attention. In the bimodal 1 RST, meditators made significantly fewer errors ($M = 4.3\%$, SD = 7.9) than controls (M = 13.9% (SD = 11.7), $t_{(34)} = -2.87$; $p < 0.01$, $d = 0.96$. Similarly, in the bimodal 2 RST, meditators made significantly fewer errors ($M = 14.8\%$, SD = 15.1) than controls ($M = 29.7\%$, SD = 16.8), $t_{(34)} = -2.79$; $p < 0.01$, $d = 0.93$. Correlation analyses on error rates across tasks for each group revealed significant correlations for meditators ($r = 0.60$, $p < 0.01$) and controls ($r = 0.64$, $p < 0.01$), indicating consistent performance across modality conditions.

Table 3 summarizes the meditators' and controls' mean RTs for the default, error, and switch responses. For each task, the RT data was analyzed by a mixed design ANOVA with group as the between-group factor and response type (default, error, and switch) as the within-group factor. As shown in Table 4, the results for the bimodal 1 RST yielded no significant effects for group ($F_{(1,\ 34)} = 0.37$; $p = 0.54$), response type ($F_{(2,\ 68)} = 1.87$; $p = 0.16$), or the group × response type interaction ($F_{(2,\ 68)} = 0.18$; $p = 0.84$). For the bimodal 2 RST, no significant effect was found for group ($F_{(1,\ 34)} = 3.59$; $p = 0.08$) or the group × response type interaction ($F_{(2,\ 68)} = 0.25$ $p = 0.78$). The response type main effect was significant ($F_{(2,\ 68)} = 15.76$; $p < 0.01$, $\eta_p^2 = 0.32$). Tukey's post hoc tests following up the response type main effect result revealed that switch RT was significantly longer than both default and error RT (both comparisons $p < 0.01$).

Taken together, the main results of experiment 2 show meditators made significantly fewer errors than controls in both bimodal versions of the RST. Moreover, the effect sizes for error rate in the two bimodal tasks were nearly the same (0.96 in bimodal 1 RST and 0.93 in bimodal 2 RST), suggesting that the meditators' advantage in bimodal sustained attention over controls was consistent regardless of which modalities the target and nontargets were assigned.

Discussion

In the present study, we compared sustained attention performance between regular FA meditators and nonmeditators in unimodal conditions—i.e., visual and auditory stimuli tested separately—and bimodal conditions—i.e., auditory and visual stimuli together. Our main results were the following: First, meditators made overall fewer errors than nonmeditators, indicating that the meditators had fewer failures of sustained attention. Second, meditators' better sustained attention was consistent across both visual and auditory unimodal and bimodal visual-auditory conditions, a finding that has not been reported before in previous studies.

Moreover, our correlational analyses in both experiments revealed error rates were consistent across stimulus conditions for both meditators and nonmeditator controls. These correlational results are consistent with Seli et al. (2012a) who show similar correlational results across visual and auditory stimulus conditions and bimodal audiovisual conditions using the SART in a nonmeditation-related study. Similar to the conclusions of Seli et al. (2012a), these correlational results suggest that with the RST we are assessing a central, modality nonspecific attentional process.

Together, these findings add to previous research in two ways: (1) our results provide further support for previous studies showing an association between meditation and superior sustained attention (Chambers et al. 2008; Lutz et al. 2009; MacLean et al. 2010; Morrison et al. 2014; Mrazek et al. 2012; Valentine and Sweet 1999; Zeidan et al. 2010), and (2) we extend this research with novel results suggesting that FA meditation is associated with general, modality nonspecific, superior sustained attention.

We acknowledge that our study is correlational. Thus, our findings alone do not allow us to draw causal conclusions by attributing enhanced sustained attention to meditation practice. One key issue for correlational studies on meditation and attention, such as ours, is whether observed better attentional performance was caused by meditation practice or if individuals with a priori enhanced attentional abilities were simply more likely to have engaged in meditation and become regular practitioners.

To study the causal relationship between meditation and enhanced attentional skills, we would have had to train naive subjects, ideally without any prior meditation experience, in some meditation training regime and compare their pre- and posttraining task performance. However, we did not have the means to train subjects in meditation and our only option was to recruit experienced meditators. Moreover, we and others (e.g., Hodgins and Adair 2010) argue that several experimental studies have indeed shown causal effects of meditation training on attentional enhancement (e.g., Chambers et al. 2008; Lutz et al. 2009; Slagter et al. 2007). Some prior studies have shown that relatively short-term training, as brief as four days to two weeks, can improve attentional performance (Tang et al. 2007; van Leeuwen et al. 2012), including sustained attention (Mrazek et al. 2012; Zeidan et al. 2010). Thus, our goal in the present study was to simply explore the extent of the putative superior sustained attention in regular FA meditators.

An important question to ask is, how do we reconcile the findings of the present study, along with the previous studies also showing enhanced sustained attention performance in meditators (Chambers et al. 2008; Lutz et al. 2009; MacLean et al. 2010; Morrison et al. 2014; Mrazek et al. 2012; Valentine and Sweet 1999; Zeidan et al. 2010), with studies that failed to find such evidence (Anderson et al. 2007; Cusen et al. 2010; Josefsson and Broberg 2011; Lykins et al. 2012)? The reasons for these inconsistent findings are unclear and may be related to methodological differences. However, comparing those studies that show a positive association of enhanced sustained attention and meditators with those studies that failed to find such an association for potential methodological differences that might account for the different results is not straightforward. Both sets of studies are similarly variable with respect to experimental task, sample size, and demographic characteristics.

Of those studies that failed to find an advantage for meditators in sustained attention, two employed the SART (Cusen et al. 2010; Josefsson and Broberg 2011) and two employed a variation of the conventional continuous performance task that involved responding to infrequent stimuli among frequent distractors (Anderson et al. 2007; Lykins et al. 2012). Lykins et al. (2012) also assessed sustained and selective attention using the Ruff 2 and 7 pencil-and-paper test (Ruff and Allen 1996). The sample sizes among these studies ranged from 12 meditators and 18 controls (Cusen et al. 2010) to 39 meditators and 33 controls (Anderson et al. 2007).

For those studies that report a sustained attention advantage for meditators, two also employed the SART (Morrison et al. 2014; Mrazek et al. 2012), two also employed continuous performance tasks (Lutz et al. 2009; MacLean et al. 2010), another two used counting tasks that involved counting the infrequent occurrence of an auditory tone (Valentine and Sweet 1999) or visually presented word (Chambers et al. 2008), and one study used an n-back task (Zeidan et al. 2010). Sample sizes among these studies also were varied ranging from 19 meditators and 24 controls (Valentine and Sweet 1999) to 30 meditators and 30 controls (MacLean et al. 2010).

Similarly, demographic characteristics (i.e., age, gender proportion, education level) are also diverse across all these studies. For example, some studies recruited primarily undergraduate university students with relatively low average ages (e.g., 26 and 19 average years of age in Josefsson and Broberg 2011and Mrazek et al. 2012, respectively). Other studies recruited from the general community, which resulted in a broader age range and higher average ages (e.g., 47 and 48 average years of age in Cusen et al. 2010 and MacLean et al. 2010, respectively). Taken together, such heterogeneity presents a major challenge for attributing the mixed findings in the literature to methodological differences of experimental task, sample size, and demographic characteristics.

One possible explanation for these inconsistent findings might be related to the different meditation styles studied. Specifically, whether and to what extent these studies involved FA meditation. As previously mentioned, FA and OM meditation involve cultivating different types of attentional states. OM meditation involves broadly distributed attention to an ongoing stream of mental objects and physical sensations that might arise without any explicit attentional focus. In contrast, FA meditation is a meditative form of a sustained attention task involving sustaining focused attention on an explicit object for prolonged periods for the purpose of developing better concentrative attention (Lutz et al. 2008;

Raffone and Srinivasan 2010; Wallace 1999). Thus, one might expect relatively greater benefits to sustained focused attention skills with FA meditation practice; however, we do not claim that OM meditation cannot be associated with enhanced sustained attention at all (see Valentine and Sweet 1999).

All the previously cited studies that found enhanced sustained attention included FA meditators. Four explicitly tested the effect of FA mediation practice on sustained attention (Lutz et al. 2009; MacLean et al. 2010; Mrazek et al. 2012; Zeidan et al. 2010). Two involved mindfulness meditation training of novice meditators that combined FA and OM practice (Chambers et al. 2008; Morrison et al. 2014). Lastly, one study tested both FA and OM meditators (Valentine and Sweet 1999). Our findings here contribute to this previous research by showing corroborating evidence that FA meditators are associated with superior sustained attention and this enhancement occurs across modalities.

In contrast, FA meditation was generally less represented in the four cited studies that failed to find enhanced sustained attention performance in meditators. Two studies involved mindfulness meditation (Anderson et al. 2007; Cusen et al. 2010). One study tested meditators from a wide range of meditation practices (e.g., mindfulness, compassion, and yoga), of whom only about 20% identified themselves as FA practitioners (Josefsson and Broberg 2011). The last study tested only OM practitioners (Lykins et al. 2012).

It should be noted that in those studies that involve mindfulness training, FA meditation was, to varying degrees, incorporated in their training programs. Also, FA meditation is often a starting point for many meditators before progressing to OM practice (Lutz et al. 2008). However, in these cited studies that included mindfulness and OM meditation, it is impossible to know how much training or practice was devoted to FA meditation, if any, which could also account for the conflicting results between the studies that found a positive association between mindfulness (OM) meditation and sustained attention (Chambers et al. 2008; Morrison et al. 2014) and those that did not (Anderson et al. 2007; Cusen et al. 2010). Altogether, more research is needed to clarify whether and to what extent different meditation styles enhance different attentional skills.

Much of the current evidence indicates that meditation practice alters both attentional and perceptual abilities (e.g., Carter et al. 2005; Lutz et al. 2009). Our results in the present study add to this body of evidence by showing that FA meditators exhibited superior sustained attention across visual and auditory modalities under unimodal and the more demanding bimodal conditions. Taking previous results showing FA meditation practice improves sustained attention (Lutz et al. 2009; Mrazek et al. 2012; Zeidan et al. 2010) and those presented here together suggest that sustained attention benefits from FA meditation reflect general, modality nonspecific, enhancement of attentional control.

Neuroimaging data reveal a substantial cortical overlap of frontoparietal brain areas involved in the control of visual and auditory attention (Krumbholz et al. 2008; Wu et al. 2007), including the anterior cingulate cortex (ACC) and the dorsolateral prefrontal cortex (DLPFC), suggesting that these attentional control areas are supramodal in nature. Evidence from lesion and neuroimaging studies indicates that the ACC and DLPFC play critical roles in sustained attention task performance, regardless of stimulus modality (Sarter et al. 2001). Meditation is associated with distributed activity across the frontoparietal attention network (Malinowski 2013); most notably, FA meditation modulates ACC and DLPFC activity, and the degree of activity in these regions is correlated with FA meditation experience (Brefczynski-Lewis et al. 2007; Hasenkamp and Barsalou 2012; Manna et al. 2010; Short et al. 2010), which these researchers postulate might in turn be correlated with better sustained attention.

Our findings presented here further support the notion that meditation is associated with better executive attentional control and, taken together with previous studies, has implications for better understanding the extent to which improvements in attentional control mechanisms through meditation generalize across sensory domains. The observation of generality using basic experimental paradigms suggests that meditation training may increase the efficiency of executive attentional control in a manner that can generalize beyond the laboratory. Future research is needed to extend the apparent generality of the current findings to more complex, natural tasks (e.g., driving) and explore the efficacy of meditation as an attentional training exercise with real-world benefits.

In summary, the goal of the present study was to further examine the nature of sustained attention performance in regular FA meditators relative to nonmeditators and characterize the extent to which meditators' performance generalizes across different modalities. We assessed sustained attention performance under unimodal and bimodal conditions. The present results show FA meditators performed better than nonmeditators in all modality conditions. Correlational analyses showed that performance was consistent across visual and auditory conditions in experiment 1 and both bimodal conditions in experiment 2, suggesting that RST performance is meditated by a central underlying sustained attention mechanism. Together, these findings that FA meditation is associated with superior sustained attention across different modalities suggest that concentrative meditation practice might enhance general, modality nonspecific attention processes.

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Author Contributions PB executed the study, conducted data analyses, and collaborated on the design and writing of study; JM collaborated with the design of the study and contributed to the editing of the final manuscript; and SLP designed the study, conducted data analyses, and wrote the manuscript.

Compliance with Ethical Standards This study was approved by the Human Ethics Committee of Victoria University of Wellington. All procedures performed in this study adhere to the ethical standards of the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all research participants in this study.

Conflict of Interest The authors declare that they have no conflict of interest.

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