J Cogn Enhanc (2017) 1:127–140
DOI 10.1007/s41465-017-0019-2

ORIGINAL ARTICLE

Sequence Learning Enhancement Following Single-Session Meditation Is Dependent on Metacontrol Mode and Experienced Effort

Maarten A. Immink[1] · Lorenza S. Colzato[2,3,4] · Marije Stolte[2,5] · Bernhard Hommel[2]

Received: 15 December 2016 / Accepted: 4 April 2017 / Published online: 24 April 2017

Abstract Focused attention (FAM) and open monitoring (OMM) meditation types establish distinct metacontrol states that have immediate effects on how attention allocation strategies are utilised in subsequent, unrelated tasks. Because attention allocation is a central factor in sequential action, the present experiment investigated whether a single-session of FAM and OMM enhanced subsequent sequence performance and learning. Relative to a control listening task, a single session of FAM or OMM resulted in heightened sequence performance without affecting sequence learning on average. However, the level of effort experienced in the meditation conditions was found to significantly correlate with sequence learning indices and post hoc analyses revealed that low effort level in both meditation groups was associated with significantly greater general sequence performance improvements. Interestingly, the degree of sequence-specific learning that brought about these improvements was enhanced only by OMM and only in those reporting low effort level with this meditation type. Thus, only the combination of low effort and OMM established a cognitive control state that was beneficial for the acquisition of complex sequence structures. This work provides further insights into instantaneous effects of FAM and OMM on goal-oriented cognitive function while also raising important questions about the control of mediation-induced states.

Keywords Meditation · Attention · Sequence learning · Cognitive control · Effort · Goal-directed behavior

✉ Maarten A. Immink
maarten.immink@unisa.edu.au

1 School of Health Sciences & Cognitive Neuroscience Laboratory, University of South Australia, Adelaide, Australia

2 Cognitive Psychology Unit & Leiden Institute for Brain and Cognition, Leiden University, Leiden, The Netherlands

3 Department of Cognitive Psychology, Institute of Cognitive Neuroscience, Faculty of Psychology, Ruhr University Bochum, Bochum, Germany

4 Institute for Sports and Sport Science, University of Kassel, Kassel, Germany

5 Faculty of Social and Behavioral Sciences, Special Education: Cognitive and Motor Disabilities, Utrecht University, Utrecht, The Netherlands

Introduction

Meditation is increasingly being recognised for its potential to enhance human cognition based on growing empirical evidence that meditation improves function in a range of cognitive processes (Ainsworth et al. 2013; Gallant 2016; Hasenkamp et al. 2012; Hodgins and Adair 2010; Immink 2016; Malinowski 2013; Miyake et al. 2000; Slagter et al. 2007; Tang et al. 2015; van den Hurk et al. 2010; Zeidan et al. 2010) and reduces age-related cognitive decline (Gard et al. 2014). These benefits are thought to arise from the manner by which meditation engages regulatory mechanisms resulting in improved attention control and function of downstream cognitive processes such as working memory and interference control (Brefczynski-Lewis et al. 2007; Holzel et al. 2011; Malinowski 2013; Moore et al. 2012; Moore and Malinowski 2009). Meditation types differ with respect to how they influence attention control and this is the primary characteristic by which focused attention meditation (FAM) and open monitoring meditation (OMM) are distinguished (Lippelt et al. 2014; Lutz et al. 2008; Manna et al. 2010).

Control States in Focused Attention and Open Monitoring Meditation Types

In FAM, attention is narrowed to selectively focus on an external object such as a candle flame or internal sensorial experience such as breathing. To meet this goal, FAM employs top-down control processes that constrain attention allocation (Colzato et al. 2016). Consistent with this concept, FAM has been shown to increase sustained attention (Brefczynski-Lewis et al. 2007; Carter et al. 2005; van Leeuwen et al. 2012). During OMM, attention is widened to allow a more receptive and encompassing awareness of the sensorial, metacognitive and affective experiences occurring in each moment. With no singular internal or external object to selectively focus on, OMM instead emphasises continuous monitoring of awareness (Lutz et al. 2008; Vago and Silbersweig 2012). This wider scope of attention has been shown to benefit attention performance specifically in situations where the target stimulus is unexpected (Valentine and Sweet 1999). While FAM and OMM influences on attention could be considered as representing opposing forms of cognitive control or executive function, the complexity of the goal-oriented processes underlying these meditation types can be better understood from the metacontrol perspective proposed by Hommel (2015). Metacontrol describes the control of cognitive control as emerging from competition between task persistence and flexibility. Persistence promotes increased concentration on goal-relevant information and suppression of irrelevant information whereas flexibility reduces competition between relevant and irrelevant information to allow for implementation of multiple task approaches or solutions. Following this perspective, the goal of FAM to sustain attention establishes persistence metacontrol policies, which can be thought of as promoting serial, convergent thinking, while the goal of OMM to monitor awareness establishes flexible policies promoting parallel, divergent thinking (Colzato et al. 2012, 2014; Hommel 2015).

Meditation influences on regulatory mechanisms have been assumed to require a period of meditation training (Brefczynski-Lewis et al. 2007; Hodgins and Adair 2010; Malinowski 2013; Tang et al. 2007; van Leeuwen et al. 2012). However, it has been demonstrated that FAM and OMM provide instantaneous effects on metacontrol states even in naïve meditators (Colzato et al. 2015a, b, 2016; Lippelt et al. 2014). Moreover, it has been reported that control states established by FAM and OMM extend beyond the session of meditation to influence control policies in subsequent, unrelated tasks (Colzato et al. 2012, 2015a, b; Meiran et al. 2002). For example, Colzato et al. (2015a) reported that in comparison to OMM, a single-session of FAM subsequently increased attentional blink responses, illustrating that this meditation type establishes lasting metacontrol states that increase attention selectivity for target stimuli. Colzato et al. (2015b) had participants complete a 17-min session of FAM or OMM prior to completion of a Simon task, a 2-choice key pressing task that contrasts performance with and without response conflict. While FAM and OMM resulted in comparable levels of response conflict, those who had completed OMM prior to the Simon task displayed higher trial-to-trial adaptation to previous conflict. Because of its lasting effects on unrelated tasks, meditation represents a valuable heuristic for furthering our understanding of mechanisms that enhance human cognition including the processes that underlie behaviors that humans commonly rely on.

Modes of Control in Sequential Action

Sequential actions are an example of behavior that features prominently in most of the daily activities that humans undertake including those related to work (e.g., typing, operating machinery), performing sport related skills (e.g., tennis serve, kicking a penalty goal in football/soccer), the arts (e.g., playing a musical instrument, sculpting), and personal-care (e.g., brushing teeth, dressing, cooking). For the purpose of the present work, sequential action is defined as a sequence of movements that are serially ordered in order to achieve a task goal (Abrahamse et al. 2013; Sakai et al. 2004). The sequence of movements that underlie sequential action are ultimately the result of the outflow arising from underlying cognitive processes that are shared by other behaviors including those that do not involve movement. Thus, sequential action is a form of goal-oriented behavior and as such, it would be reasonable to expect that metacontrol states (Hommel 2015) influence sequential action. Despite this, the role of competition between goal persistence and cognitive flexibility in sequence learning and consequently, the possibility that metacontrol states established by previous goal-oriented tasks can influence sequence performance and learning has not featured in current models of sequential action acquisition (Abrahamse et al. 2010, 2013; Clegg et al. 1998; Daltrozzo and Conway 2014; Keele et al. 2003; Schwarb and Schumacher 2012; Tubau et al. 2007).

Since sequential action performance is based on autonomous response elements, the learner can successfully accomplish the sequence goal either by performing each sequence element independently or by developing and implementing an integrated plan formed by associations between response elements (Hommel 1996). The former type of control represents stimulus-driven responding

(Schneider and Shiffrin 1977; Stroop 1992) since the production of each response element is driven by local information, including stimuli signaling the response element. In previous models of sequence learning, this form of sequential action control has been referred to as a "prepared-reflex" (Hommel 2000), stimulus-based planning (Tubau et al. 2007), a reaction mode (Abrahamse et al. 2010, 2013), low-level encoding (Clegg et al. 1998) and a unidimensional system (Keele et al. 2003) and is henceforth referred to as stimulus-oriented responding. Because stimulus-oriented responding relies on sustained attention on target information and avoidance of distraction by irrelevant information, it would seem reasonable to expect that this mode of sequence learning relies on metacontrol states that support goal persistence. Goal persistence, however, might be too inflexible to allow the learner to perceive the complex structure by which response elements relate to one another (Hommel 2015). To have access to global sequence information, control must be relaxed (Amer et al. 2016) and thus metacontrol states that promote cognitive flexibility would be expected to benefit more optimal forms of sequence learning whereby the development of rich internalised plans provide processing efficiency in the production of each sequence element (Elsner and Hommel 2001; Holland 2008; Kiesel and Hoffmann 2004). This form of sequence learning is here referred to as sequence-oriented responding to capture the spirit of previous references to this type of sequence learning including response-based planning (Tubau et al. 2007), multidimensional representation (Keele et al. 2003), abstract-rule formation (Abrahamse et al. 2013), and intermediate level associations (Clegg et al. 1998).

Both stimulus-oriented and sequenced-oriented responding modes support performance improvements across practice, though the basis of these improvements is unique to the responding mode that is used during practice. For example, stimulus-oriented responding decreases response latency due to strengthened stimulus-response associations and increased capacity to selectively attend to target information. Because this type of performance improvement is typically exhibited even when the practiced task does not involve a sequence structure, such as the practice of simple reaction time tasks, it has been described as general practice effects (Abrahamse and Noordzij 2011). Performance improvement associated with learning under sequence-oriented responding instead represents sequence-specific learning (Abrahamse and Noordzij 2011; Robertson 2007; Willingham 1999) since here, efficiencies contributing to response latency reductions are based on established internalised sequence plans. These efficiencies are specific to the structure of practiced sequence and so, performance gains established by sequence-specific learning are lost in situations where the sequence structure is changed or removed.

Previous Investigation into the Instantaneous Effects of Single-Session Meditation on Sequence Learning

Despite the apparent overlapping themes between metacontrol states established in FAM and OMM meditation types and metacontrol states likely to influence sequence learning, to date, only one previous study has investigated single-session meditation influences on sequence learning. In an experiment reported by Chan et al. (2016) meditation naïve participants undertook sequence learning either immediately after a session of FAM or after a brief delay that interceded FAM and sequence learning. Comparison of sequence learning performance with a third control condition, involving no pre-learning meditation, revealed sequence learning enhancements from a session of FAM. However, the nature of these enhancements differed with respect to the timing of the FAM session relative to initiation of sequence learning. Specifically, sequence learning immediately after FAM provided for enhancement of general practice effects while inclusion of a delay between FAM and sequence learning resulted in enhancement of sequence-specific learning. These results illustrate the extent to which FAM establishes metacontrol states of goal persistence that consequently promote stimulus-oriented responding modes of sequence learning. The inclusion of a brief delay period between FAM and sequence learning allows for relaxation of cognitive control and consequently, greater utilisation of sequence-oriented responding modes of sequence learning.

The Present Experiment

The present experiment aimed to provide a further assessment of single-session meditation enhancement of sequence performance and learning. In addition to a FAM meditation type investigated by Chan et al. (2016), the present experiment also included an OMM meditation type to provide a more generalizable test of single-session meditation effects on sequential action performance and learning. Moreover, the inclusion of both FAM and OMM meditation types offered an opportunity to investigate whether the unique metacontrol states established by FAM and OMM (Colzato et al. 2012, 2015a, 2016; Lippelt et al. 2014) contributed to divergent forms of sequence learning enhancement. Specifically, there is the potential for persistence metacontrol state established by FAM (Lippelt et al. 2014) to transfer (Hommel 2015) into subsequent sequence learning resulting in enhanced stimulus-oriented responding. If this is so, sequence learning gains observed following a single-session of FAM would be expected to more closely align with general practice effects (Abrahamse and

Noordzij 2011) meaning that improvements in performance would be less reliant on the specific sequential structure present during learning. OMM, in contrast, establishes flexible metacontrol states and therefore weakens top-down control (Colzato et al. 2015a; Lippelt et al. 2014). Transfer of flexible metacontrol states (Hommel 2015) from OMM to sequence learning would result in greater availability of global sequence structure information (Amer et al. 2016) and thus enhance sequence-oriented responding. Consequently, performance improvements following OMM would be expected to more closely align with sequence-specific learning (Abrahamse and Noordzij 2011; Robertson 2007; Willingham 1999) where improvements in performance are reliant on the presence of the learned sequential structure.

Metacontrol states established by FAM and OMM might be associated with dissimilar levels of effort during meditation. As such, evaluation of meditation effort might provide further insights into the instantaneous effects of meditation and more specifically, FAM and OMM, on sequence learning. For example, in early experiences with meditation techniques, meditation effort has been shown to be higher with OMM as compared to FAM (Lumma et al. 2015). Considering that effort reflects the degree of cognitive demand experienced (Hockey 2011), this finding is relevant for the present topic as enhancement of sequence-specific learning has been demonstrated following completion of an unrelated task with high cognitive demand (Borragan et al. 2016). Increased cognitive demands by a preceding, unrelated task, according to Borragan et al. (2016), resulted in weakening of top-down control, which has been shown by others to benefit sequence-specific learning (Finn et al. 2014; Foerde et al. 2006; Galea et al. 2010). If OMM elicits higher levels of effort than FAM (Lumma et al. 2015), then OMM would result in greater depletion of control resources and consequently, weaker top-down control (Baumeister et al. 1994, 2007).

Methods

Participants

Seventy-two meditation naïve volunteers (mean age 19.7 ± 2.0 years; 61 right-handed, 3 mix-handed based on the Edinburgh Handedness Inventory – Short Form; Veale 2014) participated in the present experiment. Although current affiliation with the university or education level was not explicitly recorded as a participant characteristic, some of the participants were undergraduate students who received partial course credit for participation while other participants were postgraduate students and members of the community who did not receive any course credit or any financial compensation for participation. The research protocol was approved by the local human research ethics committee (Leiden University, Faculty of Social and Behavioral Sciences) and all volunteers provided written informed consent prior to participation. Participants (60 female) were randomly and equally distributed in three experimental groups. Prior to sequence learning, 24 participants completed an open monitoring meditation (OMM) session, 24 completed a focused attention meditation (FAM) session and 24 completed a control listening condition. Data from three participants (1 from OMM, 2 from FAM) was excluded from analysis as more than 5% of their performance trials were identified as outliers. Outliers were identified for trials where performance exceeded the mean plus 3 standard deviations (Abrahamse and Verwey 2008).

Serial Reaction Time (SRT) Task

The SRT task paradigm (Nissen and Bullemer 1987) was employed in order to investigate the instantaneous effects of meditation states on sequence learning. The SRT task paradigm allows improvements in reaction time performance to be delineated as representing either general practice effects (Abrahamse and Noordzij 2011) or sequence-specific learning (Robertson 2007; Willingham 1999). The enhancement of general practice effects were assumed to reflect reliance on stimulus-oriented responding (Schneider and Shiffrin 1977; Stroop 1992; Tubau et al. 2007) since reductions in reaction time persist even when there is no sequential pattern present. In contrast, the enhancement of sequence-specific learning was assumed to imply increased capacity for sequence-oriented responding (Tubau et al. 2007) where reductions in reaction time are possible due to higher order associations formed and supported by a repeating sequence of responses (Robertson 2007; Willingham 1999).

The SRT task, illustrated in Fig. 1, was conducted using E-Prime® 2.0 version 2.0.10.356 (Psychological Software Tools Inc., Sharpsburg, PA, USA). Stimuli involved a row of four hollow boxes (each approximately 2° × 2°) that were spatially mapped to four response keys that were numbered 1 to 4, from left to right. The keys were pressed with the participants' index and middle fingers of the left (middle finger on key 1 and index finger on key 2) and right hand (index finger on key 3 and middle finger of key 4). The response key was signaled when one of the four boxes was filled in red. After each response, a 50-ms response-stimulus interval (RSI) preceded stimulus presentation for the next response. Inaccurate responses were notified with an error message and tone. Each block consisted of 120 trials, where a trial involved the presentation of one stimulus and the production of one response. At the end of each block, performance feedback indicating block averaged reaction time and error trial count was presented and followed by a 30-s rest interval.

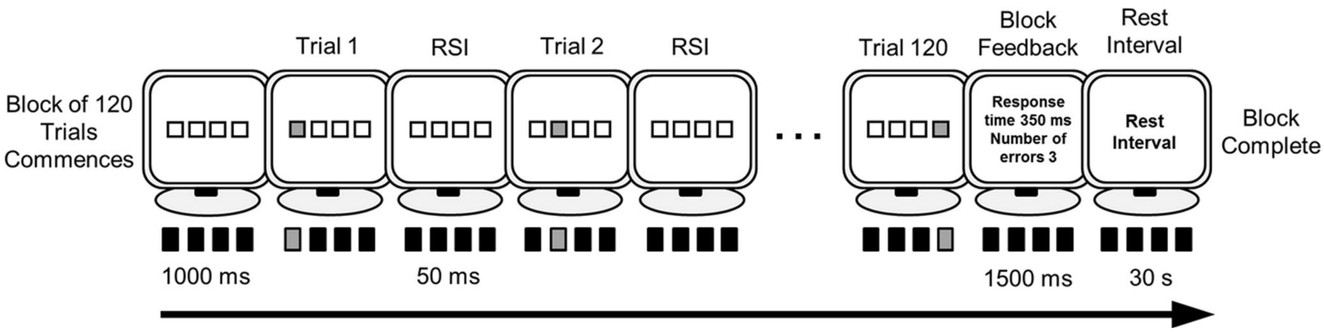

Fig. 1 Example of a block in the serial reaction time (SRT) task. *RSI* response-stimulus interval

Individual performance on the SRT task was based on response accuracy percentage and mean reaction time (MRT) measures that were calculated for each of the 3 baseline blocks and each of the 14 sequence learning blocks. Response accuracy percentage was calculated as percentage of trials in each block where the response was accurate. To calculate MRT, reaction time data from trials determined to be outliers (Abrahamse and Verwey 2008), which constituted 1.3% of the data, and from error trials were first removed.

In addition to response accuracy percentage and MRT performance for each block of the SRT task, overall performance improvement percentage, a composite score of learning improvement across the first 12 learning blocks, was calculated for each participant. This was calculated by first taking the ratio of MRT in sequence learning block 12 relative to sequence learning block 1, then subtracting this ratio from 1, and finally multiplying by 100. A larger overall performance improvement percentage indicated a greater decrease in MRT from sequence learning block 1 to 12. In order to measure the extent by which MRT performance in sequence learning block 12 relied on the embedded sequence, a sequence-specific learning percentage score was calculated for each participant by subtracting 1 from the ratio of MRT in block 13 relative block 12 MRT and then multiplying by 100. A greater reliance on the embedded sequence to perform the SRT task was reflected in larger sequence-specific learning percentages. Finally, a sequence interference percentage score was calculated to determine the extent by which transfer block 13 induced interference on the level of sequence learning acquired in block 12. Sequence interference percentage was calculated by subtracting 1 from the ratio of MRT in block 14 relative block 12 MRT and then multiplying by 100. Increasing sequence interference percentage values were indicative of greater disruption of the established sequence structure by the inserted transfer block involving a randomized order. Negative sequence interference percentage values are indicative of further performance gains between sequence learning blocks 12 and 14.

Procedure

Participants individually attended the laboratory to participate in the experimental procedure illustrated in Fig. 2. Participants first received written instructions for the SRT task in Dutch language. Instructions indicated to participants that they were to use the appropriate finger to press the response key that corresponded to the red filled box as quickly and as accurately as possible. Both speed of response and accuracy were indicated to be equally important for performance. Participants then completed three baseline blocks of the SRT task, where target location followed a pseudorandom order with the conditions that stimulus presentation was not repeated on consecutive trials and target location occurred with equal proportion in each block. Participants next completed a 17-min session of either FAM, OMM or a control condition each of which were described to participants as a mental exercise. In all conditions, recorded audio was presented in Dutch and played through headphones. Participants were seated and asked to

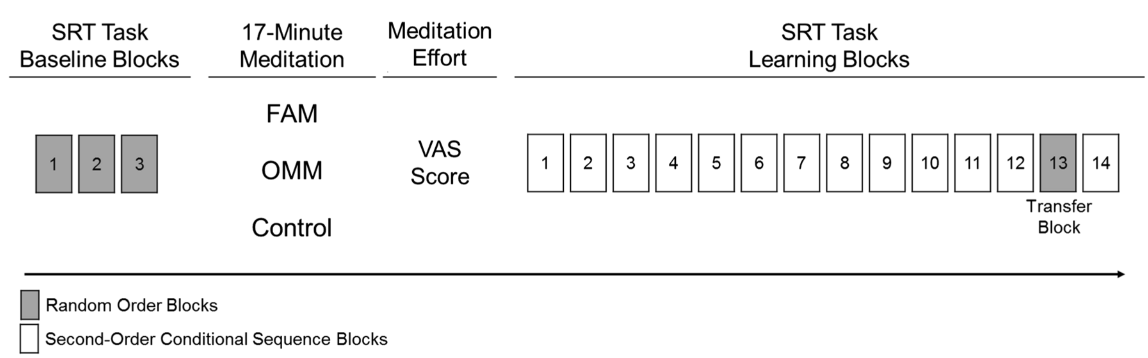

Fig. 2 Procedure for meditation sessions, measurement of meditation effort and serial reaction time (SRT) task baseline and learning blocks. *FAM* focused attention meditation, *OMM* open monitoring meditation, *VAS* visual analogue scale

keep their eyes closed, to refrain from moving and to follow the audio exercise as best as possible. Instructions for FAM and OMM were based on transcripts previously developed and validated by Baas et al. (2014) and previously investigated for their effects on cognitive control by Colzato and colleagues (Colzato et al. 2012, 2015a, b, 2016). In the FAM condition, a male voice guided participants in a step-by-step manner to focus and sustain their attention on their own breathing and to bring their attention back to their breathing whenever their attention had wandered. In the OMM condition, the same male voice guided participants in a step-by-step manner to monitoring their awareness of feelings, thoughts, and bodily sensations from moment-to-moment without conceptual elaboration or emotional reactivity. In the control condition, participants listened to a medley of instructional audio fragments involving descriptions of roman history, cooking recipes, agricultural history and debating skills. Each fragment was spoken by a different male voice and these voices were distinct to the voice in the FAM and OMM conditions. After the meditation or control sessions, participants opened their eyes and then completed a visual analogue scale (VAS) to report how much effort (Lumma et al. 2015) they experienced in completing the previous meditation or control session ("How demanding was the exercise for you?") on a 100-point scale where 0 = not at all and 100 = maximum. Participants then completed 14 sequence learning blocks of the SRT task. Unknown to participants, blocks 1 to 12 included a 12-item repeating second-order conditional (SOC) sequence (121342314324, Reed and Johnson 1994). Then, for block 13, a transfer test approach was used to distinguish between general practice effects from sequence-specific learning effects (Abrahamse and Noordzij 2011; Robertson 2007; Willingham 1999). This transfer block involved presenting the target location in a random order in a similar fashion to baseline blocks. In block 14, the SOC sequence was re-introduced.

Data Analysis

Response accuracy percentage for baseline and sequence learning blocks were separately analyzed using a 3 (group: FAM, OMM, control) × 3 (blocks: 1–3) ANOVA, with repeated measures on the last factor. For both baseline ($M = 96.8\%$, $SD = 2.04$) and sequence learning blocks ($M = 96.8\%$, $SD = 1.67$), there were no significant group effects (baseline, $p = .36$ and learning, $p = .53$) or group × block interactions (baseline, $p = .51$ and learning, $p = .78$). Furthermore, there was no significant correlation between response accuracy percentage and reaction time performance ($p = .77$). Consequently, response accuracy percentage was not reported as a SRT task performance measure.

MRT for the three baseline blocks was submitted to a 3 (group: FAM, OMM, control) × 3 (blocks: 1–3) ANOVA, with repeated measures on the last factor. To test for sequence learning enhancement following a single-session meditation, sequence learning MRT was compared between those who had previously completed a meditation (participants in FAM or OMM conditions) and those who completed the control condition. For this purpose, MRT for each participant was averaged across the 14 sequence learning blocks and submitted to an independent-samples *t* test. To then test for specific effects of FAM and OMM on sequence learning in comparison to the control condition, MRT was then submitted to 3 (group: FAM, OMM, control) × 14 (blocks: 1–14) ANOVA, with repeated measures on the last factor. Greenhouse-Geisser corrections were implemented where the assumption of sphericity was violated but for clarity, effects were reported with original degrees of freedom. Effect sizes were calculated using partial-eta squared (η_p^2; small = 0.01, medium = 0.06, large = 0.14; Green and Salkind 2005). Post hoc analysis was conducted following significant group effects or significant group × block interactions using Fisher's least significant difference (LSD).

To further test for sequence learning enhancement following a single-session meditation, individual overall performance improvement percentage scores were submitted to an independent-samples *t* test to compare those who had completed a single-session of meditation (FAM or OMM) prior to sequence learning to those in the control condition. To delineate effects of FAM, OMM and control conditions on overall performance improvement, sequence-specific learning and sequence interference percentage scores as well as effort VAS scores, these measures were separately submitted to one-way between subjects ANOVA. In addition, correlations between effort and overall performance improvement, sequence-specific learning and sequence interference measures were tested by calculating Pearson product-moment correlation coefficients.

Results

Baseline Performance

For MRT in baseline blocks, which occurred prior to meditation or control sessions, there was no significant effect of group ($F[2, 66] = 1.64$, $p = .20$) and no significant group by block interaction ($F[4, 132] = 0.38$, $p = .78$) . A significant block effect, $F(2, 132) = 51.04$, $p = .0001$, $\eta_p^2 = .44$, was based on a significant decrease ($p = .0001$) in MRT from baseline block 1 ($M = 432.8$ ms, $SD = 48.7$) to block 2 ($M = 408.0$ ms, $SD = 42.1$) but no significant change ($p = .97$) in MRT between baseline block 2 and 3 ($M = 408.1$ ms, $SD = 40.6$). See Fig. 3 for baseline MRT performance.

Sequence Learning Performance

Comparison of aggregated MRT from sequence learning blocks 1 to 14 between preceding meditation (FAM and

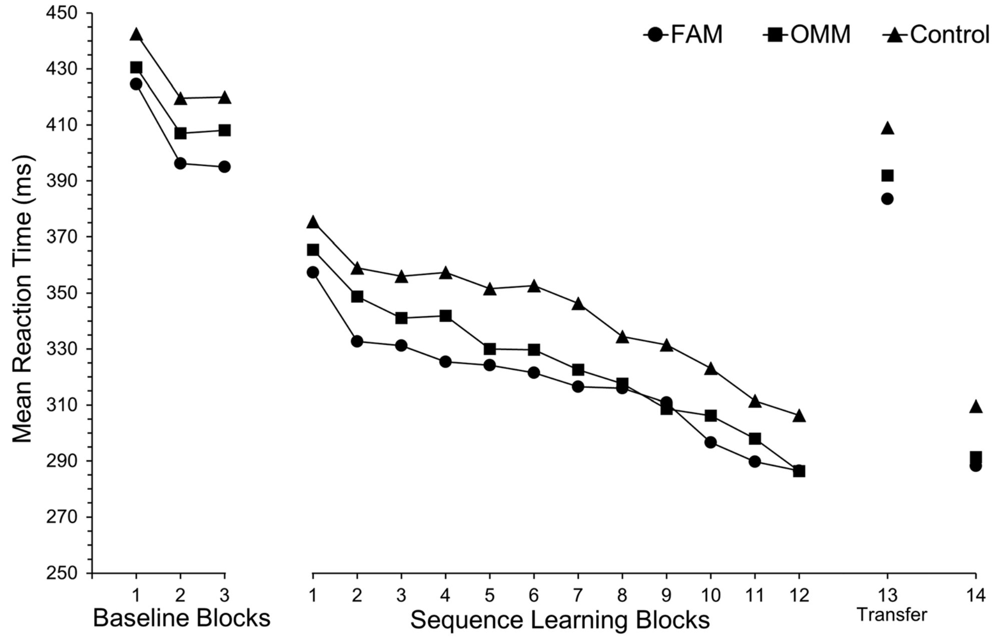

Fig. 3 Mean reaction time performance for meditation condition groups in serial reaction time (SRT) task baseline and sequence learning blocks. *FAM* focused attention meditation, *OMM* open monitoring meditation

OMM combined) and control groups revealed significantly shorter MRT performance following a single-session of meditation (M = 323.6 ms, SD = 39.1) relative to the control condition (M = 344.56 ms, SD = 32.5), $t(67) = -2.24$, $p = 0.029$. Subsequent analysis of MRT in sequence learning blocks for FAM, OMM and control conditions revealed no significant effect of group effect (F[2, 66] = 2.68, p = .076), no significant group × block interaction (F[26, 858] = 0.75, p = .81) but a significant effect of block, $F(13, 858) = 153.35$, p = .0001, η_p^2 = .70. Post hoc analysis indicated that across blocks 1 to 12, significant decreases in MRT occurred between blocks (p = .03 and below) with the exception that MRT was not significantly different between blocks 3 and 4 (p = .49) and blocks 5 and 6 (p = .80). Block 13 MRT (M = 395.2 ms, SD = 36.4) was significantly longer (p = .0001) than all other sequence learning blocks. Block 14 MRT (M = 296.7 ms, SD = 46.5) was significantly shorter than MRT in blocks 1 to 10 and block 13 (all p = .0001) but was not significantly difference from MRT in block 11 (p = .27) and 12 (p = .32). See Fig. 3 for MRT performance in sequence learning blocks.

Overall Performance Improvement, Sequence-Specific Learning, Sequence Interference and Effort

Comparison of overall performance improvement percentage between meditation (FAM and OMM combined) and control groups indicated no significant difference in overall performance improvement between meditation (M = 20.9%, SD = 8.7) and control (M = 18.2%, SD = 10.3) conditions, $t(67) = -1.15$, p = .26. Subsequent analysis of sequence learning indicators in FAM, OMM and control groups revealed no significant group effects for overall performance improvement (F[2, 66] = 0.96, p = .39), sequence-specific learning (F[2, 66] = 0.46, p = .63) and sequence interference (F[2, 66] = 0.20, p = .82) percentages. Similarly, there was no significant group effect for effort VAS scores, $F(2, 66) = 1.97$, p = .15. Correlation between effort VAS score (M = 49.9, SD = 26.0) and overall performance improvement percentage (M = 19.9%, SD = 9.3) was significant, $r(69) = -0.27$, p = .024, as was the correlation between effort VAS score and sequence-specific learning percentage (M = 36.7%, SD = 16.8), $r(69) = -0.31$, p = .009. Effort VAS score and sequence interference (M = 1.1%, SD = 9.7) were not significantly correlated, $r(69) = -0.068$, p = .58.

Meditation Effort Influences on Sequence Learning

As effort significantly correlated with measures of overall performance improvement and sequence-specific learning, participants in meditation and control conditions were classified into high and low effort groups in order to re-analyze sequence learning performance with an additional between-subject effort level factor. Participants reporting VAS effort scores at or the overall mean of effort scores (M = 49.9, SD = 26.0) were categorised into a low effort group (N = 33) while those with scores above the overall mean were categorised into a high effort group (N = 36). The number of high and low effort participants within each group did not significantly differ between groups, X^2 (2, N = 69) = 3.87, p = .14. Effort VAS scores were significantly higher for the high effort group (M = 71.3, SD = 14.2) than the low effort group (M = 26.5, SD = 11.63), $t(67) = 14.24$, p = .0001.

MRT in sequence learning blocks was again submitted to ANOVA with the new effort level factor included with group and block factors, see Fig. 4. The main effect of effort level

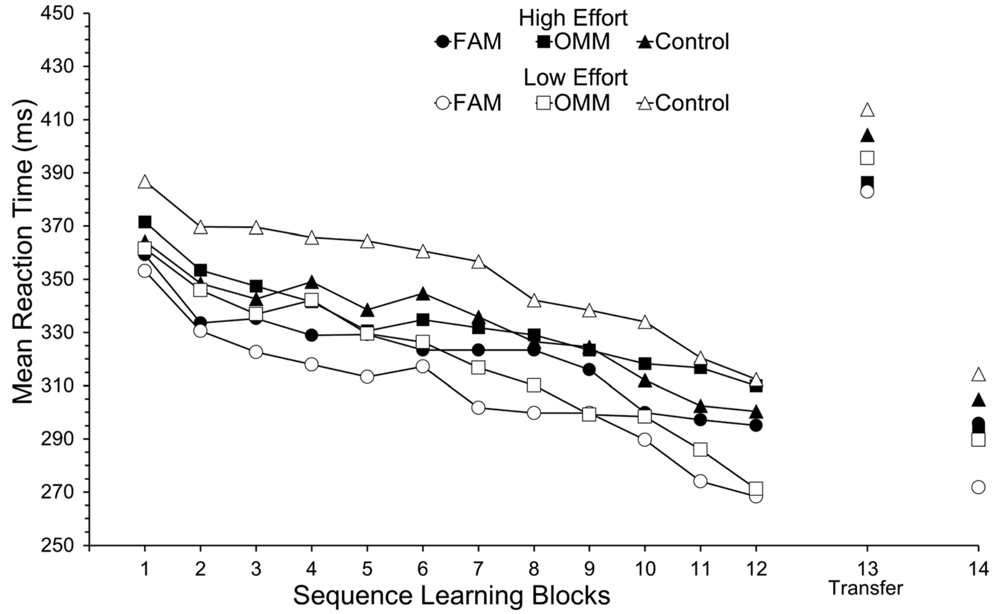

Fig. 4 Mean reaction time performance in serial reaction time (SRT) task sequence learning blocks as a function of meditation and effort conditions. *FAM* focused attention meditation, *OMM* open monitoring meditation

($F[1, 63] = 0.11$, $p = .74$) as well as the group × effort level ($F[2, 63] = 1.35$, $p = .27$) and group × effort level × block ($F[26, 819] = 1.00$, $p = .45$) interactions were not significant. However, the effort level × block interaction was significant, $F(13, 819) = 2.2$, $p = .045$, $\eta_p^2 = .034$. Post hoc analysis indicated that while MRT in each block was not significantly different between effort level groups, including in the transfer block 13, the effort level groups differed with respect to the manner by which MRT decreased across the sequence learning blocks. For example, in the high effort group, MRT was not significantly different between blocks 2, 3 and 4 and blocks 5, 6, 7 and 8 ($p = .10$ and above) while in the low effort group, MRT was not significantly different between blocks 3 and 4 and blocks 5 and 6 ($p = .60$ and above).

Overall performance improvement, sequence-specific learning and sequence interference measures were separately submitted to ANOVA with group and effort level factors, see Fig. 5. Low effort responders ($M = 22.7\%$, $SD = 10.7$) demonstrated significantly larger overall performance improvement than high effort responders ($M = 17.3\%$, $SD = 7.1$), $F(1, 63) = 5.98$, $p = .017$, $\eta_p^2 = .087$. The group × effort level interaction was not significant ($F[2, 63] = 0.87$, $p = .42$) for overall performance improvement. The effect of effort level for sequence-specific learning percentage was significant, $F(1, 63) = 10.7$, $p = .002$, $\eta_p^2 = .145$, but this was superseded by a significant group × effort level interaction, $F(2, 63) = 3.4$, $p = .041$, $\eta_p^2 = .097$. Post hoc analysis indicated that in participants who experienced the control session, the index of sequence-specific learning did not differ significantly ($p = .96$) between low effort ($M = 34.6\%$, $SD = 15.4$) and high effort ($M = 34.9\%$, $SD = 12.6$) responders. In contrast, with participants who experienced FAM or OMM sessions, low effort groups demonstrated significantly higher ($p = .034$, .001, respectively) sequence-specific learning ($M = 46.4\%$, $SD = 28.5$ and $M = 48.3\%$, $SD = 15.6$, respectively) than the high effort group ($M = 31.2\%$, $SD = 10.7$ and $M = 25.5\%$, $SD = 10.0$, respectively). In addition, sequence-specific learning did not significantly differ between groups in those placed in the high effort group ($p = .17$ and above). With low effort, sequence-specific learning was not significantly different between those who had experienced FAM and control sessions ($p = .11$) and between those who experienced FAM and OMM sessions ($p = .80$). Low effort, OMM conditions, on the other hand, demonstrated significantly higher sequence-specific learning than low effort control conditions ($p = .027$). While the effect of effort level on sequence interference approached significance, $F(1, 63) = 3.4$, $p = .071$, the group × effort level interaction was significant, $F(2, 63) = 3.6$, $p = .032$, $\eta_p^2 = .103$. Post hoc analysis indicated that the source of this interaction was based on low effort, OMM conditions ($M = 7.2\%$, $SD = 10.4$) demonstrating significantly higher sequence interference ($p = .002$) than high effort, OMM conditions ($M = -5.6\%$, $SD = 6.2$) while sequence interference between low and high effort groups did not significantly differ between those who experienced FAM ($p = .91$) or control ($p = .86$) sessions. Differences in sequence interference between high effort, OMM conditions and high effort, control conditions ($M = 1.8\%$, $SD = 10.2$) sessions approached significance ($p = .072$) while there were no significant differences in sequence interference in other group comparisons in high effort ($p = .12$ and above) and low effort ($p = .10$ and above) groups.

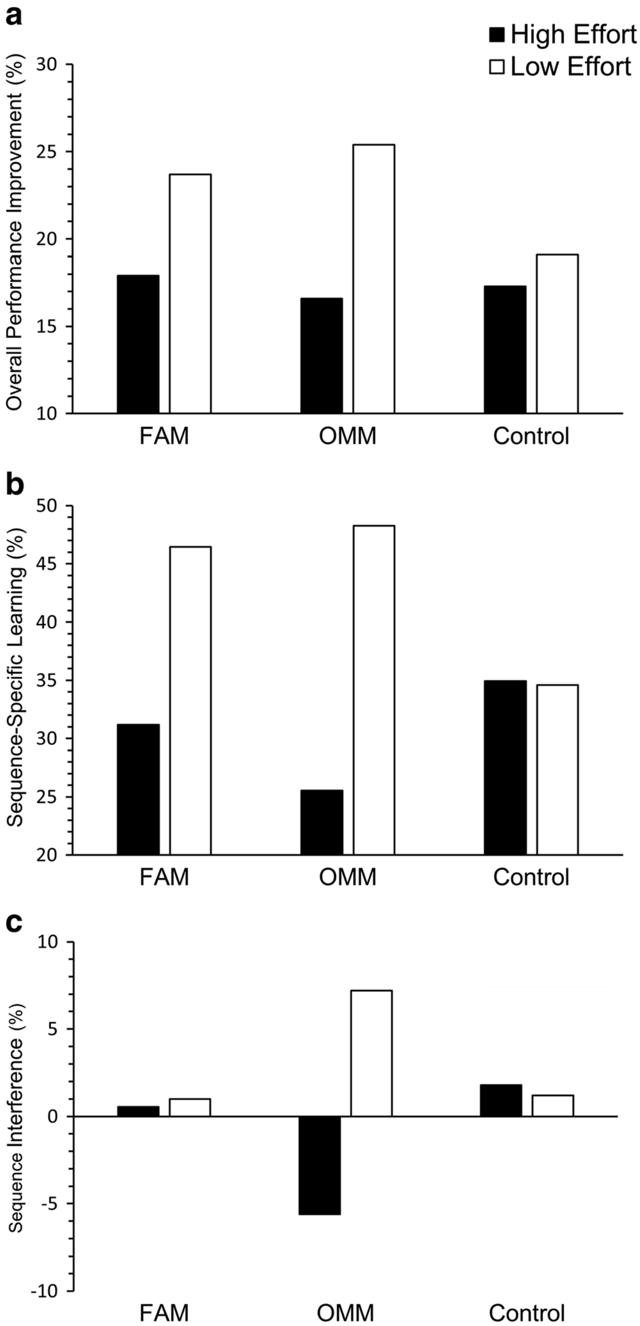

Fig. 5 Percentage overall performance improvement (**a**), sequence-specific learning (**b**), and sequence interference (**c**) for meditation and effort conditions preceding serial reaction time (SRT) task learning blocks. *FAM* focused attention meditation, *OMM* open monitoring meditation

Discussion

The aim of the present experiment was to investigate if a single-session of meditation enhances subsequent sequence learning. Both FAM and OMM were predicted to lend benefits for sequence learning; however, as these meditation types are thought to establish distinct metacontrol states (Colzato et al. 2015a, b, 2016; Hommel 2015; Lippelt et al. 2014), there was the potential for FAM and OMM to differ with respect to promotion of general practice effects or sequence-specific learning (Abrahamse and Noordzij 2011; Robertson 2007; Willingham 1999). FAM was predicted to display enhancement of performance through general practice effects since this meditation type establishes goal persistence metacontrol states that promote a stimulus-oriented responding mode of sequence performance. Metacontrol in OMM, in contrast, encourages cognitive flexibility, which supports sequence-oriented responding modes of sequence learning. Thus, OMM was predicted to enhance sequence-specific learning.

Single-Session Meditation Enhancement of Performance Versus Sequence Learning

To test the prediction that sequence learning is enhanced following a single-session of meditation, performance was first compared on the basis of whether meditation (FAM and OMM) or control conditions preceded the task. Overall, MRT was significantly shorter following meditation. This finding is consistent with a previous report of enhanced SRT task performance following a single-session of FAM (Chan et al. 2016) and at the same time, this finding extends the previous report by illustrating that in addition to FAM, OMM also provides instantaneous enhancement of performance in a sequential action task. More generally, the present case of heightened performance following meditation lends further support to a growing body of evidence demonstrating the capacity of meditation to enhance cognitive performance including in tasks where performance relies on attention control (Colzato et al. 2015a, b, 2016; Tang et al. 2007).

As the aim of the present experiment was to investigate sequence learning in addition to performance, the improvement in performance across sequence learning blocks was then compared between meditation and control groups. Meditation and control groups did not significantly differ with respect to performance improvement in the SRT task. Furthermore, there was no apparent enhancement of sequence learning outcomes when the specific types of meditation, FAM and OMM, were compared to one another and to the control condition. Together, these findings suggest that despite the observed benefits of meditation for performance, sequence learning is not enhanced by a single-session of mediation in general or FAM or OMM meditation types specifically; though, this conclusion would be somewhat premature since analysis of the effort associated with meditation yielded a more complex pattern by which FAM and OMM influence sequence learning.

Effort in Focused Attention and Open Monitoring Meditation Types

Meditation effort was investigated in the present experiment to pursue a previous report of higher effort with early experiences with OMM as compared to FAM (Lumma et al. 2015). Higher effort was thought to reflect increased demands under OMM relative to FAM and under this heightened demand, control resources would be exhausted resulting in weakening of control (Baumeister et al. 1994, 2007) and consequently, enhancement of sequence-specific learning (Borragan et al. 2016). Contrary to Lumma et al. (2015), however, effort in the present experiment did not significantly differ between OMM and FAM meditation types and these did not elicit any greater effort than the control condition. Disparity between the present results and those reported by Lumma et al. (2015) might be attributable to differences in the level of experience with FAM and OMM meditation types at the time effort was measured. Specifically, Lumma et al. (2015) first measured effort following 3 weeks of experience with FAM and OMM meditation types while in the present experiment, effort was measured in the first experience with the allocated meditation type.

Meditation Type and Effort Interact to Influence Sequence Learning

Despite the absence of differences in effort between meditation types and the control condition, there were significant negative correlations between effort and overall practice improvement and effort and sequence-specific learning. In response to these correlations and to investigate if effort moderated the influence of meditation on sequence learning, participants were categorised into high and low effort groups. Inclusion of the effort level in analyses of SRT task learning blocks revealed that irrespective of the meditation or control session experienced prior to sequence learning, low effort conditions exhibited significantly higher overall performance improvement than high effort conditions. Moreover, to achieve these performance gains, those in low effort conditions displayed more extensive utilisation of the embedded sequence structure as evidenced by significantly larger sequence-specific learning percentages. While effort level and meditation factors did not interact to influence overall performance improvements, sequence-specific learning, in contrast, depended on the interaction between effort level and meditation conditions. Prior to more in depth examination of this interaction, some discussion of how the present effects of effort on sequence learning compare to previous work by Borragan et al. (2016) and the notion of control resource depletion (Baumeister et al. 1994, 2007) is warranted.

Recall that Borragan et al. (2016) demonstrated facilitation of SRT task performance including greater sequence-specific learning following increased cognitive fatigue. This is in contrast to the present pattern of suppressed overall performance improvement and sequence-specific learning following high effort. A noteworthy point is that the present experiment measured effort while Borragan et al. (2016) measured cognitive fatigue. At this point, it is not clear why sequence-specific learning benefitted from low effort in the present experiment but benefitted from high cognitive fatigue previously (Borragan et al. 2016) given that high effort in response to increased demands is what is thought to underlie cognitive fatigue (Hockey 2011) and consequently, reduced control regulation (Baumeister et al. 1994, 2007).

Returning now to the interaction between meditation and effort on sequence-specific learning allows for closer inspection of the present findings in relation to the aim of the experiment. Initial analyses of sequence-specific learning and sequence interference measures did not reveal any significant benefit of meditation over the control condition or any differences between meditation types. Subsequent consideration of the level of effort associated with meditation and control sessions, exposed a very different pattern. In comparison to the control condition, the benefit of a single-session of meditation for sequence-specific learning was demonstrated following OMM but only in those reporting low effort. In contrast, low effort during FAM did not provide sequence-specific learning benefits relative to the control condition. Those responding high effort in FAM or OMM did not exhibit any benefit for sequence-specific learning relative to the control condition. Thus, only in those who experienced low effort during FAM and OMM do the present results follow what might be expected based on the notion that FAM establishes goal persistence metacontrol states while OMM establishes metacontrol states that allow for more flexible implementation of cognitive processes (Colzato et al. 2015a, b, 2016; Lippelt et al. 2014).

An extension of the notion that OMM establishes flexible control states that promote sequence-oriented responding modes of learning is to expect that OMM would result in the learner being particularly sensitive to the effects of interference when the sequence structure is changed (Brashers-Krug et at. 1996). Indeed, only following OMM did the random-ordered transfer block cause a loss of performance in the final block where the sequence structure was re-introduced. That interference was only observed with low effort OMM while high effort OMM displayed performance gains following the transfer block is consistent with the present interpretation that flexible metacontrol was only established by low effort OMM. Whereas cognitive flexibility established by low effort OMM prompted use of sequence-oriented responding during the learning blocks, increased interference following low effort OMM represents a continued attempt to implement sequence-oriented responding modes even when the sequence structure was removed in the transfer block. This attempt to form new response associations in the transfer block destabilised previously established sequence structure associations causing loss of performance from that displayed prior to the transfer block.

The present pattern of results is consistent with previous demonstrations of convergent thinking following FAM and divergent thinking following OMM (Colzato et al. 2012, 2014). Moreover, the present findings indicate that in addition to utilisation of local or global task information (Colzato et al. 2016), adaptation to stimulus-response conflicts (Colzato et al. 2015b) and attention allocation efficiency (Colzato et al. 2015a), metacontrol states following FAM and OMM also provide immediate influences for human sequential action. A unique contribution from the present experiment is the implication that metacontrol states established by FAM and OMM and their immediate effects on human cognition, sequence learning, in particular, is intervened by meditation effort. Thus, the present experiment raises important questions about how engaging in meditation is controlled in and of itself.

Future Directions to Clarify the Relationship Between Effort, Meditation and Sequence Learning

Future work is needed to determine the relationship between cognitive demands, effort and fatigue and the control of sequence learning and if this relationship is dependent on the nature of the task experienced prior to sequence learning. Increased effort or fatigue experienced as a consequence of more demanding control in meditation might subsequently influence sequence learning differently than when effort or fatigue arises from increased demands associated with computer-based cognitive tasks. More broadly, future work should be directed at examining the underlying factors by which individuals experience differing levels of effort in their initial exposure to meditation. The segregation of effort level in the present experiment might be explained by individual preferences for performing goal-oriented tasks under persistence or flexibility metacontrol dimensions (Hommel 2015). This might be especially so when individuals undertake novel task goals such as sustaining attention on breathing in FAM or monitoring awareness in OMM. High effort in early meditation experiences might arise in individuals for whom the inflexibility of top-down control is a more basic default state (Lippelt et al. 2014; Lutz et al. 2008; Vago and Silbersweig 2012), especially when there is a strong risk of mind wandering or distraction (Hasenkamp et al. 2012; Tops et al. 2014). Low effort might reflect individuals who prefer more flexible control to explore the novel task or because they deem flexibility to be more suitable for the task. Aside from what might cause individual differences in meditation effort, the important issue is that if divergent levels of meditation effort reflect different metacontrol states that are consistent or inconsistent with the nature of the meditation technique, then differences in meditation effort might be washing out what is hypothesized to be the opposing metacontrol states of FAM and OMM.

Interestingly, in the present control condition, which involved listening to a narration of historical and methodological information, the proportion of high and low effort responders was equivalent to proportions observed in the meditation groups. As with FAM and OMM conditions, those in the control condition who reported high effort might also be employing inflexible metacontrol processes to maintain attention on the narration against the pressure of mind wandering even when there was no explicit instruction to do so. Thus, it is apparent that similar to meditation conditions, participants in the control condition were engaging the audio information as opposed to letting their mind wander for the entire duration of the session. However, even as the control condition resulted in both high and low effort levels, the manner by which the control condition interacted with effort level in influencing sequence-specific learning was different to that observed following FAM and OMM meditation types.

Limitations

There are several limitations to the present experiment first of which might have implications for the generalizability of the results. The participants represent adults with a high level of education given their association with a university including as undergraduate and graduate students. In addition, the sample had a higher percentage of females than what might be expected in the adult population meaning that the typical gender proportions are not represented in the present experiment. Another limitation relates to the measures of sequence learning employed in the present experiment. It is possible that the current analyses of performance in the SRT task might not be suitable to detect more subtle influences of meditation on sequence learning. For example, measures that assess temporal (Sakai et al. 2003) or rhythmic (Sakai et al. 2004) characteristics of sequenced behavior could provide further insights into the potential for meditation to enhance the acquisition of sequential action. Further, meditation might influence the manner by which sequential action is represented (Delevoye-Turrell and Bobineau 2012), which might not necessarily be reflected in speeded measures of sequential action performance such as reaction time. Finally, the present experiment included a control condition which was intended to share with FAM and OMM processes associated with listening to audio-recorded information. However, beyond the omission of the salient features of focusing attention in FAM and monitoring awareness in OMM, the control condition included other differences that might have introduced some unintentional effects on effort and subsequent sequence learning. For example, the recording in the control condition involved changing narrative themes and narrator voices.

Summary

The present experiment offers important contributions to the understanding of how consciousness and cognitive processes shape the performance and acquisition of sequential action in humans. The findings illustrate that regulatory processes that govern sequence learning (Clegg et al. 1998; Keele et al. 2003; Tubau et al. 2007) can themselves be regulated by metacontrol states (Hommel 2015) established by preceding goal-oriented tasks, represented here as meditation. A single session of meditation does appear to enhance sequence performance and further to this, a single session of meditation enhances sequence learning, though the type of performance improvement associated with learning depends on metacontrol features of FAM and OMM meditation types and the level of effort experienced in these meditation types. Specifically, this experiment demonstrated that the more robust form of learning, sequence-specific learning, was enhanced by low levels of effort in OMM relative to the control condition. This finding is consistent with the notion that complex forms of learning benefit from diminished control (Amer et al. 2016). From the metacontrol perspective (Hommel 2015), the goal of widening awareness in OMM biased control states towards flexibility and for this purpose, top-down control was weakened. However, flexible control was only truly established in those who experienced low effort levels during OMM as their high effort meditation type counterparts had defaulted to top-down control strategies despite the encompassing nature of OMM. Flexible control states established by low effort OMM transferred to subsequent sequence learning whereby cognitive flexibility afforded access to richer sources of task information including embedded sequential structures. This enabled performance improvements to be borne out of sequence-oriented responding as opposed to stimulus-oriented responding (Abrahamse et al. 2010; Clegg et al. 1998; Keele et al. 2003; Tubau et al. 2007).

References

Abrahamse, E. L., & Noordzij, M. L. (2011). Designing training programs for perceptual-motor skills: practical implications from the serial reaction time task. *European Review of Applied Psychology-Revue Europeenne De Psychologie Appliquee, 61*(2), 65–76. doi:10.1016/j.erap.2010.12.001.

Abrahamse, E. L., & Verwey, W. B. (2008). Context dependent learning in the serial RT task. *Psychological Research-Psychologische Forschung, 72*(4), 397–404. doi:10.1007/s00426-007-0123-5.

Abrahamse, E. L., Jiménez, L., Verwey, W. B., & Clegg, B. A. (2010). Representing serial action and perception. *Psychonomic Bulletin & Review, 17*(5), 603–623. doi:10.3758/pbr.17.5.603.

Abrahamse, E. L., Ruitenberg, M. F. L., de Kleine, E., & Verwey, W. B. (2013). Control of automated behavior: insights from the discrete sequence production task. *Frontiers in Human Neuroscience*, *7*. doi: 10.3389/fnhum.2013.00082

Ainsworth, B., Eddershaw, R., Meron, D., Baldwin, D. S., & Garner, M. (2013). The effect of focused attention and open monitoring meditation on attention network function in healthy volunteers. *Psychiatry Research, 210*(3), 1226–1231. doi:10.1016/j.psychres.2013.09.002.

Amer, T., Campbell, K. L., & Hasher, L. (2016). Cognitive control as a double-edged sword. *Trends in Cognitive Sciences, 20*(12), 905–915.

Baas, M., Nevicka, B., & Ten Velden, F. S. (2014). Specific mindfulness skills differentially predict creative performance. *Personality and Social Psychology Bulletin, 40*(9), 1092–1106. doi:10.1177/0146167214535813.

Baumeister, R. F., Heatherton, T. F., & Tice, D. M. (1994). *Losing control: how and why people fail at self-regulation*. San Diego, CA: Academic Press.

Baumeister, R. F., Vohs, K. D., & Tice, D. M. (2007). The strength model of self-control. *Current Directions in Psychological Science, 16*(6), 351–355.

Borragan, G., Slama, H., Destrebecqz, A., & Peigneux, P. (2016). Cognitive fatigue facilitates procedural sequence learning. Frontiers in Human Neuroscience*, 10.* doi: 10.3389/fnhum.2016.00086

Brashers-Krug, T., Shadmehr, R., & Bizzi, E. (1996). Consolidation in human motor memory. *Nature, 382*(6588), 252–255. doi:10.1038/382252a0.

Brefczynski-Lewis, J. A., Lutz, A., Schaefer, H. S., Levinson, D. B., & Davidson, R. J. (2007). Neural correlates of attentional expertise in long-term meditation practitioners. *Proceedings of the National Academy of Sciences of the United States of America, 104*(27), 11483–11488. doi:10.1073/pnas.0606552104.

Carter, O. L., Presti, D. E., Callistemon, C., Ungerer, Y., Liu, G. B., & Pettigrew, J. D. (2005). Meditation alters perceptual rivalry in Tibetan Buddhist monks. *Current Biology, 15*(11), R412–R413. doi:10.1016/j.cub.2005.05.043.

Chan, R. W., Immink, M. A., Lushington, K., & Mosewich, A. D. (2016). Stimulus or response based sequence learning is determined by temporal placement of a preceding focused attention meditation. *Journal of Sport & Exercise Psychology, 38*(S), S52.

Clegg, B. A., DiGirolamo, G. J., & Keele, S. W. (1998). Sequence learning. *Trends in Cognitive Sciences, 2*(8), 275–281. doi:10.1016/S1364-6613(98)01202-9.

Colzato, L. S., Ozturk, A., & Hommel, B. (2012). Meditate to create: the impact of focused-attention and open-monitoring training on convergent and divergent thinking. *Frontiers in Psychology*, 3. doi: 10.3389/fpsyg.2012.00116

Colzato, L. S., Szapora, A., Lippelt, D. P., & Hommel, B. (2014). Prior meditation practice modulates performance and strategy use in convergent- and divergent-thinking problems. *Mindfulness*, 1–7. doi:10.1007/s12671-014-0352-9.

Colzato, L. S., Sellaro, R., Samara, I., Baas, M., & Hommel, B. (2015a). Meditation-induced states predict attentional control over time. *Consciousness and Cognition, 37*, 57–62. doi:10.1016/j.concog.2015.08.006.

Colzato, L. S., Sellaro, R., Samara, I., & Hommel, B. (2015b). Meditation-induced cognitive-control states regulate response-conflict adaptation: evidence from trial-to-trial adjustments in the Simon task. *Consciousness and Cognition, 35*, 110–114. doi:10.1016/j.concog.2015.04.012.

Colzato, L. S., van der Wel, P., Sellaro, R., & Hommel, B. (2016). A single bout of meditation biases cognitive control but not attentional focusing: evidence from the global-local task. *Consciousness and Cognition, 39*, 1–7. doi:10.1016/j.concog.2015.11.003.

Daltrozzo, J., & Conway, C. M. (2014). Neurocognitive mechanisms of statistical-sequential learning: what do event-related potentials tell us? *Frontiers in Human Neuroscience,* 8. doi: 10.3389/fnhum.2014.00437

Delevoye-Turrell, Y. N., & Bobineau, C. (2012). Motor consciousness during intention-based and stimulus-based actions: modulating attention resources through mindfulness meditation. *Frontiers in Psychology*, 3. doi: 10.3389/fpsyg.2012.00290

Elsner, B., & Hommel, B. (2001). Effect anticipation and action control. *Journal of Experimental Psychology-Human Perception and Performance, 27*(1), 229–240. doi:10.1037/0096-1523.27.1.229.

Finn, A. S., Lee, T., Kraus, A., & Kam, C. L. H. (2014). When it hurts (and helps) to try: the role of effort in language learning. *PloS One, 9*(7). doi:10.1371/journal.pone.0101806.

Foerde, K., Knowlton, B. J., & Poldrack, R. A. (2006). Modulation of competing memory systems by distraction. *Proceedings of the National Academy of Sciences of the United States of America, 103*(31), 11778–11783. doi:10.1073/pnas.0602659103.

Galea, J. M., Albert, N. B., Ditye, T., & Miall, R. C. (2010). Disruption of the dorsolateral prefrontal cortex facilitates the consolidation of procedural skills. *Journal of Cognitive Neuroscience, 22*(6), 1158–1164. doi:10.1162/jocn.2009.21259.

Gallant, S. N. (2016). Mindfulness meditation practice and executive functioning: breaking down the benefit. *Consciousness and Cognition, 40*, 116–130. doi:10.1016/j.concog.2016.01.005.

Gard, T., Holzel, B. K., & Lazar, S. W. (2014). The potential effects of meditation on age-related cognitive decline: a systematic review. *Advances in Meditation Research: Neuroscience and Clinical Applications, 1307*, 89–103. doi:10.1111/nyas.12348.

Green, S. B., & Salkind, N. J. (2005). *Using SPSS for Windows and Macintosh: analyzing and understanding data* (4th ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Hasenkamp, W., Wilson-Mendenhall, C. D., Duncan, E., & Barsalou, L. W. (2012). Mind wandering and attention during focused meditation: a fine-grained temporal analysis of fluctuating cognitive states. *NeuroImage, 59*(1), 750–760. doi:10.1016/j.neuroimage.2011.07.008.

Hockey, G. R. J. (2011). A motivational control theory of cognitive fatigue. In P. L. Ackerman (Ed.), *Cognitive fatigue: multidisciplinary perspectives on current research and future applications* (pp. 167–188). Washington, DC: American Psychological Association.

Hodgins, H. S., & Adair, K. C. (2010). Attentional processes and meditation. *Consciousness and Cognition, 19*(4), 872–878. doi:10.1016/j.concog.2010.04.002.

Holland, P. C. (2008). Cognitive versus stimulus-response theories of learning. *Learning & Behavior, 36*(3), 227–241. doi:10.3758/Lb.36.3.227.

Holzel, B. K., Lazar, S. W., Gard, T., Schuman-Olivier, Z., Vago, D. R., & Ott, U. (2011). How does mindfulness meditation work? Proposing mechanisms of action from a conceptual and neural perspective. *Perspectives on Psychological Science, 6*(6), 537–559. doi:10.1177/1745691611419671.

Hommel, B. (1996). The cognitive representation of action: automatic integration of perceived action effects. *Psychological Research-Psychologische Forschung, 59*(3), 176–186. doi:10.1007/Bf00425832.

Hommel, B. (2000). The prepared reflex: automaticity and control in stimulus-response translation. In M. S. & D. J. (Ed.), *Control of cognitive processes: attention and performance* (pp. 247–273). Cambridge, MA: MIT Press.

Hommel, B. (2015). Between persistence and flexibility: the Yin and Yang of action control. *Advances in Motivation Science, 2*, 33–67.

Immink, M. A. (2016). Post-training meditation promotes motor memory consolidation. *Frontiers in Psychology*, 7. doi: 10.3389/fpsyg.2016.01698

Keele, S. W., Ivry, R., Mayr, U., Hazeltine, E., & Heuer, H. (2003). The cognitive and neural architecture of sequence representation. *Psychological Review, 110*(2), 316–339. doi:10.1037/0033-295x.110.2.316.

Kiesel, A., & Hoffmann, J. (2004). Variable action effects: response control by context-specific effect anticipations. *Psychological Research-Psychologische Forschung, 68*(2–3), 155–162. doi:10.1007/s00426-003-0152-7.

Lippelt, D. P., Hommel, B., & Colzato, L. S. (2014). Focused attention, open monitoring and loving kindness meditation: effects on attention, conflict monitoring, and creativity—a review. *Frontiers in Psychology,* 5. doi: 10.3389/fpsyg.2014.01083

Lumma, A. L., Kok, B. E., & Singer, T. (2015). Is meditation always relaxing? Investigating heart rate, heart rate variability, experienced effort and likeability during training of three types of meditation. *International Journal of Psychophysiology, 97*(1), 38–45. doi:10.1016/j.ijpsycho.2015.04.017.

Lutz, A., Slagter, H. A., Dunne, J. D., & Davidson, R. J. (2008). Attention regulation and monitoring in meditation. *Trends in Cognitive Sciences, 12*(4), 163–169. doi:10.1016/j.tics.2008.01.005.

Malinowski, P. (2013). Neural mechanisms of attentional control in mindfulness meditation. *Frontiers in Neuroscience*, 7. doi: 10.3389/fnins.2013.00008

Manna, A., Raffone, A., Perrucci, M. G., Nardo, D., Ferretti, A., Tartaro, A., et al. (2010). Neural correlates of focused attention and cognitive monitoring in meditation. *Brain Research Bulletin, 82*(1–2), 46–56. doi:10.1016/j.brainresbull.2010.03.001.

Meiran, N., Hommel, B., Bibi, U., & Lev, I. (2002). Consciousness and control in task switching. *Consciousness and Cognition, 11*(1), 10–33. doi:10.1006/ecog.2001.0521.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cognitive Psychology, 41*(1), 49–100. doi:10.1006/cogp.1999.0734.

Moore, A., & Malinowski, P. (2009). Meditation, mindfulness and cognitive flexibility. *Consciousness and Cognition, 18*(1), 176–186. doi:10.1016/j.concog.2008.12.008.

Moore, A., Gruber, T., Derose, J., & Malinowski, P. (2012). Regular, brief mindfulness meditation practice improves electrophysiological markers of attentional control. *Frontiers in Human Neuroscience*, 6. doi: 10.3389/fnhum.2012.00018

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning—evidence from performance-measures. *Cognitive Psychology, 19*(1), 1–32. doi:10.1016/0010-0285(87)90002-8.

Reed, J., & Johnson, P. (1994). Assessing implicit learning with indirect tests—determining what is learned about sequence structure. *Journal of Experimental Psychology-Learning Memory and Cognition, 20*(3), 585–594. doi:10.1037//0278-7393.20.3.585.

Robertson, E. M. (2007). The serial reaction time task: implicit motor skill learning? *Journal of Neuroscience, 27*(38), 10073–10075. doi:10.1523/Jneurosci.2747-07.2007.

Sakai, K., Kitaguchi, K., & Hikosaka, O. (2003). Chunking during human visuomotor sequence learning. *Experimental Brain Research, 152*(2), 229–242. doi:10.1007/s00221-003-1548-8.

Sakai, K., Hikosaka, O., & Nakamura, K. (2004). Emergence of rhythm during motor learning. *Trends in Cognitive Sciences, 8*(12), 547–553. doi:10.1016/j.tics.2004.10.005.

Schneider, W., & Shiffrin, R. M. (1977). Controlled and automatic human information-processing.1. Detection, search, and attention. *Psychological Review, 84*(1), 1–66. doi:10.1037/0033-295x.84.1.1.

Schwarb, H., & Schumacher, E. H. (2012). Generalized lessons about sequence learning from the study of the serial reaction time task. *Advances in Cognitive Psychology, 8*(2), 165–178. doi:10.5709/acp-0113-1.

Slagter, H. A., Lutz, A., Greischar, L. L., Francis, A. D., Nieuwenhuis, S., Davis, J. M., & Davidson, R. J. (2007). Mental training affects distribution of limited brain resources. *PLoS Biology, 5*(6), 1228–1235. doi:10.1371/journal.pbio.0050138.

Stroop, J. R. (1992). Studies of interference in serial verbal reactions (Reprinted from Journal Experimental-Psychology, Vol 18, Pg 643–662, 1935). Journal of Experimental Psychology-General, 121(1), 15–23. Retrieved from <Go to ISI>://WOS:A1992HE76400004

Tang, Y. Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., et al. (2007). Short-term meditation training improves attention and self-regulation. *Proceedings of the National Academy of Sciences, 104*(43), 17152–17156. doi:10.1073/pnas.0707678104.

Tang, Y. Y., Holzel, B. K., & Posner, M. I. (2015). The neuroscience of mindfulness meditation. *Nature Reviews Neuroscience, 16*(4), 213–U280. doi:10.1038/nrn3916.

Tops, M., Boksem, M. A. S., Quirin, M., IJzerman, H., & Koole, S. L. (2014). Internally directed cognition and mindfulness: an integrative perspective derived from predictive and reactive control systems theory. *Frontiers in Psychology, 5*. doi: 10.3389/fpsyg.2014.00429

Tubau, E., Hommel, B., & Lopez-Moliner, J. (2007). Modes of executive control in sequence learning: from stimulus-based to plan-based control. *Journal of Experimental Psychology-General, 136*(1), 43–63. doi:10.1037/0096-3445.136.1.43.

Vago, D. R., & Silbersweig, D. A. (2012). Self-awareness, self-regulation, and self-transcendence (S-ART): a framework for understanding the neurobiological mechanisms of mindfulness. Frontiers in Human Neuroscience, 6. doi: 10.3389/fnhum.2012.00296

Valentine, E. R., & Sweet, P. L. (1999). Meditation and attention: a comparison of the effects of concentrative and mindfulness meditation on sustained attention. *Mental Health, Religion & Culture, 2*(1), 59–70.

van den Hurk, P. A. M., Giommi, F., Gielen, S. C., Speckens, A. E. M., & Barendregt, H. P. (2010). Greater efficiency in attentional processing related to mindfulness meditation. *Quarterly Journal of Experimental Psychology, 63*(6), 1168–1180. doi:10.1080/17470210903249365.

van Leeuwen, S., Singer, W., & Melloni, L. (2012). Meditation increases the depth of information processing and improves the allocation of attention in space. *Frontiers in Human Neuroscience*, 6. doi: 10.3389/fnhum.2012.00133

Veale, J. F. (2014). Edinburgh handedness inventory—short form: a revised version based on confirmatory factor analysis. *Laterality, 19*(2), 164–177. doi:10.1080/1357650x.2013.783045.

Willingham, D. B. (1999). Implicit motor sequence learning is not purely perceptual. *Memory & Cognition, 27*(3), 561–572. doi:10.3758/Bf03211549.

Zeidan, F., Johnson, S. K., Diamond, B. J., David, Z., & Goolkasian, P. (2010). Mindfulness meditation improves cognition: evidence of brief mental training. *Consciousness and Cognition, 19*(2), 597–605. doi:10.1016/j.concog.2010.03.014.