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A comparison of single-session focused attention meditation and computerised attention task
instantaneous effects on cognitive control in sequence learning

Russell W. Chan^{1,3}, Maarten A. Immink^{1,3*} and Kurt Lushington²

¹School of Health Sciences, ²School of Psychology, Social Work and Social Policy,
³Centre for Cognitive and Systems Neuroscience, Australia, Adelaide, South Australia

*Corresponding author:

Russell W. Chan

Email: russellchanweili@gmail.com

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ABSTRACT:

Chan et al. (2017) demonstrated that top-down control states established in FAM persist to influence subsequent sequence learning through increased stimulus-based planning. To test if top-down control influences on attention allocation and contribute to sequence learning effects of FAM, we compared against a computerised attention task (CAT). We investigated if effort, arousal or pleasure associated with FAM or CAT, explained the influence on sequence learning. Relative to Control, FAM and CAT resulted in shorter reaction time (RT) in the SRTT. FAM resulted in a greater rate of improvement than both CAT and control across training blocks of the SRTT, aligned with general practice benefits associated with reliance on stimulus-based planning. Neither effort, arousal or pleasure associated with FAM, CAT or control conditions correlated with SRTT performance or learning indices. Enhanced sequence learning following FAM is attributed to increased top-down control states established by FAM that transfer to subsequent sequence learning.

Keywords: sequence learning; meditation; attention; effort; pleasure; arousal; cognitive control

Highlights/ Key points:

- Serial reaction time performance is enhanced by a single-session of focused-attention meditation or a computerised attention task
- In comparison to a computerised attention task, focused-attention meditation supports greater rates of general practice effects associated with development of more efficient stimulus-based planning processes.
- Focused-attention meditation and computerised attention tasks both establish states of increased top-down control states resulting in enhanced subsequent performance while focused-attention meditation appears to uniquely utilise increased top-down control to enhance learning processes associated efficient use of target stimuli to select responses.

1. Introduction

Motor sequences are an integral part of everyday life. Activities of daily living such as driving to work, typing up documents, or preparing a meal, allow us to navigate and interact with the environment successfully. Although these motor sequences are performed with automaticity, cognitive research has yet to provide clear theoretical perspectives on information processing and sequence learning strategies. Recently, cognitive processes utilised in goal-directed behaviours are thought to play a crucial role in sequence learning which leads to the idea that movement sequences can be executed with different learning strategies (Verwey, Shea, & Wright, 2015). For example, cognitive control is a key component in sequence learning and govern the manner that attention is utilised in goal-directed behaviours. This raises the possibility that factors which influence cognitive control may also impact motor sequence learning. Of recent interest is the impact of meditation on cognitive control and especially attention, for subsequent cognitive processes utilised in various goal-directed behaviours. While different forms of meditation exist (Nash & Newberg, 2013), focused attention meditation (FAM) in particular appears to influence attentional control processes (Lutz, Slagter, Dunne, & Davidson, 2008). FAM is characterised by maintaining sustained attention on a specific instructed object (e.g. breath or body awareness) (Lutz et al., 2008; Slagter, Davidson, & Lutz, 2011). It has been shown to constrain attention in a narrow manner which, in turn, bias cognitive control to function in a convergent style for subsequent cognitive tasks (Colzato, Sellaro, Samara, Baas, & Hommel, 2015; Colzato, Sellaro, Samara, & Hommel, 2015). The cognitive control effects of FAM have also been shown to extend to complex sequence learning (Chan, Immink, & Lushington, 2017; Immink, Colzato, Stolte, & Hommel, 2017). Theoretical models of FAM (Malinowski, 2013; Tang, Holzel, & Posner, 2015) have proposed that as an outcome of practise core psychological processes such as effort (Immink et al., 2017; Lumma, Kok, & Singer, 2015), arousal (Amihai & Kozhevnikov, 2015), and pleasure have an influence on cognitive control but remain poorly understood. We provide a brief review of evidence for FAM on cognitive control and models of sequence learning strategies.

1.1. Cognitive control in sequence learning

Motor sequence learning research has provided several cognitive control paradigms that explain the acquisition and representation of sequential action (Abrahamse & Noordzij, 2011; Verwey et al., 2015; Verwey & Wright, 2014). Common amongst these are the interactions between attention, memory and executive functions and the development of

models for task representation, information processing and error resolution for learning improvements over time (Abrahamse, Jimenez, Verwey, & Clegg, 2010; Abrahamse & Noordzij, 2011; Daltrozzo & Conway, 2014; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Verwey et al., 2015). These models converge onto two strategies that stem from cognitive control (Verwey & Wright, 2014), namely responding to stimuli in an external stimulus-based control, or using sequence-specific representations via an internal plan-based control to engage in sequence learning (Tubau, Hommel, & Lopez-Moliner, 2007; Verwey & Clegg, 2005; Verwey et al., 2015). Importantly, these two strategies demonstrate that movement sequences can be executed with different processing strategies, which signifies that sequence learning is a cognitive task that relies on both central and perceptual processes (Verwey et al., 2015). This highlights the crucial role of cognitive control during learning (Tubau et al., 2007), where factors prior to and during learning can often bias cognitive control and therefore learning strategy.

Although both stimulus-based control and plan-based control learning strategies predict improved sequence learning with practice, the processes underlying performance improvement would differ. This can be demonstrated using the motor learning paradigm known as the Serial Reaction Timed Task (SRTT: Nissen & Bullemer, 1987). In the SRTT, a stimulus appears at one of several locations on a screen and participants must respond by pressing the corresponding key according to the stimulus location on the screen. Unbeknownst to them, the order of the stimuli follows a structured sequence that repeats over several cycles. Typically after several blocks of training, a transfer block with either a new or random sequence is presented and participants' exhibit increased reaction times due to learning of the original sequence that has occurred over the training blocks. The SRTT can be used to discern which strategy was utilised during learning. For example if an individual is using stimulus-based control, response latency decreases can be explained by reinforcement of the stimulus-response associations due to a strengthened top-down attentional focus for target stimuli. In this case, the stimulus is used as the main source of information to signal the response without further elaboration in the context of the sequence (Tubau et al., 2007). Here, performance improvement is evident even when the task is lacking a sequence and can be described as general learning effects (Abrahamse & Noordzij, 2011). By contrast in plan-based control, performance improvement is associated with sequence-specific representations which means that response efficiencies in latency reductions are based on reducing stimulus reliance, and instead rely on responses and feedback (Abrahamse & Noordzij, 2011; Robertson, 2007; Willingham, 1999). The efficiencies developed are specific to an

internalised structure of the practiced sequence, and so performance gains established by plan-based control are lost when there is deviance from the learnt sequence structure.

One of the main determinants for the development of either stimulus-based or plan-based control, is cognitive control for directing attention towards task-relevant stimuli and/or inhibition of irrelevant information (Friedman & Miyake, 2004; Gallant, 2016). Where a top-down control is enhanced, a resultant convergent control style will prioritise speed and accuracy in responding to the stimulus (Colzato, Ozturk, & Hommel, 2012). In contrast, a weakened top-down control facilitates a divergent control style that searches for different plans to the problem (Colzato et al., 2012), such as response-response associations in SRTT (Verwey et al., 2015). Importantly, recent work has found that cognitive tasks like meditation can bias cognitive control and attention in either convergent or divergent control styles (Colzato et al., 2012; Colzato, Szapora, Lippelt, & Hommel, 2017), which in turn affect stimulus-based and plan-based control when it precedes learning (Chan et al., 2017; Immink et al., 2017).

1.2. Sequence learning following a single-session of focused attention meditation

Recent investigations of single-session FAM practice supported that cognitive control was biased in a convergent control style during performance of subsequent goal-directed cognitive tasks (Colzato, van der Wel, Sellaro, & Hommel, 2016; Lippelt, Hommel, & Colzato, 2014; Lutz, Jha, Dunne, & Saron, 2015; van Leeuwen, Singer, & Melloni, 2012). For direct applications in sequence learning, when FAM immediately preceded learning, stimulus-based learning was responsible for reduction in response times and improvement in general learning performance, attributed to a convergent control style (Chan et al., 2017). In contrast, Chan et al. (2017) also showed that when FAM was temporally more distant relative to sequence learning, plan-based learning was responsible for greater levels of improvements in sequence-specific learning attributed to a weakened top-down control and divergent control style. As it stands, it may be too simplistic to assume that the immediate effects of FAM in naïve participants operate in one mechanistic fashion of biasing convergent cognitive control in sequence learning and that factors such as the temporal placement of FAM relative to learning, may also alter effects in cognitive control.

Another factor that may be modulating cognitive control from single-session FAM maybe related to perceived effort during practice. Effort is considered as a representation of the degree of cognitive demand (Fairclough & Houston, 2004; Hockey, 1997), and the mobilisation of cognitive resources needed in a task (Gendolla & Wright, 2009) and therefore

may be representative of cognitive flexibility processes that can be altered from meditation practice (Malinowski, 2013). Immink et al. (2017) found that perceived effort following single-session practice of meditation exerted different effects for the cognitive control of subsequent sequence learning in naïve participants. It is therefore possible that cognitive effort during FAM maybe modulating cognitive control to either convergent or divergent control that leads to stimulus- or plan-based learning. Further cognitive control effects of effort will be discussed in a later section.

1.3. Attentional control as a mechanism by which focused attention meditation influences sequence learning

Attention is featured prominently in theoretical models of meditation (Malinowski, 2013; Tang et al., 2015) as a central construct by which the cognitive system is augmented to influence mental states. One the main issues in meditation research is the design of suitable control conditions that mimics the same cyclical phenomenon of attention in cognitive control (i.e. monitoring, disengaging, shifting, sustaining, distraction, see Malinowski, 2013) during meditation practise for operational equivalence (Davidson & Kaszniak, 2015; Hasenkamp, Wilson-Mendenhall, Duncan, & Barsalou, 2012). The attentional function prioritises goal-relevant information, but can operate like a “zoom lens” (Eriksen & St James, 1986; Lutz et al., 2015), which focuses on different details during learning. This phenomenon is coined attentional aperture and describes that attentional control with an ability to adopt a narrow (tunnelled), mid or broad (attending to many global features) range in a continuum based on the engaged task (Derakshan, Ansari, Hansard, Shoker, & Eysenck, 2009; Eriksen & St. James, 1986; Ingram, 2009; Lutz et al., 2015).

Emerging research supports that the attentional aperture responds to cognitive control over global tasks and can be augmented by meditation practice in a neurobehavioral paradigm (Lutz et al., 2015). A single-session FAM has been shown to bias attentional allocation on subsequent cognitive tasks (Colzato et al., 2012; Colzato, Sellaro, Samara, Baas, et al., 2015; Colzato, Sellaro, Samara, & Hommel, 2015; Colzato et al., 2017). Specifically, a single-session of FAM in meditation naïve participants was shown to result in larger attentional blink response consistent with the notion of an increased attentional selection for target stimuli, indicating enhanced top-down control and a biased convergent processing style (Colzato et al., 2017; Colzato et al., 2016; Lippelt et al., 2014).

Since FAM is considered to influence sequence learning through attention control, then other cognitive tasks that involve attention focusing (via narrowing effects) may be

expected to exert similar result for stimulus-based planning in sequence learning. Particularly, laboratory-based computerised attentional tasks that are goal-directed, require participants to monitor stimuli through utilisation of attention and engage cognitive control to successfully meet task objectives (Basner & Dinges, 2011). When participants are less engaged or distracted, lapses in attention occur which are in a similar vein to cyclical cognitive control processes during meditation practice, where reengagement of task requires disengagement of the distraction to maintain focus. Computerised attentional tasks are therefore operationally targeted towards the utilisation and engagement of attentional control.

1.4. Other potential mechanisms by which focused attention meditation influences sequence learning: effort, arousal and pleasure

Although attention control in FAM is centralised, it is also a cognitive resource shared between core processes such as cognitive flexibility and emotion regulation thought to be influenced by meditation practice (Malinowski, 2013; Tang et al., 2015). Thus, enhanced sequential action following FAM (Chan et al., 2017) might not only be based on enhancement of attentional processes but also due to moderators of motor performance such as cognitive effort, arousal and pleasure. Earlier, we presented work that meditation increased mobilisation of cognitive resources resulting in subsequent enhanced motor performance (Immink et al., 2017). If meditation enhances sequence learning by increasing cognitive effort, it is then reasonable to suggest that similar preceding attention task might also increase effort resulting in sequence learning enhancement. Indeed Borrajan, Slama, Destrebecqz, & Peigneux (2016) showed that prior engagement in an unrelated computerised task that required high cognitive effort also affected sequence learning. Moreover, cognitive effort effects have been shown to be bidirectional and can facilitate either stimulus- or plan-based control strategies dependent on the level of engagement (Amer, Campbell, & Hasher, 2016).

In addition to effort effects, FAM practice also commonly induces positive pleasure states (Hamilton, Kitzman, & Guyotte, 2006), with low arousal, a relaxed and tranquil but alert state of mind (Kabat-Zinn et al., 1992; Lazar et al., 2000; Warrenburg, Pagano, Woods, & Hlastala, 1980). FAM might therefore also influence cognitive control in sequence learning through other alternative mechanisms such as arousal (Malinowski, 2013) and pleasure states (Hommel, 2015; van Steenbergen, Band, & Hommel, 2010), although there appears to be a lack of direct evidence. In essence, low arousal and positive pleasure states are typically associated with simple heuristics associated with reduced cognitive effort, more creative approaches, and a weakened top-down cognitive control (Schwarz, 1990) which is

biased towards more divergent cognitive control styles (Hommel, 2015). Indeed, Shang, Fu, Dienes, Shao, & Fu, (2013) showed that low arousal and increased pleasure states benefited sequential learning through plan-based control performance, whilst no differences in reaction time latency reductions for the SRTT between positive and negative states were found. Conversely, reduced pleasure states have narrowing effects which can occur independent of arousal levels (Easterbrook, 1959). It is thought that the narrowing acts as a shield from distraction by increasing effort and perceptual focus thus enabling concentration on a narrow stream of information at the expense of excluding relevant information (van Steenbergen et al., 2010). A process suggestive of a biased convergent cognitive control style. Pretz, Totz, & Kaufman (2010) found support for negative pleasure states to enhanced general learning performance in an artificial grammar sequencing task, but no benefit for positive mood in enhancing general or sequence-specific SRTT performance. Although effort, arousal and pleasure states can be manipulated, there is a gap in understanding whether effort, arousal and pleasure effects from FAM have a direct, indirect or operate in parallel to, influence cognitive control effects for sequence learning.

1.5. The present experiment

The goal of the current experiment was to test the effect of a single-session of FAM on subsequent motor sequence learning and whether FAM operated on a framework based on attentional control as a centralised mechanism. We proposed to compare FAM against a computerised attention task (CAT) as an active control task to strengthen our study design, in addition to a rest-only control group. The current experiment design also allowed for the replication of testing an earlier finding by Chan et al. (2017) that a single-session FAM could immediately bias cognitive control to influence subsequent sequence learning for general learning performance improvements against a rest-only control group. We predict that exposure to a single-session of FAM will bias top-down cognitive control in naïve participants by narrowing attentional control such that subsequent sequence learning relies primarily on stimulus-based control under the notion of general practice effects (Abrahamse & Noordzij, 2011), and not because of plan-based control under the notion of sequence-specific learning (Robertson, 2007; Willingham, 1999; Willingham, Wells, Farrell, & Stemwedel, 2000).

We also considered whether meditation related perceived effort, arousal and pleasure, would provide evidence to explain the immediate effects on sequential learning performance. We predict that if FAM related effort is high, arousal high, and pleasure low, a more

convergent cognitive control style would be resultant and therefore allow for benefits in general practice effect where decreasing response latencies are not attributable to a sequence structure. In contrast, if FAM related effort is low, arousal low, and pleasure high, a more divergent cognitive control style would be resultant and therefore allow for benefits in sequence-specific learning where improvements in response latencies are only evident when the sequence structure established during practice is available.

2. Methods and material

2.1. Participants

Fifty-five meditation naïve volunteers were recruited from a University course to participate in the present experiment in exchange for partial credit towards the course. We applied experimental exclusion criteria where participants needed to have at least six hours of sleep, no more than one standard alcoholic drink the night before, must not practice any form of meditation or taken part in a motor learning study within the last year by checking their names against our experimental database. Of these 55 participants, data from seven participants did not meet task performance criteria as described in section 2.6.3. Thus, data from 48 participants (24 females, 20.6 ± 2.6 years; 81.3% self-reported right-handed) remained for final analysis. Participants were unaware of the experiment aims during recruitment and provision of experiment-related information. The term ‘meditation’ was not used during the experiment to minimise participation bias. The research protocol was approved by the University of South Australia Human Research Ethics Committee and all participants provided written informed consent prior to participation.

Figure 1. Serial reaction time task (SRTT) blocks involved 120 trials each. Familiarisation Blocks involved a pseudo-random order of presentation, sequence learning blocks involved a second order conditional (SOC) sequence (121342314324; Reed & Johnson, 1994), Transfer Block involved another pseudo-random order of presentation, and in the final SRTT block the SOC sequence presented in sequence learning blocks was reinstated.

2.2. Serial Reaction Time Task

The SRTT (Nissen & Bullemer, 1987) is widely used to understand sequence learning under general practice effects (Abrahamse & Noordzij, 2011) and sequence-specific learning (Robertson, 2007; Willingham et al., 2000). The stimuli in the current experiment's SRTT involved a row of four hollow boxes that were spatially mapped to four response keys on a modified keyboard 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 signalled when one of the four boxes was filled in red. Stimuli was presented using E-Prime® 2.0 Software (Psychology Software Tools Inc., Sharpsburg, USA) on a 58.4cm-wide Alienware AW2310 LCD display running at 1680 X 1050 pixel resolution in 64-bit colour with a screen refresh setting of 120Hz. At a sitting distance of 60 cm from the display,

which was not strictly enforced, the visual angle dimension of each box was $2^\circ \times 2^\circ$ with 2° separating each box. After each response, a 50 ms response-stimulus interval occurred before the presentation of the stimulus for the next trial. Inaccurate responses were notified with an error message (“Key Error”) and tone was presented for 250 ms with the participant listening via generic over-the-ear Sennheiser headphones. At the end of each block, performance feedback was provided in terms of block averaged reaction time and count of error trials. Following feedback presentation, participants received a 30 s rest interval. Please see Figure 1 for an illustration of the SRTT.

The SRTT was organised firstly into three Familiarisation Blocks, which consisted of 120 pseudorandom stimulus presentation schedules with the condition that stimulus presentation was not repeated on consecutive trials and presented with equal proportion in each block. A trial represented the presentation of one stimulus and the production of one response. The next 12 blocks represented the main sequence Learning Blocks during the SRTT, where each comprised of 120 trials per block and a 12-item second order conditional sequence (i.e. 121342314324; Reed & Johnson, 1994) was used. Following completion of the sequence Learning Blocks, participants next completed one transfer block (Block 13) involving only pseudorandom trials, and in the final sequence learning block (Block 14), the original sequence was re-introduced.

2.3. Focused attention meditation (FAM)

The single-session of FAM was operationalised through a 22 min yoga nidra meditation technique involving four stages: preparation, directing attention to body regions, directing attention to natural breathing and completion (Saraswati, 2002). A full transcript of the meditation has been reported in Chan et al. (2017). Guided by the meditation taxonomy by Nash and Newberg (2013), yoga nidra was classified as a cognitive-directed type of meditation based on its overall goal of maintain attention on internal sensations associated with body regions and breathing. Yoga nidra was performed in a seated position and the eyes remained closed for the 22 min duration of the meditation. Instructions were audio-recorded using the voice of a male professional meditation instructor and the recording was played using E-Prime® 2.0 Software environment through headphones. Participants exposed to the single-session FAM were instructed that the aim of the task was to remain awake, not sleep, to remain still and to follow the audio instructions as best as possible.

Figure 2. The computerised attention task (CAT) was presented in one single block that lasted 22 minutes with no rest. Each trial was first presented with a fixation cross and then a random inter-stimulus interval of between 2 – 12 seconds before a pink dot appeared on the screen for the participant to respond. Participants had to press the spacebar as quickly as possible for correct trial responding. If a participant responded prior to the pink dot appearing, a message was shown that the response was ‘too fast’ and then a fixation cross would be presented to prepare for the next trial.

2.4. Computerised attention task

A single-session of FAM was compared to a single-session of a cognitive task that engaged sustained attention processes using a computerised attention task (CAT). The CAT required the participant to view the monitor and respond to the presentation of target visual stimuli. The CAT was conducted using the Psychology Experiment Building Language Perceptual Vigilance Task (Mueller & Piper, 2014). The CAT was 22 min in duration and the presented trials were in the range 149 – 164 across participants. For each trial of the CAT a fixation cross appeared in the centre of the monitor after which the target stimulus, a 2° diameter pink filled circle, appeared in the centre of the monitor following a

random interval between 2 – 12 s. Once the target stimulus appeared, participants responded as quickly as possible by pressing the spacebar. If a response occurred prior to target stimulus presentation, an error message was presented - ‘Too fast! Please wait for stimulus to appear’. Following an appropriate response, response latency feedback was presented to the participant. Reaction time (RT) performance data for each trial of the CAT was recorded and each trial was coded as too fast (response preceded stimulus), ok (where RT was between 0 and 500 ms), lapse (where RT was more than or equal to 500 ms) or sleep (where RT was greater than 3000 ms). Participants who completed the CAT performed with a mean RT of 349.9 ms in ok trials (89.8%), 2.8% of the trials were recorded as too fast, 7.4% were lapse trials and 0% were sleep trials. See Figure 2 for a pictorial representation of the CAT stimuli.

2.4. Measures of effort, arousal and pleasure.

Self-report measures of effort, arousal and pleasure were taken following a Rest period, following a cognitive Task (i.e. FAM, CAT or Control) and following the completion of the Sequence Learning. Participants were instructed that they were reporting on the task that immediately preceded measurement. Effort was measured with a 10-point Likert scale (0 = no effort to 10 = maximal effort). This method was used effectively to provide a self-judged index of overall effort (Lumma et al., 2015) which was operationally defined as a mobilisation of resources to carry out goal-directed behaviour (Gendolla & Wright, 2009). Arousal and pleasure were measured with a 9 x 9 Affect Grid, with values ranged from 1 to 9 from left to right, and from bottom to top (Russell, Weiss, & Mendelsohn, 1989). The measures of arousal (vertical axis) and pleasure (horizontal axis), were extracted from the marked positions on the grid where 1 = lowest levels of arousal and pleasure, and 9 = highest levels of arousal and pleasure. These two measures were analysed separately rather than a single global measure of affect (Colzato, Sellaro, Samara, Baas, et al., 2015). All measures were taken as pen and paper inventories from which scores were taken and entered electronically.

Figure 3. The experimental procedure. All participants firstly completed three Familiarisation Blocks that involved a pseudo-random order of presentation. After which a washout rest period of 22 minutes where they sat quietly with their eyes open was administered for all participants. At the Rest timepoint, participants completed a set of paper-based self-report measures in the form of an Affect Grid and effort Likert scale. Participants were then randomised to different groups that performed different cognitive tasks. Participants completed either a 22-minute focused-attention meditation (FAM), a 22-minute computerised attention task (CAT) or sat quietly for 22 minutes as rest-only Control. At the Task timepoint, participants were again presented with the Affect Grid and effort Likert scale. Then all participant performed the SRTT where each SRTT blocks involved 120 trials each. Sequence Learning Blocks 1 – 12 involved a second order conditional (SOC) sequence (121342314324; Reed & Johnson, 1994), Transfer Block 13 involved a pseudorandom sequence and in the final SRTT Block 14, the original SOC sequence presented in sequence Learning Blocks was reinstated. At the SRTT timepoint, participants were again presented with the Affect Grid and effort Likert Scale for completion of the experiment.

2.5. Procedure

The experimental procedure is illustrated in Figure 3. Participants received written instructions for the SRTT on the computer monitor on the use of appropriate fingers and to press the response keys that corresponded to the stimuli as accurately as possible. Response speed and accuracy was emphasised as equally important for the task. Participants completed three familiarisation SRTT blocks (Familiarisation Blocks 1 – 3) involving pseudorandom stimulus presentation for the participants to familiarise to the SRTT. After completion of the Familiarisation Blocks, all participants were required to sit quietly for 22 min, with the reason to wash out any influences of the familiarisation on arousal, pleasure and effort that might affect subsequent cognitive task engagement. Following quiet rest, participants completed measures of arousal, pleasure and effort.

Participants were then randomised into either FAM, CAT or Control experimental conditions that preceded sequence learning. Participants in the Control condition rested in a seated position with their eyes open for a duration of 22 m, which was equivalent to the

duration of FAM and the CAT. After FAM, CAT or Control conditions, participants completed measures of arousal, pleasure and effort.

Participants then commenced sequence learning with the SRTT. Participants were reminded that response speed and accuracy were of equal importance for performance. The SRTT involved 12 sequence learning blocks (Learning Blocks 1 – 12) where unknown to participants, stimulus presentation followed the repeating 12-item second order conditional sequence. The transfer block (Transfer Block 13) consisted of pseudorandom trials (same as familiarisation blocks). The insertion of the transfer block provided a test paradigm to determine the extent to which performance improvements in the sequence learning blocks relied on the original embedded sequence (Abrahamse & Noordzij, 2011; Daltrozzo & Conway, 2014). The insertion of the transfer block also challenged the stability of sequence representation acquired in the sequence learning blocks, which was evaluated by the inclusion of a final block (Learning Block 14) where the original sequence was re-introduced. After completion of the SRTT, participants completed final measures of arousal, pleasure and effort.

2.6. Data analysis

2.6.1. Reaction time

Participant RT performance was analysed through linear mixed-effects regression (LMER) models using the lme4 package (Bates, Mächler, Bolker, & Walker, 2015) in the R environment Ver. 3.4.3 (RStudio Team, 2015). In contrast to more traditional approaches with data aggregation and repeated measures in ANOVA analysis, LMER allowed for controlling for variance associated with random factors to estimate group effects on reaction time performance. In our main model, the outcome variable was - trial reaction time (ms) - and the predictor variables: (1) Group (i.e. FAM, CAT or Control), (2) Block (i.e. Familiarisation Blocks 1 – 3, Sequence Learning Blocks 1 – 14), (3) Response error (i.e. whether trial was an error or not). We specified subjects as a random factor to control for their associated intraclass correlation (i.e., random intercept models; Oberauer & Kliegl, 2006). We present type II Wald chi square tests with Kenward–Roger degrees of freedom approximation alongside the LMER results.

2.6.2. Learning indices: general learning, sequence-specific learning, and sequence interference

General learning performance was calculated for each participant to reflect the level of performance improvement (i.e., reduction in RT) across SRTT learning blocks 1 – 12, where the target second-order conditional was presented. For this, a regression analysis of correct-trial reaction times as the independent variable and trial number as a dependent variable. We determined if a linear or quadratic model was more representative of a participant's learning style by using the Curvefit analysis in SPSS Ver. 24 (IBM Corp., Armonk, N.Y., USA). With accordance to the method reported in Verstynen et al. (2012), if the ANOVA p value of the linear model was statistically more significant, the corresponding linear beta coefficient would be accepted as representative of the individual's learning over time. Consequently, if the ANOVA p value of the quadratic model was more significant the beta coefficient for both the linear and quadratic model were summated. The regression beta coefficient was considered the degree of trial RT change during learning and therefore representative of general learning performance during sequence Learning Blocks.

Sequence-specific learning percentage was calculated based on MRT performance between blocks 12 and 13. It was calculated by subtracting 1 from the ratio of MRT in block 13 relative to block 12 MRT and then multiplying by 100. Increasing percentage values were indicative of greater levels of sequence-specific learning. Sequence interference percentage was calculated by subtracting 1 from the ratio of MRT in block 14 relative to block 12 MRT and then multiplying by 100. Positive percentage values were indicative of poorer performance, whilst negative values were indicative of better performance due to faster responses relative to prior disruption. Participant general learning, sequence-specific learning and sequence interference indices were separately submitted to between-subject univariate ANOVA analysis to test for Group (FAM, CAT, Control) differences. Where a significant main effect of Group was found, post-hoc analyses were performed using LSD to determine locus of effect. Effect sizes in the univariate were based on partial-eta squared (η_p^2 ; small = 0.01, medium = 0.06, large = 0.14) (Green & Salkind, 2005). Statistical significance for all analyses were set at $p < .05$ and results are reported as means and standard deviations ($M \pm SD$).

2.6.3. Performance criteria

Performance criteria were applied to participants that were engaged in performing the SRTT, and this was done by comparing each individual's performance error, general learning performance and sequence-specific learning measures to ensure adequate levels of engagement. Based on SRTT research studies that report less than 5% error rates for SRTT

performance (Verwey & Clegg, 2005; Verwey & Wright, 2014), we set the criterion of performance error percentage (PEP) at a 5% level and listed all participants that had an overall mean PEP for all 17 blocks greater than 5%. Any participants that had a positive general learning index value (indicating slowing of reaction times as learning progressed), were also listed. We also listed participants with less than 10% sequence learning percentage values, which indicated poor performance in sequence-specific learning. Only if a participant was listed as performed poorly in all three of the performance criteria, they were removed from further analysis at this point. Seven participants' SRTT data did not meet the adequate levels in all three performance criteria (MED:2, AT:3, Control:2) and thus, their results from Familiarisation Blocks, sequence Learning Blocks, sequence learning indices, effort, arousal and pleasure measures were not included in the final analysis.

2.6.4. Self-report measures of effort, arousal and pleasure analysis

For each participant and timepoint for self-report measures, arousal and pleasure scores were separated and extracted from the Affect Grid and effort scores from the 10-point Likert scale. Participants' effort, arousal and pleasure scores were separately submitted to a 3 (Group: FAM, CAT, Control) X 3 (Timepoint: Rest, Task, and Sequence Learning) ANOVA with repeated measures on the last factor. Where a significant effect or interaction was found, post-hoc analyses using LSD determined the locus of the effect or interaction.

2.6.5. Correlation of sequence learning indices and self-report measures analysis

To better understand the effect of the different cognitive tasks (FAM, CAT, and Rest) on sequence learning, correlational analyses were conducted to test the possibility that arousal, pleasure and effort experienced at different time points mediated this relationship. Pearson's correlation coefficient (r) was used to examine the relationship between SRTT learning indices and self-report measures scores for Task and Sequence Learning timepoints.

3. Results

3.1. Familiarisation performance

LMER model analysis of familiarisation performance revealed that there was neither a significant Group x Response error interaction for trial RT ($p = .62$), nor a significant Group x Response error x Block interaction for trial RT ($p = .07$). Thus, Response error across groups were similar and the model was simplified by removing all incorrect trials and Response error as a factor for analysis of RT performance. This resulted in the exclusion of 2.4% of all

SRTT trials in Familiarisation Blocks. For the remaining correct trials during Familiarisation Blocks 1 – 3, there was no significant main effect of Group ($p = .96$), but a significant effect of Block, $\chi^2(2, N = 48) = 112.1, p < .001$, where trial RT was reducing as block numbers progressed across, indicating general learning effects across groups. There was a significant Group x Block interaction, $\chi^2(4, N = 48) = 9.9, p = .02$, such that the relationship between Blocks and trial RT changed as a function of Group, predicated mainly on Block 1 performance differences (see Figure 4 for detailed description).

Figure 4. Mean trial reaction time (RT) performance in Familiarisation Blocks 1 – 3 blocks of the serial reaction timed task (SRTT) involving pseudo-random ordered trials. Mean trial RT changed as a result of group (FAM, CAT and Control) and blocks even through Familiarisation Blocks were performed prior to experimental manipulation. The difference amongst the groups centred mainly in the first block of familiarisation where the FAM group was performing faster than CAT and Control groups. Subsequent Familiarisation Blocks 2 and 3 showed that trial RT performance was equal amongst the groups. Filled bands represent 95% confidence intervals.

Figure 5. Mean trial reaction time (RT) performance in sequence Learning Blocks of the serial reaction timed task (SRTT) involving second-ordered conditional (SOC) Sequence Learning Blocks 1 – 12, a pseudo-random ordered Transfer Block 13, and reinstatement of the learned SOC sequence in Block 14. The FAM group completed a single-session of focused attention meditation immediately prior to the SRTT while the CAT group completed computerised attention task immediately prior to the SRTT. The Control group did not complete any cognitive task prior to the SRTT. Sequence Learning Block 2 showed that CAT was performing faster than both FAM and Control. In the mid-phase of sequence Learning Blocks 4 – 8 both FAM and CAT were performing faster than Control but at the end of Learning Block 12, groups were not different. In Transfer Block 13 and learned SOC Block 14, both FAM and CAT were faster than Control. Filled bands represent 95% confidence intervals.

3.2. Sequence learning performance

LMER model analysis of sequence learning performance revealed that there was no significant Group x Response error interaction for trial RT ($p = .70$), nor was there a significant Group x Response error x Block interaction for trial RT ($p = .23$). The linear mixed model was thus simplified by removing all erroneous trials and Response error as a factor for further analysis of RT performance. This resulted in the exclusion of 3.0% of all SRTT trials in sequence Learning Blocks. The LMER for correct trials during sequence

Learning Blocks 1 – 14, revealed no significant main effect of Group on trial RT ($p = .76$), a significant effect of Block on trial RT, $\chi^2(13, N = 48) = 7796.7, p < .001$, where all groups were showing RT reductions across Learning Blocks 1 – 12, an increase in RT for Transfer Block 13 and then reduction in RT for Block 14. This RT pattern was typical of SRTT performance (Robertson, 2007; Song, Howard, & Howard, 2008). There was a significant Group x Block interaction, $\chi^2(26, N = 48) = 93.1, p < .001$, such that the relationship between Blocks and trial RT changed as a function of Group. Learning Block 2 showed faster trial RT performance in CAT compared to FAM and Control groups. Control was slower than both FAM and CAT groups from Learning Blocks 4 – 8, in Transfer and Interference Blocks. In final sequence Learning Block 12, FAM was faster than Control but not different from CAT (see Figure 5 for detailed description).

Figure 6. Sequence learning indices of general learning, sequence-specific learning and sequence interference based on performance in the serial reaction timed task (SRTT).

General learning performance was reflected as mean beta coefficient for all correct trials in each group for sequence Learning Blocks 1 – 12, where blocks involved a second order conditional (SOC) sequence pattern (A). Sequence-specific learning reflected the proportional difference as a percentage in mean RT from sequence Learning Block 12 to Transfer Block 13, where a pseudo-random ordered pattern was introduced (B). Sequence interference reflected the proportional difference as a percentage in mean RT between sequence Learning Block 12 and Block 14, which shared the same SOC sequence pattern, due to the interference experience from random ordered Transfer Block 13 (C). At the end of sequence Learning Block 12, FAM was faster than Control but not different than CAT. The FAM group completed a single-session of meditation immediately prior to the SRTT while the CAT group completed a computerised attention task prior to the SRTT. The Control group did not complete any cognitive task prior to SRTT. Error bars standard deviations.

3.3. Sequence learning indices

General learning, sequence-specific learning and sequence interference performances according to group are presented in Figure 5. Univariate ANOVA results for general learning performance revealed a significant effect for Group ($F [2, 45] = 3.8, p = .03, \eta_p^2 = .14$). Post-hoc analysis revealed that the general learning performance was significantly greater for FAM ($M = -.62 \pm .4$) compared to CAT ($M = -.36 \pm .37, p = .04$) and Control ($M = -.28 \pm .3, p = .02$). General learning performance was not different between CAT and Control ($p = .60$). There were no significant Group effects for sequence-specific learning ($p = .87$) or sequence interference ($p = .51$) indices.

Figure 7. Mean scores for effort, arousal and pleasure at Rest, Task and Sequence Learning. Participants rated their effort on a paper-based likert scale where they had to input a whole number from 0 – 10 at the different time points (A). Participants used an affect grid to rate their mood where arousal scores (B), and pleasure scores (C) were extracted and analysed separately at the different timepoints for the groups. The FAM group completed a single-session of meditation immediately prior to the SRTT while the CAT group completed a computerised attention task. The Control group did not complete any cognitive task prior to the SRTT. Error bars represent standard deviation.

3.4. Effort, arousal and pleasure

See Figure 7 for group comparisons for effort, arousal and pleasure for timepoints Rest, Task and Sequence Learning. Analysis of effort scores revealed a significant effect of Group, ($F [2, 45] = 3.8, p = .03, \eta^2_p = .15$). There was also a significant effect of Timepoint, ($F [2, 90] = 53.3, p < .001, \eta^2_p = .54$), and a significant Group x Timepoint interaction ($F [4, 90] = 3.3, p < .01, \eta^2_p = .13$). Post-hoc analysis for Group x Timepoint interaction revealed that Task effort for the CAT group ($M = 6.1 \pm 2.5$) was significantly higher than for the FAM group ($M = 3.9 \pm 2.9, p = .02$) and Control group ($M = 2.6 \pm 2.6, p < .001$). FAM and Control Task effort were not different ($p = .20$). There were no other significant interactions of effort scores at Rest or Sequence Learning.

Analysis of arousal scores revealed that there was no significant main effect of Group, ($p = .30$), but a significant effect of Timepoint, ($F [2, 90] = 111.6, p < .001, \eta^2_p = .71$). Post-hoc analysis revealed that Rest arousal ($M = 2.5 \pm 1.4$) was significantly lower than Task ($M = 3.0 \pm 1.9, p = .05$) and Sequence Learning ($M = 6.5 \pm 1.7, p < .001$). Task arousal was also significantly lower than Sequence Learning ($p < .001$). Over the course of the experiment, Arousal was increasing from Rest to Task and to Sequence Learning. There was no significant Group x Timepoint interaction ($p = .06$) for arousal.

Analysis of pleasure scores revealed a significant main effect of Group, ($F [2, 45] = 4.2, p = .02, \eta^2_p = .16$), post-hoc analysis revealed that mean pleasure for CAT group ($M = 5.8 \pm 1.7$) was significantly lower than FAM group ($M = 6.8 \pm 1.5, p < .05$), but not different from Control group ($M = 6.3 \pm 2.0, p = .26$), and there was no difference between FAM and Control groups ($p = .16$). There was neither a significant effect of Timepoint, ($p = .12$), nor a significant Group x Timepoint interaction ($p = .06$).

Table 1. Pearson's correlation coefficients among sequence learning indices of general learning, sequence-specific learning and sequence interference compared to self-report measures of effort, arousal and pleasure at the different experiment timepoints (Rest, Task and Sequence Learning).

(N = 48)	SRTT Learning Indices		
	General Learning	Sequence Specific Learning	Sequence Interference
Effort: Task	0.00	-0.15	-0.24
Effort: Sequence Learning	0.09	-0.24	-0.21
Arousal: Task	0.21	-0.02	-0.13
Arousal: Sequence Learning	0.09	-0.03	-0.06
Pleasure: Task	-0.14	0.17	0.33*
Pleasure: Sequence Learning	-0.29*	0.31*	0.17

** = Correlation significant at 0.01 level (2-tailed)

* = Correlation significant at 0.05 level (2-tailed)

3.4. Correlation of effort, arousal and pleasure with sequence learning indices

Task effort were not significantly correlated with general learning ($p = .99$), sequence-specific learning ($p = .30$) or sequence interference ($p = .10$). Sequence learning effort was also not significantly correlated with general learning ($p = .56$), sequence-specific learning ($p = .10$) or sequence interference ($p = .15$).

Task arousal were not significantly correlated with general learning ($p = .16$), sequence-specific learning ($p = .88$) or sequence interference ($p = .38$). Sequence learning arousal was also not significantly correlated with general learning ($p = .55$), sequence-specific learning ($p = .86$) and sequence interference ($p = .71$).

Task pleasure was not significantly correlated with general learning ($p = .35$) or sequence-specific learning ($p = .25$), but had weak and positive correlation with sequence interference, $r(48) = .33$, $p = .02$ (increased Task pleasure and increased interference effect). Sequence learning pleasure had a weak inverse significant correlation with general learning performance, $r(48) = -.29$, $p = .04$ (increased SRTT pleasure and increased general learning), and a weak significant correlation with sequence learning, $r(48) = .31$, $p = .03$ (increased SRTT pleasure and increased sequence-specific learning). There was no significant correlation between sequence learning pleasure and sequence interference ($p = .24$).

4. Discussion

Previously, Chan et al. (2017) demonstrated that a single-session of FAM enhanced subsequent sequential behaviour performance. Enhanced performance appeared to be afforded by efficient implementation of stimulus-based planning as opposed to plan-based planning. This was interpreted to indicate that FAM states strengthen top-down control, which are then implemented in subsequent sequence learning. As FAM is thought to involve attention control processes (Malinowski, 2013; Tang et al., 2015), we sought out to investigate if increased top-down control in sequence learning might similarly be elicited by a preceding computerised attention task. We also proposed alternative mechanisms that FAM may influence cognitive control and sequence learning through the regulation of emotional constructs such as effort, arousal and pleasure. We considered that FAM practice may result in low effort, low arousal and high pleasure, priming a plan-based (divergent control) learning strategy; or high effort, high arousal, and low pleasure, priming a stimulus-based (convergent control) learning strategy.

4.1. Effects of focused attention meditation and computerised attention task on sequential performance

For general sequence learning performance, the LMER model indicated that performance between groups differed across blocks such that in early sequence Learning Block 2, the CAT group had faster trial RT performance than CAT and Control groups. From mid-phase Learning Blocks 4 to 8, FAM and CAT groups had faster trial RT performances than the Control group. FAM and CAT groups were not different in their trial RT performances as their confidence intervals overlapped with each other. The results in the mid-phase of sequence learning was suggestive that convergent cognitive control effects in the FAM and CAT groups were enhanced, that facilitated greater stimulus-based learning and resulted in faster trial RT performances compared to Control. In final sequence Learning Block 12, the plots reveal that only FAM group was faster than Control group, and that CAT group was not faster than Control group. This is suggestive that a primed convergent cognitive control state resulting in stimulus-based learning was more enhanced in the FAM than the CAT group at the end of sequence learning.

We evaluated Learning Block 12 performance, to Transfer Block 13 and Learning Block 14, for sequence-specific learning performance. When referred to Figure 5, Block 12 to Block 13, and to Block 14 performance did not show that there were any interaction effects

between the groups in the plots. This indicated that no sequence-specific differences between the groups was evident. Additionally, all groups increased in mean trial RT for Transfer Block 13, and that FAM and CAT groups were still performing faster than the Control group, although FAM and CAT groups were not different from each other as indicated by overlapping confidence intervals. This pattern of performance likely indicated that both FAM and CAT groups were more resilient towards sequence disruption and that top-down convergent control effects were stronger than Control which facilitated stimulus-based learning enhancement even when no sequence in Transfer Block 13 was evident. When the original sequence was reintroduced in Block 14, both FAM and CAT groups maintained enhanced stimulus-based learning performances compared to Control. The next section, we discuss our findings in sequence learning indices to further understand the effects of sequence learning enhancement following a single-session meditation. This may provide us with evidence that FAM has some additional properties beyond attentional control compared to CAT.

4.2. Effects of focused attention meditation and computerised attention task on sequence learning indices

The results of sequence learning indices revealed that the FAM group had increased general learning performance benefits compared to both the CAT and Control group. These combined with the LMER results, present a successful replication of an earlier finding by Chan et al. (2017), where general performance in sequence learning for the FAM group was superior to that of the Control group. It reinforces the idea that single-session FAM narrows the attentional aperture and strengthens top-down cognitive control for convergent effects (Colzato et al., 2017; Colzato et al., 2016), which promotes stimulus-based learning for general learning performance benefits (Chan et al., 2017; Immink et al., 2017). Our results supports that stimulus-based learning benefited reaction time improvements at the trial level because of selectivity and prioritisation of stimulus information resulting in shorter response latencies without elaboration of the sequence structure (Abrahamse & Noordzij, 2011).

We considered that FAM narrowed attentional aperture and increased top-down control, and that other cognitive tasks in the form of CAT may elicit similar sequence learning performance. This notion was not supported as the FAM group had more general learning performance enhancements compared to CAT (that were not different from Control), and suggestive that FAM may have properties beyond simply attentional control to focus on goal-related information as a mechanism for its effects. In checking for levels of engagement in

our CAT group, only 10.2% of trials were considered errors, which suggest that participants in the CAT group were engaged and considered to have mobilised the attentional function adequately to perform the task. A possible explanation for FAM practice is engagement in a very unique state of consciousness that could be utilising attention as a starting function (Lutz et al., 2015) for perceptual processes needed in stimulus identification during the SRTT (Verwey et al., 2015). FAM is likely to engage metacognitive control (Hommel, 2015; Hommel & Colzato, 2017) either in parallel or subsequent of attention which allows for maintenance of persistence and/or flexible control of the current experience. Because cognitive control is subserved by metacontrol (Hommel & Colzato, 2017), it is possible that FAM through metacontrol, maintains attentional focus using two strategies: 1) by quickly dropping distractions (flexibility to switch stimuli) or 2) by blocking distractions to maintain current goal-related task (persistence in current stimuli) (Hommel, 2015; Ju & Lien, 2016). These two strategies in meditation act differently and are also unique operations within cognitive control (Gallant, 2016; Miyake et al., 2000), which require further research on their effects on sequence learning that is unfortunately beyond the scope of this paper. Although we found no evidence of single-session enhancement from CAT which might benefit subsequent sequence learning indices, it also did not deteriorate general learning performance compared to a Control condition.

There were no differences in sequence-specific learning or sequence interference indices, and this reinforces the idea that single-session FAM immediately undertaken before a learning task, does not allow for the development of divergent cognitive control style that promotes plan-based learning in subsequent sequence learning. Chan et al. (2017) found that only administering a temporal break after FAM practice facilitated greater levels of sequence-specific learning than FAM immediately prior to sequence learning. This was attributed to a weakened top-down control which facilitated plan-based learning rather than stimulus-based learning strategies. Similarly, Immink et al. (2017) found that low levels of cognitive effort engagement during FAM practice also facilitated greater levels of general learning performance but not greater levels of sequence-specific learning. The key point here is that other processes associated with FAM practice maybe contributing to how attentional effects exerts control in sequence learning.

4.3. Does the effect of focused attention meditation on sequence learning include processes related to effort, arousal and pleasure?

In addition to attention control processes, FAM is also thought to involve processes associated with cognitive flexibility and emotional regulation (Kabat-Zinn et al., 1992; Lutz et al., 2015; Malinowski, 2013; Tang et al., 2015). We investigated if regulatory processes such perceived effort, arousal and pleasure provided an explanation for the FAM-associated sequence learning effects. Compared to the Control condition, effort scores in the FAM group did not differ across experiment timepoints. However, effort associated with the CAT was significantly higher effort compared to both FAM and Control task conditions, which indicated that the computerised attention task mobilised more resources compared to meditation and quiet rest. Firstly, since our FAM group demonstrated significantly lower effort during Task and obtained greater levels of general learning performance compared to CAT group. These results were in line with Immink et al. (2017) which found that lower effort during FAM afforded greater benefits in general learning improvements during SRTT. Although Control also exhibited lower effort scores, they did not perform FAM and therefore did not obtain attentional control effects seen in the FAM group during SRTT. However, our correlation results were in contrast from Immink et al. (2017) and showed that neither cognitive task (FAM, CAT or Control), nor SRTT effort was a contributing factor for sequence learning indices.

Secondly, because Borrigan et al. (2016) demonstrated greater sequence-specific learning following increased cognitive fatigue, we would also expect the CAT group to follow this pattern because of increased effort and possibly greater levels of cognitive fatigue. Our results were in contrast and found no increases in sequence-specific learning following increased effort. One reason is that we measured effort whilst Borrigan et al. (2016) measured fatigue. We also considered that if both FAM and CAT required effort and resources to engage in the practice, then we would expect that there would be a depletion of cognitive resources and subsequent weakening of top-down control (Amer et al., 2016) to facilitate sequence-specific control strategies in comparison to the rest-only Control. Neither FAM nor the CAT group were different from Control in sequence-specific learning, which opposes the stance of weakening top-down control especially for the CAT group.

Assessment of arousal demonstrated that all groups performed similarly across experiment timepoints. This was also somewhat in contrast to our prediction and widely held notion that meditation would induce low arousal and tranquil states (Kabat-Zinn et al., 1992; Lazar et al., 2000) that may influence cognitive control and sequence learning behaviour. Moreover, arousal at the different timepoints were also not a contributing factor to sequence learning indices.

The CAT demonstrated significantly lower overall mean pleasure than the FAM group. Across the experiment, pleasure scores in CAT and FAM groups were equivalent to the Control group. As a cognitive task, FAM did not induce any pleasure differences from CAT and Control. At SRTT, groups also exhibited similar pleasure. When we investigated the relationships between pleasure at different timepoints and sequence learning indices, we found that Task pleasure positively correlated with sequence interference, and SRTT pleasure inversely correlated with general learning performance (more pleasure, more improvement), and positively correlated with sequence-specific improvement (more pleasure, more improvement).

At first, our results may be suggestive of some benefit of increased pleasure during learning, similar to the effects of positive mood for SRTT benefits shown in Shang et al. (2013). However, the results do not directly address any distant effects of meditation, even though the FAM group exhibited higher levels of overall pleasure, in line with what is often reported as an outcome of meditation practice (Fredrickson, Cohn, Coffey, Pek, & Finkel, 2008; Hamilton et al., 2006). In addition to higher pleasure, the FAM group also had enhanced general learning performance than CAT, which opposes evidence for calm pleased states to produce only limited intermediary performances in attentional tasks (Jefferies, Smilek, Eich, & Enns, 2008). Another reason that also limits direct support of FAM exerting cognitive control effects through pleasure, is that the rest-only Control condition provided little distinction between neutral and increased pleasure. Neutral states are inherently low in effort and slightly positive (Clark & Isen, 1983), which was echoed in our results, but Control did not perform as well as the FAM group in sequence learning indices. More importantly, our sequence learning results support a convergent cognitive control style and stimulus-based learning from FAM, which opposes our initial prediction that this kind of learning style would be associated with high effort and negative states. In sum, we could not find any consistent direct effects of effort, arousal and pleasure from FAM or CAT to influence cognitive control for subsequent motor sequence learning. We propose that effort, arousal and pleasure effects run in parallel but do not overlap with cognitive control effects, which overall have stronger influence over sequence learning performance.

4.4. Methodological strengths and limitations

Participants in the current study were naïve to the purpose of the experiment with the aim of limiting any potential influences associated with the expectations of benefits in meditation. The present experiment also included an active control condition in the form of a

computerised attention task to provide further insights to the mechanistic action of meditation. Although the computerised attention task was not a direct equivalent to meditation in terms of modality, it was operationalised in the sense that it served the purpose to understand if meditation had properties beyond just the utilisation of the attentional function. Another strength was that we included a washout period in the form of quiet rest after performing SRTT Familiarisation Blocks, so that any influences would be normalised and not affect the next cognitive task.

A limitation in this study but also future direction of meditation research would be to explore the notion of training. This experiment only used single-session meditation and that effects from meditation training might differ from the results presented here. Future research should question the volume of training that may be required to induce more sustained cognitive control effects. It is also probable that individual differences may be influencing both sequence learning, meditation, emotional and cognitive regulation, which we could not account for but poses a future research question of receptibility towards meditation styles (Colzato et al., 2017). Additionally, the period of sequence learning was relatively short and therefore influences of meditation on sequential performance might be different in prolonged periods of sequence learning. The SRTT was a block by block learning task and our experiment lacked the precision of monitoring effort, pleasure and arousal level changes during the 14 blocks to examine any relationship with learning improvements. Depth of engagement in meditation was also not monitored and this was because we felt that measuring depth may be suggestive to a participant the purpose of the experiment. Future research should focus on understanding the contribution of neurophysiological activity (through imaging techniques such as EEG) for meditation and during sequence learning to further elicit the neural mechanisms by which meditation enhances human performance.

4.4. Conclusion summary

The present experiment furthers the emerging literature in not just demonstrating benefits of single-session meditation, but also possible alternate mechanisms of action for subsequent motor sequence learning (Chan et al., 2017; Immink, 2016; Immink et al., 2017). We attempted to isolate and test if meditation effects were based predominantly on attentional control and demonstrated that meditation had properties beyond attentional control for general learning benefits compared to a computerised attention task. We replicated the results of an earlier experiment (Chan et al., 2017) that immediate FAM lead to general learning performance benefits because of increased convergent cognitive control that facilitated a

stimulus-based learning strategy in subsequent sequence learning. We also found that FAM was less effortful compared to a computerised attention task in naïve participants. Further, we also found that our effort findings were not in line with evidence that effortful cognitive tasks would result in weakened top-down control for subsequent sequence learning (Amer et al., 2016; Borrajan et al., 2016).

Our findings propose that meditation affects cognitive flexibility and emotional regulation processes in parallel to attentional control. Enhanced attention control and convergent states have the ability to prioritise control processes that prime stimulus-based sequence learning strategies. This prioritisation process could be due to the mobilisation of metacontrol (Hommel & Colzato, 2017) which manages the persistence and flexibility of cognitive control processes. The idea here is that persistence will “outcompete” other behaviours that are not relevant for current goals, which will eventually result in the trimming of irrelevant information and processes (in our case cognitive flexibility and emotional regulatory processes) (Hommel, 2015). This is further supported by cognitive tuning theory (Schwarz, 1990) that goals that are prioritised can override usual behavioural and cognitive control operations resultant of positive mood such as pleasure. For example, one may be in a state of high pleasure, but current task requires a high level of attention for completion and therefore mobilises resources for attentional control instead. Another possible explanation for a convergent control style with FAM is the idea that low effort cognitive tasks allow for more cognitive resources availability, and therefore increased top-down control for subsequent sequence learning through stimulus-based learning (Amer et al., 2016). Finally, high levels of pleasure could also be resultant when there is familiarity and mastery over various cognitive tasks (Lumma et al., 2015). It was possible that during 12 blocks of sequence learning some expertise of the sequence was obtained, which could explain the positive relationship between pleasure and sequence learning indices, when participants experienced improvement during learning across groups.

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