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The mindful eye: Smooth pursuit and saccadic eye movements in meditators and non-meditators

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ABSTRACT

Background: This study examined the effects of cultivated (i.e. developed through training) and dispositional (trait) mindfulness on smooth pursuit (SPEM) and antisaccade (AS) tasks known to engage the fronto-parietal network implicated in attentional and motion detection processes, and the fronto-striatal network implicated in cognitive control, respectively.

Methods: Sixty healthy men (19–59 years), of whom 30 were experienced mindfulness practitioners and 30 meditation-naïve, underwent infrared oculographic assessment of SPEM and AS performance. Trait mindfulness was assessed using the self-report Five Facet Mindfulness Questionnaire (FFMQ).

Results: Meditators, relative to meditation-naïve individuals, made significantly fewer catch-up and anticipatory saccades during the SPEM task, and had significantly lower intra-individual variability in gain and spatial error during the AS task. No SPEM or AS measure correlated significantly with FFMQ scores in meditation-naïve individuals.

Conclusions: Cultivated, but not dispositional, mindfulness is associated with improved attention and sensorimotor control as indexed by SPEM and AS tasks.

1. Introduction

Smooth pursuit and saccadic eye movements are two types of eye movements that both human and non-human primates voluntarily employ to allow the image of an object fall and maintain near to or on the fovea. The function of smooth pursuit eye movements (SPEM) is to keep a retinal image within the area of the fovea during the movement of an object. The initiation as well as the maintenance of accurate SPEM requires attentional control (Hutton & Tegally, 2005). The primary measure of pursuit accuracy is the velocity gain which corresponds to the ratio of smooth pursuit velocity over target or object velocity (100% if SPEM velocity matches the target velocity) (Lencer & Trillenberg, 2008). Other indicators of SPEM efficiency are the frequency of compensatory catch-up and intrusive anticipatory saccades made during the smooth pursuit task.

Saccades refer to the fast eye movements made to the sudden appearance of a visual target. Prosaccades require the participant to make a saccade to a single-target stimulus as soon as it appears. The antisaccade (AS) paradigm, on the other

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hand, requires the participant to inhibit a reflex-like saccade towards the target, and instead initiate a saccade in the direction opposite to the target (Hutton & Ettinger, 2006). It examines the conflict between a pre-potent stimulus that produces a strong urge to make a saccade to the target, and the overriding goal to look in the opposite direction. Correct AS performance requires accurate perception, ability to transform location information to a mirror image representation, and suppression of a saccade towards the AS stimulus. Performance is assessed as the error rate, spatial accuracy and latency of (anti)saccades (Hutton & Ettinger, 2006). Given their high test-retest reliability (Ettinger et al., 2003) and the ease of administration, SPEM and AS paradigms have been used to assess cognitive functions in a wide variety of contexts (Hutton & Ettinger, 2006; Lencer & Trillenberg, 2008). However, no published study, to our knowledge, has yet utilised these paradigms to understand the neural and cognitive influence of mindfulness as a trait ('dispositional' mindfulness) (Brown & Ryan, 2003), or mindfulness developed through training ('cultivated' mindfulness) (Ivanovski & Malhi, 2007).

Mindfulness, a translation of the Pali term *sati*, is operationalized in modern psychology as a quality of awareness that arises from paying attention to the experience on a moment-by-moment basis without judging, elaborating upon, or fixating on this experience in any way (Kabat-Zinn, 1990). Its practice typically begins with the mindfulness of bodily sensations to the awareness of feelings and thoughts, progressing to a present-centred awareness without an explicit focus, in most Buddhist traditions as well as formal intervention-style practices such as Mindfulness-Based Stress Reduction (MBSR; Kabat-Zinn, 1990) and Mindfulness-Based Cognitive Therapy (MBCT; Segal, Williams, & Teasdale, 2002). Dispositional mindfulness refers to the naturally occurring tendency to display this non-judgmental present awareness in everyday life and varies amongst individuals (Brown & Ryan, 2003).

There is growing evidence for a positive effect of cultivated mindfulness on a range of cognitive functions (reviews, Chiesa, Calati, & Serretti, 2011; Gallant, 2016). Mindfulness practice enhances stability of attention by reducing cortical noise (Lutz et al., 2009) and appears to increase information processing capacity (Slagter et al., 2007) with the cognitive system more rapidly available to process new targets (Slagter, Lutz, Greischar, Nieuwenhuis, & Davidson, 2008). It is reported to positively influence orienting attention (van den Hurk, Giommi, Gielen, Speckens, & Barendregt, 2010), dual attention (Jensen, Vangkilde, Frokjaer, & Hasselbalch, 2012) and performance on a range of tasks requiring attention and/or cognitive flexibility (Hodgins & Adair, 2010; Jha, Krompinger, & Baime, 2007; Jha, Stanley, Kiyonaga, Wong, & Gelfand, 2010; Kumari, Hamid, Brand, & Antonova, 2015; Moore, Gruber, Derose, & Malinowski, 2012; Semple, 2010; Tang et al., 2007; van den Hurk, Janssen, Giommi, Barendregt, & Gielen, 2010). According to a recent review (Gallant, 2016), mindfulness-led improvements in executive functioning, within Miyake et al.'s model (2000), are more consistently found on specific measures of inhibition (Allen et al., 2012; Heeren, Van Broeck, & Philippot, 2009; Moore & Malinowski, 2009; Sahdra et al., 2011; Teper & Inzlicht, 2013), relative to updating (Jha et al., 2010; Mrazek, Franklin, Tarchin, Baird, & Schooler, 2013) and shifting components (Anderson, Lau, Segal, & Bishop, 2007; Chambers, Lo, & Allen, 2008; Heeren et al., 2009; Moynihan et al., 2013).

There are, however, only few data at present examining the association between trait mindfulness, as measured in the general non-meditating population using self-report questionnaires (Brown & Ryan, 2003), and cognitive function, with some studies (Stillman, Feldman, Wambachm, Howard, & Howard, 2014; Stillman et al., 2016; Whitmarsh, Uddén, Barendregt, & Petersson, 2013) indicating a negative relationship between trait mindfulness and implicit learning, i.e. learning without conscious awareness.

The aim of the present study was to examine the influence of mindfulness both as a trait and developed through training on visuo-spatial attentional and voluntary inhibition processes indexed by the SPEM and AS paradigms, respectively. Based on previous report of positive effects of mindfulness practice on a range of attention, working memory and inhibition tasks (reviews, Chiesa et al., 2011; Gallant, 2016), we hypothesised that meditators, compared with meditation-naïve individuals, will show more accurate gain and lower frequency of catch-up and anticipatory saccades on the SPEM task, and a lower error rate, higher spatial accuracy and reduced within-subject variability in spatial accuracy (i.e. more consistent performance) on the AS task. Furthermore, we hypothesised tentatively (in absence of direct previous data) that in meditation-naïve individuals, trait mindfulness, as assessed by the Five Factor Mindfulness Questionnaire (FFMQ; Baer, Smith, Hopkins, Krietemeyer, & Toney, 2006), will correlate with better SPEM and AS performance, particularly on measures that significantly differentiate meditators and non-meditators.

2. Methods

2.1. Participants and design

The study involved two groups. Group 1 consisted of 30 experienced mindfulness practitioners (meditators) and Group 2 of 30 meditation-naïve individuals (all males; age range 19–59 years). All participants were assessed on a single occasion.

Meditators were recruited from local and national Buddhist centres via poster advertisement and presentations of the study and its aims at meetings of centre members. They were required to have at least 2 years of consistent meditation practice (minimum 45 min per day at least 6 days a week). Meditation-naive men were recruited from a healthy volunteer database or by circular emails sent to staff and students of King's College London, UK. They were required to have no experience of mindfulness-related practices, including meditation, yoga, tai-chi, qigong or martial arts.

Additional inclusion criteria for all participants were: (i) right-handedness (Oldfield, 1971), (ii) current IQ > 80 as assessed with the two-test version of Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999), (iii) aged 18–60 years, (iv) normal or corrected-to-normal vision, and (v) not drinking more than 28 units of alcohol per week [1 unit = 1/2 pint of beer (285 mls) or 25 ml of spirits or 1 glass of wine], or more than 6 units of caffeinated beverage a day. Those with a positive screen for any neuropsychiatric disorder, a current or past primary diagnosis of substance misuse or on regular medical prescription were not included.

The final sample with usable SPEM data consisted of 29 meditators (drawn mainly from Zen, Theravada, Vajrayana and Triratna traditions of Buddhism) and 30 meditation-naïve individuals, and with usable AS data of 27 meditators and 29 meditation-naïve individuals (see Table 1).

Study procedures were approved by the King's College London Research Ethics Committee (PNM/14/15-90). Participants provided written informed consent to their participation and were compensated for their time and travel.

2.2. Sample characterisation

Meditation history (meditation tradition/style, meditation routine) was obtained from the meditators prior to study participation. In addition, all participants completed the FFMQ (Baer et al., 2006). The FFMQ has been constructed from factor analysis done on five of the most previously popular measures of trait mindfulness, and is currently the most frequently used measure of trait mindfulness. Its five facets are observing (*Observe*, e.g. "When I'm walking, I deliberately notice the sensations of my body moving."), describing (*Describe,* e.g. "I'm good at finding words to describe my feelings."), acting with awareness (*Awareness,* e.g. "I find myself doing things without paying attention." with reverse scoring), non-judging of inner experience (*Non-judgment,* e.g. "I tell myself I shouldn't be feeling the way that I am feeling.") and non-reactivity to inner experience (*Non-reactivity,* e.g. "I watch my feelings without getting lost in them."), assessed on a 5-point Likert scale (never or rarely, rarely, sometimes, often, very often or always true) with 39 items (8 items each for *Observe*, *Describe*, *Awareness* and *Non-judgement* facets and 7 items for *Non-reactivity* facet). Higher scores indicate higher mindfulness.

2.3. Eye movements: Paradigms and procedure

Infrared oculography (IRIS 6500; Skalar Medical BV, Delft, the Netherlands) was used to record eye movements. Participants were seated in a height-adjustable chair with their head resting on a chinrest at a distance of 57 cm from the computer monitor. They were requested to remain as still as possible throughout the experiment. The visual stimulus consisted of a white circular target, with 0.3° diameter, presented on a black background on a 17-inch monitor. A 3-point (+12°, 0°, −12°; stimulus duration = 1000 ms) calibration task was carried out prior to running the SPEM, AS and prosaccade (PS) tasks.

During the SPEM task, a target dot moved horizontally across the screen, in a triangular waveform, at three different velocities (12°/s, 24°/s, 36°/s). Participants were requested to keep their gaze on this horizontally moving target as closely as possible. The target dot was initially positioned at the centre of the screen (0°). It then moved either to the left or the right side of the screen (±12°), and then to the opposite side. Each target movement from one side (e.g. −12°) to the other (e.g. +12°) is referred to as half-cycle or ramp. The target dot completed a total of 16.5 half-cycles. The first half-ramp (from 0 to ±12°) was not included in the analysis.

The PS and AS tasks used ±6° and ±12° targets, each presented 15 times in a random order (60 PS trials and 60 AS trials in separate blocks). Each PS and AS trial began with the target in the centre of the participant's visual field (0°) for a random duration of 1000–2000 ms. The target then abruptly stepped to one of the four possible peripheral locations (±6° and ±12°), along the horizontal plane, and remained there for 1000 ms before it stepped back to the central position for the next trial. During the PS task, participants were requested to look at the target when it was in the central position, and then follow it with their eyes (i.e. generate prosaccades) when it stepped to the peripheral positions. During the AS task, participants were requested to keep their gaze at the target when it was in the central position and to generate a saccadic eye movement to the

Table 1
Characteristics and mindfulness scores of the meditator and meditation-naïve groups.

	Meditators (n = 29)		Meditation-naïve (n = 30)	
	Mean (SD)	Range	Mean (SD)	Range
Age (years)	39.90 (10.25)	21–59	36.93 (10.36)	19–59
IQ[a]	118.14 (14.00)	85–135	118.45 (12.77)	94–138
Meditation practice (years)	9.78 (6.80)	2–27		
Mindfulness (FFMQ) scores[b]				
Observe	30.90 (4.78)[†]	23–39	26.14 (5.84)	14–37
Describe	30.55 (3.37)	24–37	31.05 (4.11)	23–39
Awareness	30.66 (5.49)	21–40	28.59 (4.00)	22–36
Non-judgment	33.38 (4.72)[†]	19–40	28.54 (5.52)	14–37
Non-reactivity	26.48 (4.76)[†]	17–35	21.77 (3.08)	17–29

[a] Assessed using the two-test version of Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999).

[b] n reduced to 27 meditators and 22 meditation-naïve individuals

[†] Significantly higher scores in meditators.

mirror-image projection of the target, in the opposite hemifield, when it moved to any one of the four peripheral positions. Four practice trials, one with each target location, were carried out before the experimental trials, and repeated if necessary.

All participants were assessed first on the PS task, followed by the AS and SPEM tasks. The testing took place in a quiet and darkened room. The participants were allowed to have coffee on the day of testing but were provided only with decaffeinated drinks for at least 1 h prior to being assessed on eye movement tasks. The experimental setup, oculomotor tasks and oculographic data recording and scoring procedures were the same as used in a previous study (Schmechtig et al., 2010).

2.4. Eye movement analysis

All eye movement recordings were scored blind to group membership.

2.4.1. Smooth pursuit

The time-weighted average pursuit velocity gain, frequency of catch-up saccades and frequency of anticipatory saccades were calculated for each participant, using LABVIEW 6.0 student version (2000). The time-weighted average pursuit velocity gain was calculated by dividing mean eye velocity by target velocity. This analysis included sections of pursuit which lay in the central half of each ramp (the first and last quarters excluded to avoid effects of pursuit initiation and slowing at target turnarounds). Velocity gain scores for each section of the pursuit, that were free of saccades or blinks, were time-weighted and subsequently averaged across half cycles for each target velocity (score <100% means that the eye is slower, and score >100% that it is moving faster, than the target). Saccadic frequency per second was calculated dividing the total number of anticipatory or catch-up saccades by the duration in seconds of pursuit at each target velocity (N/s). Anticipatory saccades were defined as saccades that began with the eye on or behind the target and ended ahead of it, while catch-up saccades were defined as saccades that began with the eye behind the target and served to bring the eye closer to the target. Saccades that began behind the target and ended ahead of it were defined as anticipatory saccades if more than half of amplitude was spent ahead of the target, and as catch-up saccades if more than half of amplitude was spent behind the target. Back-up saccades and square-wave jerks were not counted as their frequency was too low for a meaningful differentiation of the meditator and meditation-naïve groups. Saccades were automatically detected in EYEMAP 2.1 (AMTech, GmbH, Weinheim, Germany) using minimum amplitude (1°) and velocity (30°/s) criteria.

2.4.2. Prosaccade (PS)

Spatial accuracy (gain, spatial error) and latency, along with associated SDs, were scored for each participant using EYEMAP 2.1. PS gain was calculated as the percentage of saccade amplitude divided by target amplitude multiplied by 100 (a score of 100% represents a perfectly accurate saccade, <100% a hypometric saccade and >100 a hypermetric saccade). Spatial error (percentage) represented the residual error. It was calculated for each trial by subtracting the target amplitude from saccade amplitude and dividing it by the target amplitude, and then averaged across all trials and multiplied by 100 (higher scores indicate greater spatial error regardless of saccadic over or under-shoot). Saccadic latency represented the time (in ms) from the appearance of the target to saccade initiation.

2.4.3. Antisaccade (AS)

The AS error rate (% total) was calculated as the percentage of error trials (i.e. trials where the participant's first saccade is towards the target) over the total number of valid trials (i.e. error trials plus correct trials, excluding eye blink trials). AS gain, spatial error, latency, error rate (% total), as well as the SDs of gain, spatial error and latency were calculated for each participant. In addition, the correction rate (%) was scored to ensure that all included participants knew task requirements (~100% correction rate). AS gain, spatial error and latency were calculated following the criteria described above (for PS).

2.5. Data analysis

Group differences in age, IQ, and FFMQ scores were examined using independent sample *t*-tests.

Each SPEM measure (gain, frequency of catch-up saccades, frequency of anticipatory saccades) was analysed using a 2 (Group: meditators, meditation-naïve) × 3 (Velocity: 12°/s, 24°/s and 36°/s target velocities) analysis of variance (ANOVA) with Group as a between-subjects factor and Velocity as a within-subjects factor, followed by the analysis of simple main effects and lower order ANOVAs as appropriate to test the hypothesised differences between the meditator and meditation-naïve groups. Each AS (error rate, gain, spatial error and latency, as well as the SDs of gain, spatial error, latency) and PS measure (gain, spatial error and latency as well as SDs of these variables) was analysed using a one-way ANOVA. Effect sizes, where reported, are partial eta squared (ηp^2; the proportion of variance associated with a factor).

Correlational analyses (Pearson's *r*) were run to examine the hypothesised association between FFMQ scores and SPEM and AS measures in meditation-naïve individuals; for completeness, similar correlation analyses were conducted in meditators. Possible correlations between age and SPEM and AS variables were also examined.

All analyses were performed using the Statistical Package for Social Sciences (for Windows, version 22; IBM, New York, US). Alpha level for testing significance of effects was maintained at $p < 0.05$ unless stated otherwise.

3. Results

3.1. Sample characteristics: Meditators versus Non-meditators

Meditators scored significantly higher on *Observe* [$t\ (49) = 3.21$, $p = 0.002$], *Non-judgment* [$t(49) = 3.37$, $p = 0.001$] and *Non-reactivity* facets [$t(49) = 4.05$, $p < 0.001$] of mindfulness as assessed by the FFMQ (Baer et al., 2006) compared to meditation-naïve individuals (Table 1). The two groups did not differ in age or IQ ($p > 0.25$) (Table 1).

3.2. Eye movements: Meditators versus non-meditators

Means (SDs) for eye movement measures, separately for the meditators and meditation-naive groups, are presented in Table 2.

3.2.1. SPEM

Meditators did not differ from meditation-naïve individuals in gain at any of the three target velocities, as there was neither a main effect of Group [$F(1,57) = 1.96$, $p = 0.17$, $\eta p^2 = 0.03$] nor a Group × Velocity interaction [$F(2,114) = 0.06$, $p = 0.94$, $\eta p^2 = 0.001$]. There was only a significant main effect of Velocity showing less accurate performance with increasing velocities in both groups [$F(2,114) = 8.74$, $p < 0.001$, $\eta p^2 = 0.13$; linear $F(1,57) = 12.66$, $p = 0.001$, $\eta p^2 = 0.18$] (Table 2).

Meditators made fewer catch-up saccades than meditation-naïve individuals at 12° target velocity ($p = 0.01$) but did not differ significantly at the other two target velocities ($p > 0.13$), as revealed by the follow-up analysis of a significant Group × Velocity interaction [$F(2,114) = 3.73$, $p = 0.03$, $\eta p^2 = 0.06$]. There was a main effect of Velocity showing a higher frequency of catch-up saccades with increasing velocities in both groups [$F(2,114) = 142.06$, $p < 0.001$, $\eta p^2 = 0.71$; linear $F(1,57) = 225.79$, $p < 0.001$, $\eta p^2 = 0.78$] (Table 2).

Meditators made fewer anticipatory saccades than meditation-naïve individuals at all three velocities as demonstrated by a significant main effect of Group [$F(1,57) = 6.70$, $p = 0.01$, $\eta p^2 = 0.11$] and a non-significant Group × Velocity interaction [$F(2,114) = 0.88$, $p = 0.42$, $\eta p^2 = 0.01$]. In addition, there was a main effect of Velocity showing a higher frequency of anticipatory saccades with increasing velocities in both groups [$F(2,114) = 48.70$, $p < 0.001$, $\eta p^2 = 0.46$; linear $F(1,57) = 69.72$, $p < 0.001$, $\eta p^2 = 0.55$] (Table 2).

Table 2
Smooth pursuit (SPEM) and antisaccade (AS) performance of meditators and meditation-naïve individuals.

	Meditators (n = 27)	Meditation-naïve (n = 29)
Smooth pursuit (SPEM)		
Velocity gain	Mean (SD)	Mean (SD)
12°/s (%)	103.97 (11.98)	108.26 (25.26)
24°/s (%)	93.19 (14.26)	99.58 (17.86)
36°/s (%)	89.06 (23.41)	95.40 (30.67)
Frequency of catch-up saccades		
12°/s (N/s)	0.31 (0.13)↓	0.44 (0.22)
24°/s (N/s)	0.95 (0.43)	0.94 (0.36)
36°/s (N/s)	1.47 (0.47)	1.30 (0.57)
Frequency of anticipatory saccades		
12°/s (N/s)	0.26 (0.32)↓	0.46 (0.31)
24°/s (N/s)	0.66 (0.45)↓	0.86 (0.52)
36°/s (N/s)	0.65 (0.38)↓	0.96 (0.45)
Anti-saccade (AS)		
Error rate (%)	38.98 (24.08)	32.73 (22.81)
Gain	−104.04 (26.44)	−116.96 (33.68)
SD - Gain	44.21 (14.97)↓	54.34 (17.84)
Spatial error	38.40 (14.07)	46.41 (22.32)
SD - Spatial error	30.55 (15.33)↓	40.13 (19.12)
Latency	296.20 (46.41)	299.29 (45.44)
SD - Latency	62.55 (29.03)	69.23 (40.27)
Correction rate (%)	96.48 (10.20)	95.79 (9.04)
Pro-saccade (PS)		
Gain	101.46 (10.72)	102.03 (19.67)
SD - Gain	18.14 (6.24)	24.10 (21.73)
Latency	177.09 (21.92)	180.13 (26.42)
SD - Latency	46.13 (38.41	43.46 (39.24)

↓ Significantly lower scores in meditators.

3.2.2. AS

Meditator and meditation-naïve groups did not differ in error rate [$F(1,54) = 1.00$, $p = 0.33$, $\eta p^2 = 0.02$], latency [$F(1,54) = 0.06$, $p = 0.80$, $\eta p^2 = 0.001$], gain [$F(1,54) = 2.52$, $p = 0.12$, $\eta p^2 = 0.04$] or spatial error [$F(1,54) = 2.53$, $p = 0.12$, $\eta p^2 = 0.04$]. Meditators, however, had significantly lower SDs of gain [$F(1,54) = 5.20$, $p = 0.026$, $\eta p^2 = 0.09$] and spatial error [$F(1,54) = 4.24$, $p = 0.04$, $\eta p^2 = 0.07$] relative to meditation-naïve individuals.

3.2.3. PS

There was no difference between the two groups for any PS variables (all p values >0.18).

3.3. Correlational analyses: Trait mindfulness (FFMQ), age and eye movement measures

In meditation-naïve individuals, only two, out of 78 in total, correlations reached $p < 0.05$ (not corrected for multiple correlations), and these two were inconsistent with one showing better (fewer catch-up saccades) and the other showing worse performance (more anticipatory saccades) in association with higher scores trait mindfulness (*Describe* and *Non-judgment* facets) (Table 3). Age did not correlate with any eye movement measures.

In meditators, higher scores on the FFMQ were associated with better AS performance. Specifically, higher scores on both *Observe* and *Non-reactivity* facets were associated with lower spatial error and lower SDs of spatial error and gain, with *Non-reactivity* facet associating further with a larger gain; the correlations with other mindfulness facets were non-significant but in the same direction. In addition, older age was consistently associated with poorer AS performance (higher error rate, increased spatial error and longer latency).

4. Discussion

Supporting our hypothesis in relation to the influence of cultivated mindfulness, the present study revealed superior SPEM and AS performance in meditators relative to meditation-naïve individuals. Specifically, meditators, relative to meditation-naïve individuals, had fewer catch-up (at 12° target velocity) and anticipatory saccades (at all three target velocities) during the SPEM task, and significantly lower SDs of gain and spatial error during the AS task. The two groups did not differ significantly in AS gain and spatial error, though meditators, in line with our *a priori* hypothesis, were more stable across trials in these measures of spatial accuracy. The findings, however, offered no support for our hypothesis in relation to dispositional (trait) mindfulness. None of the five facets of the FFMQ correlated consistently positively or negatively with either SPEM or AS indices in non-meditators, though significant relationships between higher FFMQ scores (*Observe* and *Non-reactivity* facets) and more accurate and more consistent AS performance were present in meditators. In addition, older age was associated with poorer AS performance (higher error rate, increased spatial error and longer latency) in meditators.

The finding of fewer catch-up and anticipatory saccades during the SPEM task in meditators, compared to non-meditators, indicating better attentional control in long-term meditators (Hutton & Tegally, 2005), is in line with Lutz et al.'s (2008) focussed attention meditation framework. This superiority most likely developed through regular practice of mindfulness since no significant relationship was found between the SPEM indices and FFMQ scores in non-meditators. SPEM paradigms are well known to elicit activity in frontal and posterior areas that are implicated in attentional and motion detection processes (Lencer & Trillenberg, 2008; Sharpe, 2008) as well as in the neurobiological effects of mindfulness practices (Barnby, Bailey, Chambers, & Fitzgerald, 2015; Hölzel et al., 2011; Marchand, 2014). It would be valuable to further examine the neural basis of the influence of cultivated mindfulness in SPEM performance.

Our finding of significantly lower SDs of gain and spatial error during the AS task indicates lower intra-individual variability (i.e. more consistent within-session performance) in meditators, relative to non-meditators. Intra-individual variability, examined mostly in reaction time across a range of tasks, is considered to reflect lapses in attention or cognitive control (Fassbender, Scangos, Lesh, & Carter, 2014; Weissman, Roberts, Visscher, & Woldorff, 2006), sustained attention deficit (Leth-Steensen, Elbaz, & Douglas, 2000), a poor ability to successfully engage cognitive control in demanding situations (Bellgrove, Hester, & Garavan, 2004), and poor regulation of effort (Sergeant, Geurts, Huijbregts, Scheres, & Oosterlaan, 2003). Increased intra-individual variability occurs with aging (e.g. Anstey, 1999; Fozard, Vercruyssen, Reynolds, Hancock, & Quilter, 1994; Shammi, Bosman, & Stuss, 1998) and is associated with many clinical conditions, including frontal-temporal dementia (Murtha, Cismaru, Waechter, & Chertkow, 2002), attention hyperactivity deficit disorder (Leth-Steensen et al., 2000; Vaurio, Simmonds, & Mostofsky, 2009; Zahn, Kruesi, & Rapoport, 1991), schizophrenia (Schwartz et al., 1989) and traumatic brain injury (e.g. Bleiberg, Garmoe, Halpern, Reeves, Nadler, 1997; Segalowitz, Dywan, & Unsal, 1997; Stuss, Murphy, Binns, & Alexander, 2003; Stuss et al., 1989; Zahn & Mirsky, 1999). Intra-individual variability is typically most strongly present on tasks that require executive control (West, Murphy, Armillio, Craik, & Stuss, 2002) and appears particularly sensitive to frontal lobe function, with frontally-deficient clinical groups showing the greatest intra-individual variability (Murtha et al., 2002). Since all our participants were required to be free of a neuropsychiatric condition and known brain injury, the findings of lower SDs of gain and spatial error during the AS task can be taken to indicate superior executive control and frontal lobe functioning developed through training in the meditator group.

Interestingly, neuroticism has been associated with greater intra-individual variability, supposedly due to distracting worries about task performance or difficulty in those with high neuroticism (Robinson & Tamir, 2005). If mindfulness

Table 3
Pearson's correlations between mindfulness facets (FFMQ) and eye movement measures.

Meditation-naïve	Smooth pursuit (SPEM)						Anti-saccade (AS)						
	Frequency of catch-up saccades			Frequency of anticipatory saccades			Error rate	Gain	Gain SD	Spatial error	Spatial error SD	Latency	Latency SD
	12°/s	24°/s	36°/s	12°/s	24°/s	36°/s							
Age	0.115	−0.251	−0.244	0.136	0.299	0.059	−0.192	0.032	0.188	0.124	0.117	0.400	0.254
FFMQ - Observe	0.303	0.065	**−0.523***	0.294	0.169	−0.214	−0.150	−0.173	0.369	0.148	0.256	0.094	0.171
FFMQ - Describe	0.332	0.413	−0.113	0.157	0.313	0.114	−0.079	−0.067	0.293	0.212	0.257	0.365	0.136
FFMQ - Awareness	−0.022	0.140	−0.093	0.163	0.192	0.281	−0.432	0.219	−0.069	0.010	−0.090	0.020	0.007
FFMQ - Non-judgment	0.131	0.228	0.170	0.040	0.301	**0.486***	−0.295	0.277	0.026	0.059	−0.061	−0.063	−0.029
FFMQ - Non-reactivity	0.212	−0.144	0.034	0.053	0.316	0.239	−0.191	0.198	−0.204	−0.161	−0.258	−0.136	−0.210
Meditators													
Age	0.079	−0.401	−0.410	0.269	0.051	−0.295	**0.441***	**−0.478***	0.369	**0.479***	**0.435***	**0.468***	0.200
FFMQ: Observe	−0.228	0.006	−0.115	0.230	−0.193	−0.136	−0.177	0.370	**−0.503***	**−0.446***	**−0.481***	−0.264	−0.109
FFMQ: Describe	−0.075	−0.08	−0.167	0.048	−0.160	−0.221	−0.037	0.268	−0.287	−0.337	−0.256	−0.215	−0.177
FFMQ: Awareness	−0.029	0.206	0.151	0.150	−0.120	−0.023	−0.270	0.259	−0.237	−0.211	−0.237	−0.080	−0.130
FFMQ: Non-judgment	−0.103	0.243	0.020	−0.222	−0.149	0.072	−0.185	0.242	−0.247	−0.263	−0.251	−0.005	−0.080
FFMQ: Non-reactivity	0.167	0.357	0.725	0.762	0.118	0.132	−0.247	**0.444***	**−0.534****	**−0.413***	**−0.474***	−0.111	−0.249

For AS: n reduced to 27 meditators and 22 meditation-naïve individuals.

* $p \leqslant 0.05$.

** $p \leqslant 0.01$.

improves emotion regulation by exerting a positive influence on executive control processes (Teper & Inzlicht, 2013), this may, at least partly, explain both performance superiority of the meditators observed in our study and the recently demonstrated reduction in neuroticism following MBCT (Armstrong & Rimes, 2016). Furthermore, mindfulness training or practice is known to exert attenuating effects on the Default Mode Network (e.g. Brewer et al., 2011; Farb et al., 2007), associated with mind-wandering or stimulus-independent thought (Mason et al., 2007), which would further enhance the performance on the tasks employed in the current study.

This study did not reveal a meaningful pattern of correlations between dispositional mindfulness and eye movement performance indices. It may be that dispositional mindfulness, as measured by self-report questionnaires, indeed exists fairly independently of cultivated mindfulness and is conceptually unique (Rau & Williams, 2016; Wheeler, Arnkoff, & Glass, 2016). It may share some (e.g. negative association with neuroticism) but not all behavioural or neural correlates of cultivated mindfulness (Rau & Williams, 2016). Furthermore, absence of opposite traits, such as neuroticism or mindlessness, might not indicate a presence of mindfulness by necessity (Grossman & Van Dam, 2011). There were, however, meaningful and significant relationships between FFMQ scores and AS measures in meditators. Specifically, both *Observe* and *Non-reactivity* facets were correlated with lower spatial error and lower SDs of spatial error and gain, with *Non-reactivity* facet correlating further with a larger gain. Correlations of the three remaining mindfulness facets with these AS parameters, although in the same direction, were non-significant. Taken together, these observations may suggest that earlier-noted consistent mindfulness training-led improvements found across studies in the inhibition component of executive control (review, Gallant, 2016), may be mediated most strongly by *Observe* and *Non-reactivity* aspects of mindfulness training.

Our study has some limitations. First, it examined the effects of cultivated mindfulness on eye movement control in a cross-sectional design, without any knowledge of the meditators' eye movement performance prior to them starting mindfulness practice. Future research could examine the effects of shorter duration mindfulness-based interventions (MBIs) on SPEM and AS performance. If the results show improved SPEM and AS performance following MBIs, they would not only add to our understanding of the neural and cognitive effects of mindfulness but would also provide easily quantifiable and objective markers to index mindfulness training effects and its neurobiological underpinnings. Second, the findings of this study, which involved only men, cannot be generalized to women. Further research is needed to examine the influence of mindfulness in eye movement control in women, preferably controlling for menstrual phases, given menstrual phase-related variability in other psychophysiological measures of attention and inhibitory function (Kumari, 2011).

In conclusion, this is the first study, to our knowledge, to have examined and shown superior SPEM and AS performance in established meditators, relative to meditation-naïve individuals. The findings suggest that mindfulness meditation improves attention and the stability of responding on visuo-motor tasks. Future studies are needed to confirm these effects using within-subjects designs (pre- and post-mindfulness training) and firmly establish whether eye movement tasks hold promise as objective measures of mindfulness training.

Conflict of Interest

The authors declare no conflict of interest.

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The sponsors had no role in study design; in the collection, analysis and interpretation of data; in the writing of the report; or in the decision to submit the paper for publication.

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