Meditation-induced cognitive-control states regulate working memory task performance

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Abstract

Single-bout focused-attention meditation (FAM) and open-monitoring meditation (OMM) are assumed to bias metacontrol states towards more persistent versus more flexible processing, respectively. In Experiment 1, we tested whether monitoring and updating of WM representations in an N-Back task with high (3-back), medium (2-back), and low (1-back) WM demands (varied within participants) is affected by preceding single-bout FAM or OMM meditation (varied between participants and compared to a control group). Results showed that FAM promotes WM performance in the medium (2-back), but not in the high (3-back) or low (1-back) demand condition, while OMM did not affect WM performance. A replication of the 2-back condition only (Experiment 2) showed no meditation effect, but a replication of the 3-back condition only (Experiment 3) produced a similar pattern as the 2-back condition in Experiment 1, with FAM promoting performance as compared to OMM and the control condition. Taken altogether, these findings suggest that single-bout FAM does promote WM performance but only if the capacity demands are neither too high nor too low.

Keywords: Single-bout; Focused attention meditation; Open monitoring meditation; Working memory; N-Back Task; metacontrol state

1. Introduction

Meditation is a mental activity affecting mindfulness and awareness, which in numerous studies has been shown to have significant effects on various attentional processes (van den Hurk et al., 2010), emotional regulation (Tang, Holzel, & Posner, 2015), executive functions (Colzato, van der Wel, Sellaro, & Hommel, 2016; Colzato, Sellaro, Samara, Baas, & Hommel, 2015a), working memory capacity (Vugt & Amishi, 2011; Mrazek et al, 2013; Quach, 2014; Jha et al., 2010), response inhibition (Gallant, 2016; Colzato, Sellaro, Samara, & Hommel, 2015b), cognitive flexibility (Moore & Malinowski, 2009), creativity performance (Colzato, Szapora, Lippelt, & Hommel, 2017b), sequence learning (Immink, Colzato, Stolte, & Hommel, 2017), and self-awareness (Tang, Holzel, & Posner, 2015), both in experienced practitioners and novices (Basso et al., 2019).

1.1. Meditation types

Different kinds of meditation have been used in various studies, and they are likely to induce different kinds of effects (Lutz et al., 2008). Currently the most researched and theoretically best understood types of meditation (Colzato, Ozturk, & Hommel, 2012; Lippelt, Hommel, & Colzato, 2014) are focused attention meditation (FAM) and open monitoring meditation (OMM). Usually, FAM is the starting point for any novice meditator (Lutz et al., 2008; Vago and Silbersweig, 2012). During FAM, the meditator is required to focus attention on a chosen event, such as breathing. To maintain this focus, the meditator has to constantly monitor the concentration on the chosen event, to avoid or ignore distraction, and bring back attention to breathing once the focus is lost (Tops et al., 2014). During OMM, the focus of the meditation becomes the monitoring of awareness itself (Lutz et al., 2008; Vago and Silbersweig, 2012). In contrast to FAM, there is no specific event in the internal or external environment that the meditator has to focus on; the aim is rather to stay in the monitoring and consciousness state, broaden attentive to any experience and notice what is going on in one’s mind, without thinking or selective attention.

1.2. Meditation and Cognitive Control

Pioneering studies that looked into the impact of meditation on cognition investigated meditation practitioners with substantial experience in meditating (e.g., Colzato et al., 2012). As correlational designs of this sort make it difficult to disentangle effects of the actual meditation process and of the traits of the individual who has chosen to meditate, other studies have investigated originally naïve participants after having been randomly assigned to a meditation-practice group or a control group. The results were comparable (for overviews, see Lebuda et al., 2016; Lippelt et al., 2014), suggesting that the causal factor is indeed the practice of meditation. However, even though practice-based studies effectively address the problem of self-selection, they leave open whether the obtained effects are due to structural trait-like changes that the extended or longer-termed meditation training induces or due to the state that engaging in single-bout meditation instruction establishes. First studies looking into this issue by directly comparing experienced meditators with naïve participants without any meditation training found no differences between these two groups. For instance, Colzato et al. (2017b) compared practitioners with experience in OMM and FAM of 3.3 years on average with entirely naïve participants in two creativity tasks. Practitioners and novices received the same 20-minute single-bout FAM or OMM instruction presented by a professional meditation instructor before carrying out the two tasks. While there were some indications that the practitioners tended to follow a different strategy in one of the creativity tasks, the overall outcome (improved divergent thinking through OMM) showed no differences between practitioners and novices, demonstrating that a one-time 20-minute instruction is sufficient to induce a state that affects cognitive processing.

Further direct comparisons are lacking, but there is converging evidence that practitioners and novices are equally affected by single-bout meditation instructions. For instance, FAM has been shown to increase conflict monitoring and top-down control adjustments in response-conflict tasks in both longer-term meditation-trained participants (Tang et al., 2007) and naïve participants presented with single-bout 17-min audio recordings of FAM and OMM instructions (developed by Baas et al., 2014). Along the same lines, OMM was found to improve the integration of successive visual stimuli in both longer-term meditation-trained participants (Slagter et al., 2007) and naïve participants after listening single-bout 17-minute audio recordings (Colzato, Sellaro, Samara, Baas & Hommel, 2015). These and other observations have led Hommel and Colzato (2017a, 2017b) to assume that single-bout meditation instructions effectively bias the cognitive control states of individuals. More specifically, because FAM typically calls for sustaining selective attention (Lutz, Jha, Dunne, & Saron, 2015), it is likely to improve the meditator's performance in tasks that require persistence and cognitive focus, such as needed for increasing top-down cognitive control (Tang et al. 2007; Colzato et al. 2015b; Colzato, van der Wel, Sellaro & Hommel, 2016). OMM in turn involves the attentive monitoring of any kind of experience without any particular focus, which can be assumed to bias the cognitive system towards flexibility, as needed in divergent thinking tasks (Colzato et al., 2017b) or the integration of movement sequences (Immink et al., 2017), so that performance in flexibility-heavy tasks should benefit.

1.3. Meditation and Working memory

Working memory (WM) is assumed to be a capacity-limited cognitive system that can (help to) temporarily store and manipulate information for processing (Baddeley, 1992). The N-Back task, introduced by Kirchner (1958), is a widely used experimental paradigm for assessing WM performance (Perrig, 2010). The task involves multiple processes, such as encoding on-line stimuli, sustained monitoring, and updating, as well as matching the current stimuli to one shown before in the stimulus sequence (Owen, McMillan, Laird, & Bullmore, 2005; Colzato, Jongkees, Sellaro, & Hommel, 2013; Verhaeghen & Basak, 2005). In its most typical version, the participant is asked to monitor the identity of a series of stimuli, and to decide whether the current stimulus is the same as or different from the one presented N trials previously. In our present task version, N was pre-set to be as 1, 2, or 3, the idea being that a larger N is associated with higher WM demands (Kane et al., 2007).

Of particular interest for our present study, evidence indicated a connection between longer-term meditation training and WM (Vugt & Amishi, 2011; Mrazek et al, 2013; Quach, 2014), but only few studies investigated the relationship between longer-term meditation training (no single-bout meditation instruction studies yet) and N-Back task performance and they failed to provide a clear picture. In Basso et al. (2019), non-experienced meditators participated in daily 13-min audio-guided meditation sessions (using what was called Journey Meditation) for a total duration of 8 weeks. The same was done by a control group, except that its participants listened to a neutral podcast. Compared to the control group, meditation enhanced N-Back task performance, especially in accuracy, for all WM loads. However, the meditation training group showed very poor performance in the pre-measure, so that the finding might reflect regression to the mean rather than meditation training-produced enhancement. Another study (Goodrich, Wahbeh, Mooney, Miller, & Oken, 2015) used mindfulness meditation training to improve N-Back task performance. No significant improvement was found but given that the sample comprised of no more than seven participants, this may be due to power issues. Yet another study (Zeidan, et al., 2010) showed a positive effect of meditation on 2-Back task performance. Practice in mindfulness meditation (Shamatha) training was used for the experimental group while the control group listened to an audio book for the same number of sessions. There was no effect for accuracy and reaction time, but a significant group by session interaction for hit rates—which were increased in the meditation group. However, this study did not assess 1-back and 3-back conditions, so that the evidence remains very limited and unsystematic.

1.4. Aim and hypothesis of this study

The theoretical aim of the study was twofold: First, we were interested to study the impact of single presentations of meditation instructions (as in the studies of Colzato et al., 2015b; 2017b and others) on N-Back performance in a reasonably powered sample with a broader range of conditions, 1-, 2-, and 3-Back in particular. Like previous studies, we investigated naïve participants without meditation training. However, in contrast to previous studies, we did not have participants undergo any meditation training but exposed them to only one single bout of meditation, just like in the studies of Baas et al. (2014), Colzato et al. (2017b), and others. For consistency reasons, we did so by presenting participants (all Chinese) with audio recordings of the translation of the original recordings of Baas et al. (2014) from Dutch into Chinese. Our reason to use only single bouts of meditation was that this would allow us to separate pure state effects induced by the single-bout meditation instruction from more skill-related (trait-like) effects that are likely to emerge through extended practice or longer-term training.

Second, we were interested to use the rather transparent FAM and OMM (in contrast to other, often ill-defined techniques), and see whether they impact performance differently. As indicated above, these two kinds of longer-term meditation training differ in style and a number of previous studies have indeed demonstrated that they affect cognitive performance in different ways (e.g., Tsai & Chou, 2016). As suggested by Hommel and Colzato (2017a), single-bout FAM and OMM instructions are likely to establish different kinds of biases of cognitive control states, which is likely to produce different kinds of effects.

However, while these theoretical considerations suggest that FAM and OMM may affect N-Back performance in different ways, the direction of this prediction is less obvious. This is because the N-Back relies on both processes that are likely to benefit from persistence, like the maintenance of the reference item and the sustained monitoring, and processes that are likely to benefit from flexibility, like the repeated updating of WM (Miyake et al., 2000). Given that it is difficult to predict whether the former or the latter are affected by meditation, we were not committed to a particular direction of the effect. We thus entertain two hypothesis, the first being that (even single bouts of) FAM improves N-Back task performance more than (single bouts of) OMM, because with a more top-down and persistence mental state, participants can keep their sustained attention on the series of stimuli, thus they get benefit when they compare the current identity with a previous identity. Alternatively, OMM may improve N-Back task performance more than FAM, because with a less top-down and flexible mental state, participants can more easily update their WM, thus they get benefit. We also considered it possible that these effects show up only, or at least more strongly with higher load, as suitable strategies should become more important as capacity becomes sparse.

2. Experiment 1

2.1. Participants

Ninety-six participants, all of them students from Southwest University in China, were recruited. Thirty-two participants (mean age = 20.78, age range 18-23, std = 1.36, 4 males) underwent FAM, and another 32 participants (mean age = 21.94, age range 19-25, STD = 1.78, 9 males) underwent OMM, while the remaining 32 participants (mean age = 21.50, age range 17-25, STD = 1.72, 9 males) were assigned to the control condition.

All participants had normal or corrected to-normal vision, were naive with regard to the hypotheses of the experiment, and received payment for their participation. Participants gave their informed consent before the study, which was conducted in accordance with the ethical standards of the Declaration of Helsinki and with the ethical guidelines of the local human research ethics committee at Southwest University. The methods were carried out in accordance with the relevant guidelines and regulations approved by the Research Ethical Committee of Southwest University (Chongqing, China).

2.2. Meditation

Two single-bout meditation instruction types, FAM and OMM were used in this study. The meditation audios were almost the same as in previous studies (Colzato et al., 2017b), but with two modifications: firstly, the included verbal instructions were translated from Dutch into Chinese; and secondly, the time length of each audio was shortened to 11 minutes, as some redundant introductory and explanatory content was excluded. This length of meditation is in accordance with other brief meditation practices that have been proven effective (Basso et al., 2019).

During FAM, the participant was guided to focus on his or her breathing, the instructor verbally guided the participant by asking him/her to direct attention to their breathing and to redirect attention when mind wandering. During OMM, the participant was guided to follow and be aware of his or her breath, then broaden attention more and more, monitoring but without selecting, and keep awareness of the consciousness.

In order to qualify the kind of possible differences between the meditation types, we also added a control group in which participants did not engage in any meditation. They performed the identical pre and post N-Back tasks but were asked to relax (sit around doing nothing) for a time interval corresponding to the duration of the single-bout meditation instruction (Colzato et al., 2015a, 2016).

2.3. N-Back task

The N-Back tasks used in experiment 1 were adopted from a previous study (Colzato et al., 2013). Responses were made by pressing the ‘f’ key and the ‘j’ key of the QWERTY computer keyboard with the left and right index finger, respectively. Stimulus presentation and data collection were controlled using E-Prime 1.0 software. A stream of single visual numbers (from 0 to 9) was presented, with stimulus–onset asynchrony as 2000 ms and duration of presentation as 1000 ms. Participants used the two responses to identify targets (presented in 33% of the trials) and non-targets, respectively. Half of the participants pressed the f-key in response to a target and the j-key in response to a non-target; the other half of the participants received the opposite mapping. Target definition differed with respect to the experimental condition. In the 1-back condition, targets were defined as stimuli within the sequence that were identical to the immediately preceding one. In the 2-back condition, participants had to respond if the presented letter matched the one that was presented two trials before. In the 3-back condition, participants had to respond if the presented letter matched the one that was presented three trials before.

Each condition consisted of 9 practice trials followed by two blocks of 30 stimuli each, and the sequence of conditions was fully counterbalanced. Stimulus presentation was pseudo-randomized to avoid the occurrence of lure trials, e.g., non-target letters that match a recent letter in the sequence but not the letter in the N-Back position (see Kane et al., 2007).

2.4. Procedure

All participants were tested individually. Upon arrival, participants underwent the pre-measurement of the N-Back task, in which the sequence of 1-back, 2-back and 3-back tasks was completely randomized. Then they were to sit and do nothing or put on the headset and listen to the single-bout meditation instruction audio, either FAM or OMM, for about 11 minutes. After that, participants carried out the other two N-Back tasks, also with the sequence randomized.

2.5. Statistical analysis

A significance level of $p < 0.05$ was adopted for all statistical tests. Given that the two considered hypotheses imply effects going into opposite directions, all direct tests of meditation-group effects were two-tailed.

For the N-Back task, repeated-measures 2×3×3 ANOVAs with session (pre- vs. posttest) and load (1-back vs. 2-back vs. 3-back) as within-subjects factors, and meditation type (FAM vs. OMM vs. control) as between-subject factor, were carried out on reaction times (RTs) from valid trials as well as the sensitivity index d' (Swets, Tanner, & Birdsall, 1961) was calculated for all eighteen conditions separately (Haatveit et al., 2010). Especially for sensitivity index d' computing, ceiling hit and floor false alarm rates were adjusted using the formulas: 1-1/(2n) for 100% hit rates, and 1/(2n) for zero false alarm rates, where n was the number of total hits or false alarms (Macmillan & Creelman, 1991; Colzato et al., 2013). As the sensitivity index d' represents accuracy according to the signal detection approach, we did not repeatedly report the raw accuracy results.

2.6. Sensitivity index d' results

The analysis of pretest performance did not show any significant pre-experimental difference between the three meditation type groups, $p = 0.959$, in repeated-measures 3×3 ANOVAs with load (1-back vs. 2-back vs. 3-back) as within-subjects factors, and meditation type (FAM vs. OMM vs. control) as between-subject factor. The planned 2×3×3 repeated measures ANOVA produced significant main effects of session, $F(1,93) = 86.66$, $p < 0.001$, $p\eta^2 = 0.48$, indicating an increase of d' from the pretest (Mean = 2.43, SE = 0.06) to the posttest (Mean = 2.78, SE = 0.06); and load, $F(2,186) = 214.82$, $p < 0.001$, $p\eta^2 = 0.70$, indicating a decrease of d' with increasing load—as one would expect. LSD Post hoc revealed significant difference between 1-back (Mean = 3.47, SE = 0.05) and 2-back (Mean = 2.60, SE = 0.08), with Mean difference = 0.88, $p < 0.001$; 1- and 3-back (Mean = 1.74, SE = 0.09), with Mean difference = 1.73, $p < 0.001$; also 2- and 3-back, with Mean difference = 0.86, $p < 0.001$.

Session interacted with load, $F(2,186) = 8.62$, $p < 0.001$, $p\eta^2 = 0.09$, and this interaction was further modified by a three-way interaction of session, load, and meditation, $F(4,186) = 3.28$, $p = 0.013$, $p\eta^2 = 0.07$. No other significant effect was found, with $Fs < 1.58$, $ps > 0.21$. The means for all conditions are presented in Table 1.

The three-way interaction was further analyzed by subtracting d' in the pretest from d' in the posttest, and to use the resulting d' change value as input for univariate analyses with group/meditation type as the fixed factor, separately for each load condition. Fisher's LSD was used for post-hoc multiple comparisons tests. No significant group effect was found for 1- and 3-back conditions, $ps > 0.26$. However, the group effect was significant for the 2-Back condition, $F(2,93) = 6.11$, $p = 0.003$, $p\eta^2 = 0.12$: d' change value was significantly higher in the FAM group than in the OMM group (Mean Difference = 0.61, SE = 0.18, $p = 0.001$) and significantly higher in the FAM than in the control group (Mean Difference = 0.42, SE = 0.18, $p = 0.021$), with no difference between OMM and control group, $p = 0.289$.

2.7. Reaction time (RT) results

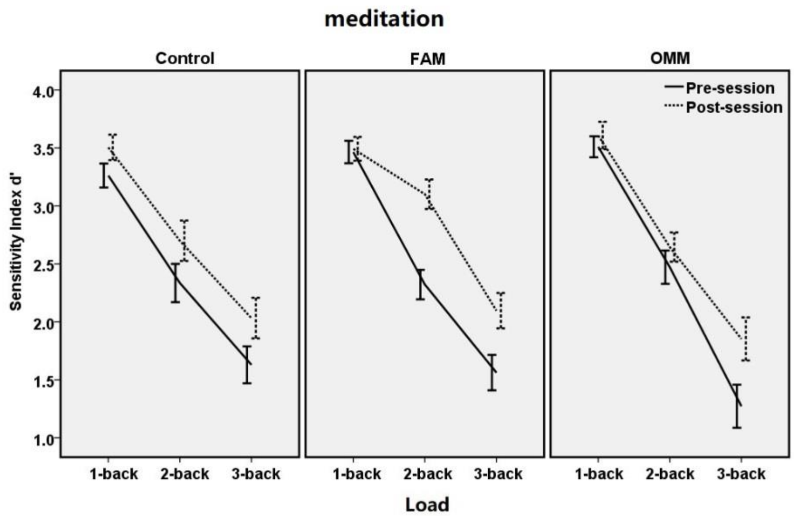
The analysis of pretest performance did not show any significant pre-experimental difference between the three meditation type groups, $p = 0.086$. The planned 2×3×3 repeated measures ANOVA produced significant main effects of session, $F(1,93) = 89.16$, $p < 0.001$, $p\eta^2 = 0.49$, indicating a reduction of RT from the pretest (Mean = 676.20, SE = 11.32) to the posttest (Mean = 621.53, SE = 10.98); and load, $F(2,186) = 111.32$, $p < 0.001$, $p\eta^2 = 0.55$, indicating the expected increase of RT with increasing load. LSD post hoc tests revealed significant difference between the 1-back (Mean = 557.76, SE = 8.12) and the 2-back condition (Mean = 669.78, SE = 12.62), with Mean difference = 112.02, $p < 0.001$; between the 1- and 3-back condition (Mean = 719.05, SE = 15.68), with Mean difference = 161.29, $p < 0.001$, and between the 2- and 3-back condition (Mean difference = 49.27, $p < 0.001$).

Session interacted with load, $F(2,186) = 9.51$, $p < 0.001$, $p\eta^2 = 0.09$. Two-tailed paired t-tests were used to compare pre- and posttest performance separately for each load, showing that the session effect was significant for all three conditions: for the 1-back condition, $t(95) = 4.98$, $p < 0.001$, $d = 0.35$; the 2-back condition, $t(95) = 8.45$, $p < 0.001$, $d = 0.56$; and the 3-back condition, $t(95) = 6.14$, $p < 0.001$, $d = 0.37$. We also found a significant interaction effect between meditation and load, $F(4,186) = 3.45$, $p = 0.010$, $p\eta^2$

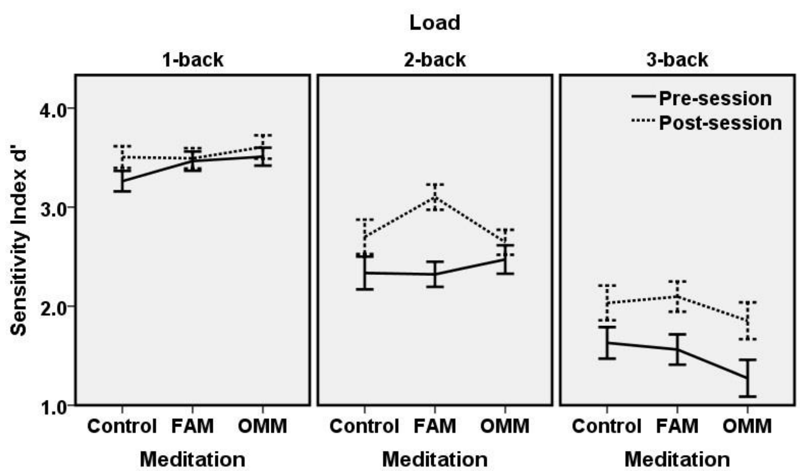
= 0.07. The interaction indicates that the load effect was more pronounced in the FAM group than in the other two groups. However, given that this effect was already present before the manipulation, we consider that a characteristic of the particular sample without a particular theoretical implication. No other significant effect was found, Fs < 2.7, ps > 0.07.

Table 1. Mean sensitivity index d', reaction times (in ms), and standard deviation (in parentheses) for single-bout FAM, OMM instructions, and control group as a function of load (1-back, 2-back, and 3-back task) and session (pre and post).

Meditation type	Focused Attention Meditation		Open Monitoring Meditation		Control	
1-back						
Session	pre	post	pre	post	pre	post
Sensitivity index d'	3.46 (.55)	3.49 (.58)	3.51 (.51)	3.61 (.67)	3.26 (0.58)	3.51 (0.62)
Reaction Time	582.46 (86.17)	551.08 (87.43)	572.12 (83.20)	530.68 (84.97)	562.18 (79.79)	548.02 (84.69)
2-back						
Sensitivity index d'	2.32 (.72)	3.10 (.72)	2.47 (.81)	2.65 (.71)	2.34 (0.93)	2.70 (0.99)
Reaction Time	738.89 (132.34)	662.73 (146.45)	694.42 (129.54)	618.31 (109.91)	686.50 (137.03)	617.79 (127.51)
3-back						
Sensitivity index d'	1.56 (.86)	2.10 (.86)	1.27 (1.05)	1.85 (1.05)	1.63 (0.90)	2.03 (0.99)
Reaction Time	813.71 (179.02)	756.99 (200.75)	723.62 (168.77)	656.52 (134.15)	711.84 (144.61)	651.63 (128.23)



meditation
Control
FAM
OMM
Pre-session
Post-session
Sensitivity Index d'
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1-back
2-back
3-back
Load



Load
1-back
2-back
3-back
Pre-session
Post-session
Sensitivity Index d'
4.0
3.0
2.0
1.0
Control
FAM
OMM
Meditation

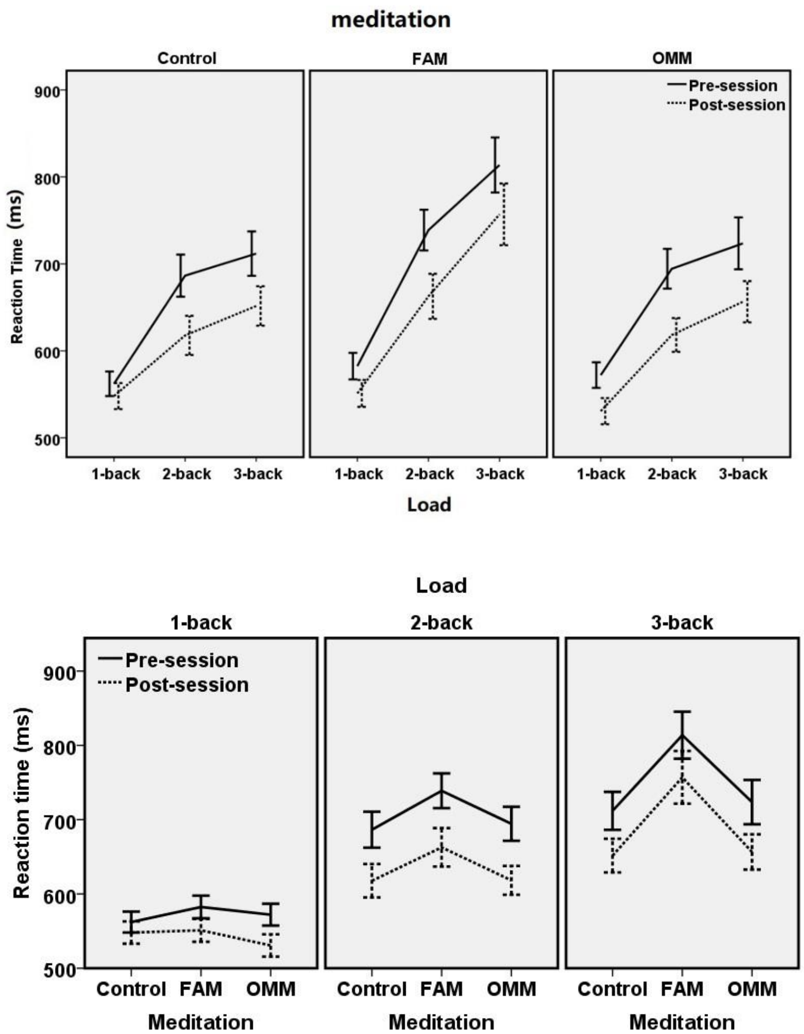


Figure 1. Sensitivity index d', and reaction time (ms) as a function of load (1-back vs. 2-back vs. 3-back), session (pre and post) and single-bout meditation instruction types (FAM, OMM and control). All error bars represent ±1 standard error.

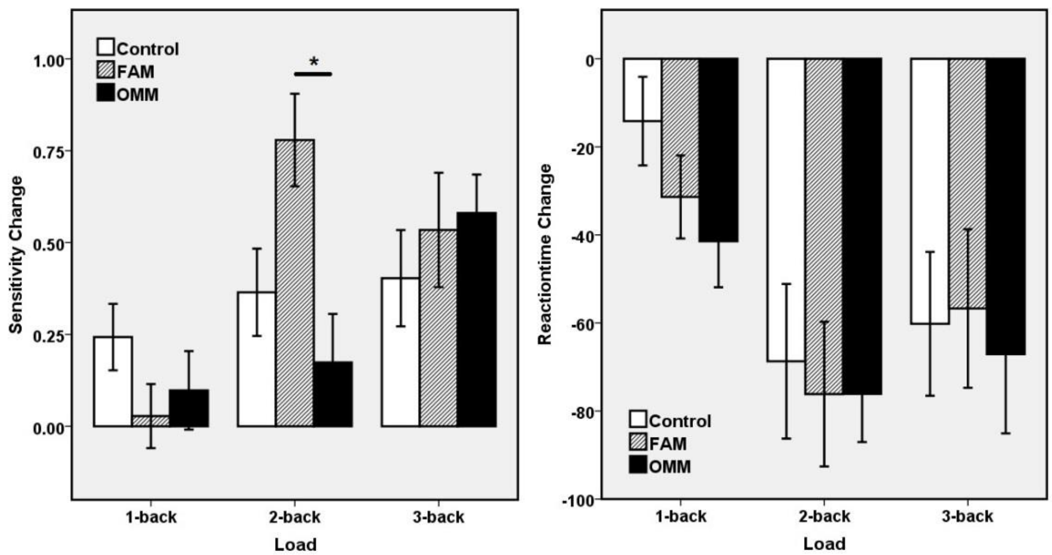


Figure 2. Data in pre session was subtracted from post session. Sensitivity index d' change, and reaction time (ms) change as a function of load (1-back vs. 2-back vs. 3-back), and single-bout meditation instruction type (FAM, OMM and control). All error bars represent ±1 standard error.

2.8. Post hoc power analysis

As we chose our sample size to fit with previous studies but without a formal power analysis, we checked whether our sample was sufficiently large. We used G*power (Faul, Erdfelder, Buchner, & Lang, 2009), based on the above sample sizes (32 participants for each of three single-bout meditation groups) and effect sizes (for the d’ results, meditation/group effect $p\eta^2$ (Cohen, 1988) equals to 0.12 for the pre and post difference in the combined 2-Back condition), and ran a post hoc power analysis. The power for interactions was approximately .90. Accordingly, we consider the size of our sample sufficient to detect the sought-for differences.

2.9. Discussion

We found a significant effect of meditation on 2-back task performance for the Sensitivity index d’ (but not for reaction times). Specifically, d’ change was significantly increased in the FAM group, but only in the 2-back condition. While the kind and direction of the meditation effect makes theoretical sense, it remains unclear why such an effect might be specific to the 2-back task. Given the rather trivial character of the 1-back condition, which amounts to the absence of any real WM demand, it is easy to see why an effect that is assumed to target WM performance needs some more contribution of WM to show up—as in the 2-back condition. On the one hand, this line of thinking would suggest that the effect is even stronger in the 3-back condition, which was clearly not the case. On the other hand, however, the fact that we varied WM demands within participants and that we did so in different sequences might have rendered the 3-back too challenging to leave operates in space for possible meditation-induced improvements. We tested this possibility by manipulating WM demands between participants in Experiment 2 (2-back condition) and 3 (3-back condition).

3. Experiment 2

3.1. Participants

Another ninety-six participants from Southwest University, all of them Chinese students, were tested. Thirty-two participants (mean age = 19.75, age range 17-23, STD = 1.54, 4 males) underwent FAM, and another 32 participants (mean age = 19.87, age range 17-22, STD = 1.41, 5 males) underwent OMM, while the remaining 32 participants (mean age = 19.66, age range 17-23, STD = 1.52, 10 males) were assigned to the control condition. This sample size was determined based on the power analysis run in Experiment 1.

3.2. Design and Procedure

Design and procedure are almost the same as in Experiment 1, except that only the 2-back task was administered. Results were analyzed by means of repeated-measures 2×3 ANOVAs with session (pre- vs. posttest) as within-participant factors, and meditation type (FAM vs. OMM vs. control) as between-participant factor.

3.3. Sensitivity index d’ results

The analysis of pretest performance did not show any significant pre-experimental difference between the three meditation type groups, $p = 0.757$, in a univariate ANOVA with meditation type (FAM vs. OMM vs. control) as between-participant factor.

The 2×3 ANOVA produced a significant main effect of session, $F(1,93) = 54.14$, $p < 0.001$, $p\eta^2 = 0.37$, indicating an increase of d' from the pretest (Mean = 2.44, SE = 0.07) to the posttest (Mean = 3.01, SE = 0.08). No other significant effect was found, with $Fs < 0.37$, $ps > 0.69$. The detailed d' information for all conditions is presented in Table 2.

3.4. Reaction time (RT) results

The analysis of pretest performance did not show any significant pre-experimental difference between the three meditation type groups, $p = 0.973$, in a univariate ANOVA with meditation type (FAM vs. OMM vs. control) as between-participant factor.

The 2×3 ANOVA produced a significant main effect of session, $F(1,93) = 51.64$, $p < 0.001$, $p\eta^2 = 0.36$, indicating a decrease of RT from the pretest (Mean = 757.61, SE = 13.49) to the posttest (Mean = 693.59, SE = 13.00). No other significant effect was found, with $Fs < 1.22$, $ps > 0.30$. The detailed RT information for all conditions is presented in Table 2.

Table 2. Mean sensitivity index d', reaction times (in ms), and standard deviation (in parentheses) for single-bout FAM, OMM instructions, and control group as a function of session (pre and post) for only 2-back task.

Meditation type	Focused Attention Meditation		Open Monitoring Meditation		Control	
2-back						
Session	pre	post	pre	post	pre	post
Sensitivity index d'	2.50 (0.79)	3.08 (0.71)	2.45 (0.62)	3.02 (0.80)	2.37 (0.76)	2.95 (0.73)
Reaction Time	761.36 (157.27)	679.58 (134.11)	753.61 (120.86)	691.22 (105.75)	757.86 (114.26)	709.97 (139.74)

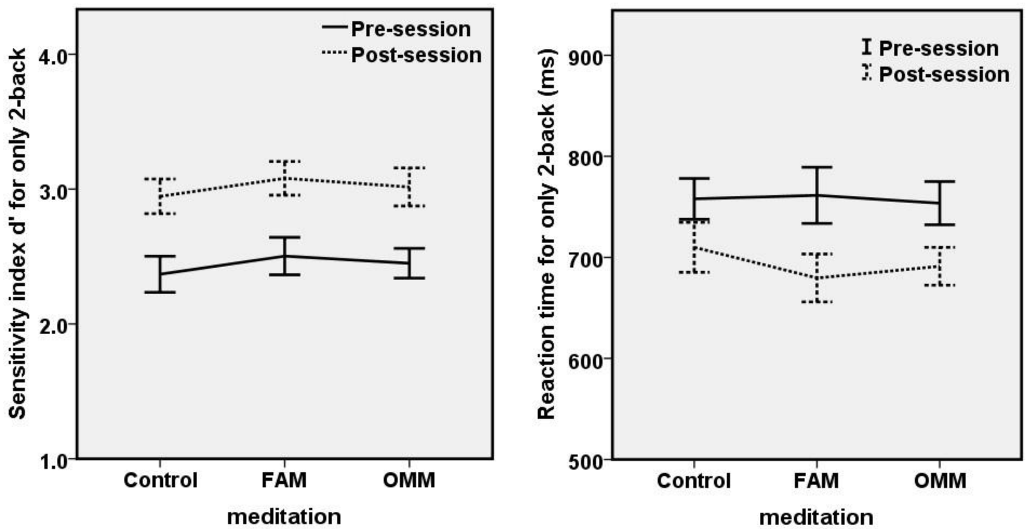


Figure 3. Sensitivity index d' and reaction time (ms) as a function of session (pre and post) and single-bout meditation instruction types (FAM, OMM, and control) for the 2-back task. All error bars represent ±1 standard error.

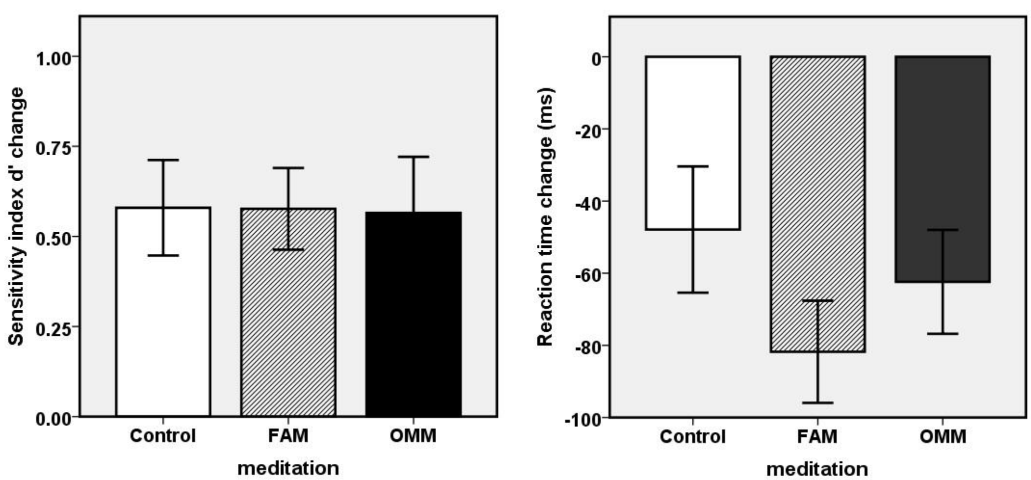


Figure 4. Data in pre session was subtracted from post session. Sensitivity index d' change, and reaction time (ms) change as a function of single-bout meditation instruction types (FAM, OMM, and control) for the 2-back task. All error bars represent ±1 standard error.

4. Experiment 3

4.1. Participants

Another ninety-six participants from Southwest University, all of them Chinese students, were tested. Thirty-two participants (mean age =19.84, age range 18-23, STD = 1.44, 5 males) underwent FAM, and another 32 participants (mean age = 20.84, age range 18-25, STD = 2.30, 4 males) underwent OMM, while the remaining 32 participants (mean age = 20.09, age range 18-23, STD = 0.98, 4 males) were assigned to the control condition. This sample size was determined based on the power analysis run in Experiment 1.

4.2. Design and Procedure

Design, procedure, and statistical analyses were as in Experiment 2, except that all participants carried out the 3-back task only.

4.3. Sensitivity index d' results

The analysis of pretest performance did not show any significant pre-experimental difference between the three meditation type groups, $p = 0.210$, in a univariate ANOVA with meditation type (FAM vs. OMM vs. control) as between-participant factor.

The ANOVA produced a significant main effect of session, $F(1,93) = 44.10$, $p < 0.001$, $p\eta^2 = 0.32$, indicating an increase of d' from the pretest (Mean = 1.32, SE = 0.08) to the posttest (Mean = 1.72, SE = 0.10), and a significant interaction between session and meditation type, $F(2,93) = 4.25$, $p = 0.017$, $p\eta^2 = 0.08$. The meditation type effect was not significant, $p = 0.23$. The detailed d' information for all conditions is presented in Table 3.

We again subtracted d' in the pretest from d' in the posttest, and used the resulting d' change value as input for univariate analyses, with meditation type as the fixed factor. Fisher's LSD was used for post-hoc multiple comparisons tests. The meditation group effect was found to be significant: d' change value was significantly higher in the FAM group than in the OMM group (Mean Difference = 0.42, SE = 0.15, $p = 0.006$); and significantly higher than in the control group (Mean Difference = 0.31, SE = 0.15, $p = 0.039$), while there was no difference between control and OMM group, $p = 0.475$.

4.4. Reaction time (RT) results

The analysis of pretest performance did not show any significant pre-experimental difference between the three meditation type groups, $p = 0.735$, in a univariate ANOVA with meditation type (FAM vs. OMM vs. control) as between-participant factor.

The ANOVA produced a significant main effect of session, $F(1,93) = 15.85$, $p < 0.001$, $p\eta^2 = 0.15$, indicating a decrease of RT from the pretest (Mean = 770.92, SE = 16.02) to the posttest (Mean = 750.04, SE = 15.73). No other significant effect was found, with Fs < 0.35, ps > 0.71. The detailed RT information for all conditions is presented in Table 3.

Table 3. Mean sensitivity index d', reaction times (in ms), and standard deviation (in parentheses) for single-bout FAM, OMM instructions, and control group as a function of session (pre and post) for the 3-back task.

Meditation type	Focused Attention Meditation		Open Monitoring Meditation		Control	
Only 3-back in Experiment 2						
Session	pre	post	pre	post	pre	post
Sensitivity index d'	1.32 (0.78)	1.96 (1.08)	1.49 (0.82)	1.72 (0.94)	1.15 (0.72)	1.48 (0.89)
Reaction Time	797.92 (142.83)	766.12 (125.00)	767.78 (169.77)	734.59 (167.64)	777.08 (157.07)	749.41 (165.95)

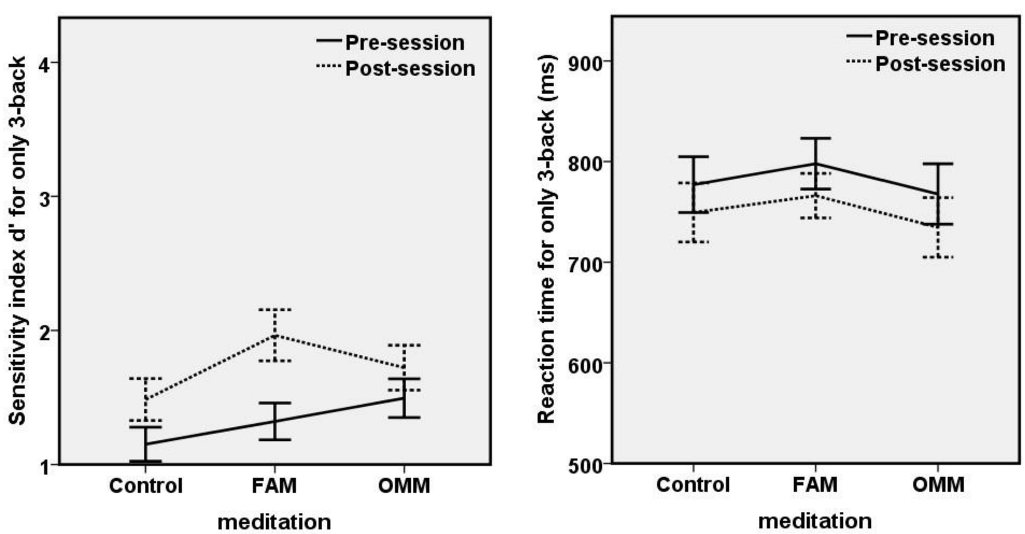


Figure 5. Sensitivity index d' and reaction time (ms) as a function of session (pre and post) and single-bout meditation instruction types (FAM, OMM, and control) for the 3-back task. All error bars represent ±1 standard error.

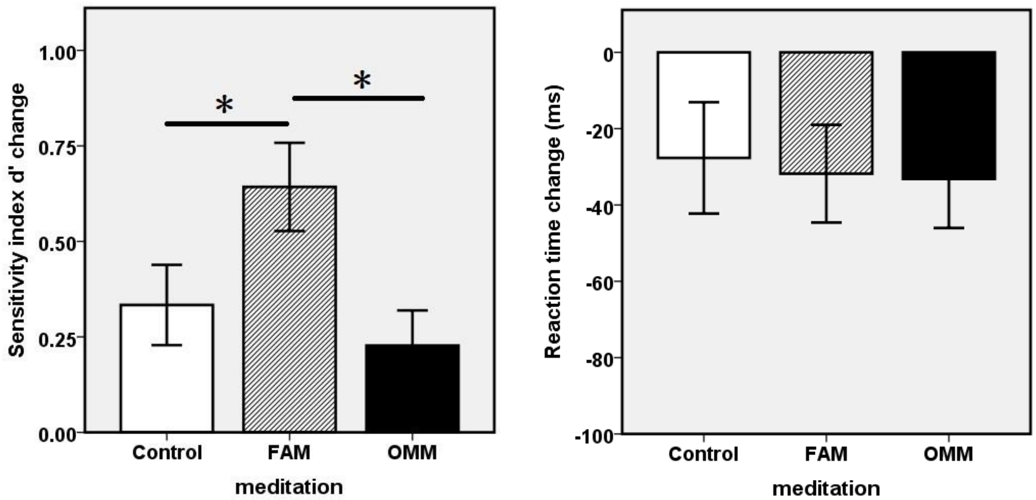


Figure 6. Data in pre session was subtracted from post session. Sensitivity index d' change, and reaction time (ms) change as a function of single-bout meditation instruction types (FAM, OMM, and control) for only 3-back task. All error bars represent ±1 standard error.

4.5. Discussion

When tested in separate groups, the 2-back condition (tested in Experiment 2) showed no meditation effect whereas the 3-back condition (tested in Experiment 3) produced the same outcome pattern as observed for the 2-back condition in Experiment 1. On the one hand, these outcomes suggest that FAM has the potential to facilitate WM performance in an N-back task. On the other hand, however, the particular condition in which such effects can be found seems to depend on the task context.

5. General Discussion

The aim of the present experiment was to investigate whether WM performance as assessed by an N-Back task can be affected by single-bout meditation instruction in general and, if so, whether FAM and OMM affect this performance in different ways. We obtained sizable load effects that confirm that our task version worked as expected. Regarding our first aim, sensitivity index showed an impact of single-bout meditation instruction on WM performance in some of the load conditions. This finding is consistent with previous studies (Zeidan et al., 2010) and shows that even unpracticed single-session meditation in novices is able to impact WM. This in turn is consistent with the idea that meditation establishes mental/neural states that modulate cognitive processes (Hommel & Colzato, 2017a).

With regard to our second aim, the findings indicate systematically different effects of single-bout FAM and OMM instruction on N-Back performance, as Experiments 1 and 3 indicate. In the conditions where such effects can be found, their overall patterns are very similar. For one, they show up in the sensitivity index d’ but not in RTs—which indeed turned out to be not particularly diagnostic or reliable in other N-Back studies as well (Redick & Lindsey, 2013; Zeidan et al., 2010). For another, the two meditation types clearly differed in their impact, as all significant effects were restricted to FAM, which improved WM performance, whereas OMM had no effect, which is consistent with our theoretical expectations. As discussed in the introduction, these meditation types are thought to establish different metacontrol states with different, presumably opposite characteristics, with FAM instruction establishing a state that increases top-down control, focus, and maintenance; and OMM instruction establishing a state that reduces top-down control, broadens the focus, and prepares for change (Colzato et al., 2015a, b, 2016; Colzato & Hommel, 2017a; Hommel, 2015; Lippelt et al., 2014).

From a metacontrol perspective, finding FAM to promote WM performance suggests that the meditation instruction supported WM processes related to persistence, that is, to selectivity and goal-directedness (Hommel & Colzato, 2017a,b). Given that N-Back tasks arguably comprise of both processes related to persistence and processes related to flexibility, we had no theoretical reasons to predict whether the former would be more or less sensitive to meditation interventions than the latter, which is why we also considered the opposite outcome. Such an opposite outcome would have indicated that the flexibility-related aspects of the task, like switching, updating, etc., were more sensitive to meditation, whereas our actual results suggest that aspects related to maintenance, stability, and persistence are more sensitive. What remains is the question why such an effect only showed up in the 2-back task in Experiment 1 and the 3-back task in Experiment 3. Given the negligible demands of the 1-back condition on WM, the finding of a stronger effect in the combined 2-back condition is unsurprising and makes theoretical sense. The difference between combined 2-back and combined 3-back conditions is more interesting, however. We can only speculate what this pattern may indicate, but it is possible that metacontrol-related manipulations like meditation can only operate within existing capacity. Indeed, Mekern, Sjoerds, and Hommel (2019) found evidence suggesting that individual metacontrol biases only show up under conditions in which the task is sufficiently easy to not overly tax the capacity limitations of the individual, but disappear as the task demands further increase. It may thus be that the within-participant manipulation of load in Experiment 1 was taxing participants to a degree that did not leave sufficient space for metacontrol states to exert measurable impact. Such a scenario would also fit our observation that performance in the 3-back task in Experiment 1 was very comparable across all three groups. Hence, performance in the 3-back condition of Experiment 1 may have been suffered from the challenging task context, which is why the same condition did show an effect in Experiment 3, where this context was less complex and challenging.

The observation that single-bout FAM instruction had a positive effect on N-Back performance is consistent with earlier studies showing benefits of more extended/longer-term meditation training for working memory tasks (Jha et al., 2017, 2019). However, given that longer term meditation training usually included both FAM and OMM training (e.g., Zeidan et al., 2010; Jha et al., 2019), it remained unclear which of the two is effective. Our present findings suggest that single-bout FAM instruction may be more effective than single-bout OMM instruction, for which we did not find a significant effect for all conditions in three experiments. For one, this might be a power issue. Note that the numerical pattern was as expected from the metacontrol hypothesis, with single-bout FAM increasing and single-bout OMM decreasing performance in d’. It may have been the case that the single-bout FAM induction was easier (to understand) or worked better for other reasons, so that the single-bout OMM-induced decrease was weaker or more variable. If so, a larger sample would be expected to demonstrate a significant single-bout

OMM effect. For another, or perhaps relatedly, OMM might need more practice to show measurable impact on N-Back task performance. Such as one long term meditation training study (Rooks et al., 2017) showed, greater engagement (i.e., practice time) in mindfulness training (some combination of FAM and OMM) predicted greater benefits in sustained attention. If so, one would expect more significant OMM effects with more extended/longer term training, but not single-bout instructions, and this may be even true for more demanding tasks like the higher Back condition. Thus, more direct comparisons of meditation training and single-bout meditation would be an interesting future direction.

To the degree that single-bout meditation turns out to be a useful and effective method of intervention, it would be interesting to see whether other working-memory functions and tasks can be supported, especially in the elderly or populations suffering from long-time depression, anxiety (as mindfulness training studies suggest: Grossman, Niemann, Schmidt, & Walach, 2004), or addiction. Another interesting future direction would be the characterization of the neural mechanism underlying effects of both single-bout meditation and longer-term meditation training, given the different results in current work and some studies using longer term mindfulness meditation in which combined FAM and OMM training were used. Also, the neural mechanism underlying effects of single-bout FAM and OMM instruction may be investigated, given that they showed different effects in the present study. Possible neural mechanism may be derive from related studies, for example metacontrol approach suggests a key role of prefrontal and striatal dopaminergic pathways (Hommel & Colzato, 2017b), including the prefrontal cortex (Zhang, Sjoerds & Hommel, 2020). Given that our N-Back task is considered to tax working memory, this would fit the assumption that working memory capacity and executive control functions rely on prefrontal cortex (cf., Kane & Engle, 2002) and observations that longer term meditation training has an impact on frontal and parietal networks (Ziegler et al., 2019). Future studies might thus more closely monitor single-bout meditation-induced activities and changes, especially in prefrontal cortex, and use dopaminergic manipulations to support, interfere with, or even mimic meditation-induced mental/neural states.

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Informed consent: Informed consents were obtained from all participants included in this study.

Author contribution: KM and ND developed the study concept. ND prepared the meditation materials. All authors contributed to the study design. Data collection was performed by ND. Data analysis and manuscript drafting were performed by KM, and BH provided critical revisions. All authors approved the final version of the manuscript for submission. The authors would like to thank Dr. Roberta Sellaro for her help in translating the meditation materials and advice on the N-Back task; and thank the editor and reviewers for their valuable suggestions.

Reference

Baddeley A. Working memory. *Science, 1992, 255*, 556–559

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

Basso, J. C., McHale, A., Ende, V., Oberlin, D. J., & Suzuki, W. A. (2019). Brief, daily meditation enhances attention, memory, mood, and emotional regulation in non-experienced meditators. *Behavioural brain research, 356*, 208–220.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, New Jersey: Lawrence Erlbaum Associates.

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, 3:116*.

Colzato, L., Jongkees, B., Sellaro, R., & Hommel, B. (2013). Working memory reloaded: tyrosine repletes updating in the N-Back task. *Frontiers in Behavioral Neuroscience, 7: 200*.

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.

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.

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.

Colzato, L.S., & Hommel, B. (2017a). Meditation. In: L.S. Colzato (ed.), *Theory-driven approaches to cognitive enhancement* (pp. 225-237). New York: Springer.

Colzato, L.S., Szapora, A., Lippelt, D., & Hommel, B. (2017b). Prior meditation practice modulates performance and strategy use in convergent- and divergent-thinking problems. *Mindfulness, 8*, 10-18.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods, 41*(4), 1149–1160.

Goodrich, E., Wahbeh, H., Mooney, A., Miller, M., & Oken, B. S. (2015). Teaching mindfulness meditation to adults with severe speech and physical impairments: An exploratory study. *Neuropsychological rehabilitation*, *25*, 708–732.

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

Grossman, P., Niemann, L., Schmidt, S., & Walach, H. (2004). Mindfulness-based stress reduction and health benefits: A meta-analysis. *Journal of Psychosomatic Research, 57*, 35–43.

Haatveit, B. C., Sundet, K., Hugdahl, K., Ueland, T., Melle, I., & Andreassen, O. A. (2010). The validity of d prime as a working memory index: results from the "Bergen N-Back task". *Journal of clinical and experimental neuropsychology, 32,* 871–880.

Hommel, B. (2015). Between persistence and flexibility: The Yin and Yang of action control. In: A. J. Elliot (ed.), *Advances in motivation science*, vol. 2 (pp. 33–67). New York: Elsevier.

Hommel, B., & Colzato, L.S. (2017a). Meditation and metacontrol. *Journal of Cognitive Enhancement, 1*, 115-121.

Hommel, B., & Colzato, L.S. (2017b). The social transmission of metacontrol policies: Mechanisms underlying the interpersonal transfer of persistence and flexibility. *Neuroscience and Biobehavioral Reviews, 81*, 43-58.

Immink, M.A., Colzato, L.S., Stolte, M., & Hommel, B. (2017). Sequence learning enhancement following single-session meditation is dependent on metacontrol mode and experienced effort. *Journal of Cognitive Enhancement, 1*, 127–140.

Jha, A. P., Stanley, E. A., Kiyonaga, A., Wong, L., & Gelfand, L. (2010). Examining the protective effects of mindfulness training on working memory capacity and affective experience. *Emotion, 10*, 54-64.

Jha, A. P., Witkin, J. E., Morrison, A. B., Rostrup, N., & Stanley, E. (2017). Short-form mindfulness training protects against working memory degradation over high-demand intervals. *Journal of Cognitive Enhancement, 1*, 154-171.

Jha, A. P., Denkova, E., Zanesco, A. P., Witkin, J. E., Rooks, J., & Rogers, S. L. (2019). Does Mindfulness Training Help Working Memory 'Work'Better?. *Current opinion in psychology, 28*, 273–278

Rooks, J. D., Morrison, A. B., Goolsarran, M., Rogers, S. L., & Jha, A. P. (2017). "We Are Talking About Practice": the Influence of Mindfulness vs. Relaxation Training on

Athletes' Attention and Well-Being over High-Demand Intervals. *Journal of Cognitive Enhancement, 1*, 141-153.

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic bulletin & review, 9*, 637-671.

Kane, M. J., Conway, Andrew R. A., Miura, Timothy K., & Colflesh, Gregory J. H. (2007). Working memory, attention control, and the N-Back task: a question of construct validity. *Journal of Experimental Psychology Learning Memory & Cognition, 33,* 615–622.

Kirchner, W. K. (1958). Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology, 55*, 352–358.

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, 5:1083*.

Lutz, A., Jha, A. P., Dunne, J. D., & Saron, C. D. (2015). Investigating the phenomenological and neurocognitive matrix of mindfulness-related practices. *American Psychologist, 70*, 632–658.

Lutz, A., Slagter, H. A., Dunne, J. D., & Davidson, R. J. (2008). Attention regulation and monitoring in meditation. *Trends in Cognitive Sciences, 12*, 163–169.

Macmillan, N. A., and Creelman, C. D. (1991). *Detection Theory: A User's Guide*. Cambridge: Cambridge University Press.

Mekern, V.N., Sjoerds, Z., & Hommel, B. (2019). How metacontrol biases and adaptivity impact performance in cognitive search tasks. *Cognition, 182,* 251–259.

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*, 49–100.

Moore, A., & Malinowski, P.. (2009). Meditation, mindfulness and cognitive flexibility. *Consciousness and Cognition, 18*, 176–186.

Mrazek, M. D., Franklin, M. S., Tarchin, D., Baird, B., & Schooler, J. W. (2013). Mindfulness training improves working memory capacity and GRE performance while reducing mind wandering. *Psychological Science, 24*, 776–781.

Owen, A. M., McMillan, K. M., Laird, A. R., & Bullmore, E. (2005). N-Back working memory paradigm: A meta-analysis of normative functional neuroimaging studies. *Human brain mapping, 25*, 46–59.

Perrig, W. J.. (2010). The concurrent validity of the N-Back task as a working memory measure. *Memory, 18*, 394–412.

Quach, D. (2014). *Differential effects of sitting meditation and hatha yoga on working memory, stress, anxiety, and mindfulness among adolescents in a school setting*. Dissertations & Theses - Alliant International University.

Redick, T. S., & Lindsey, D. R. (2013). Complex span and n-back measures of working memory: a meta-analysis. *Psychonomic Bulletin & Review*, *20,* 1102–1113.

Slagter, H.A., Lutz, A., Greischar, L.L., Francis, A. D., Nieuwenhuis, S., Davis, J., & Davidson, R.J. (2007). Mental training affects distribution of limited brain resources. *PLoS Biology, 5(6)*, e138.

Swets, J. A., Tanner Jr, W. P., & Birdsall, T. G. (1961). Decision processes in perception. *Psychological review, 68*, 301-340.

Tang, Y. Y., Ma, Y., Wang, J., Fan, Y., Feng, S., Lu, Q., Yu, Q., Sui, D., Rothbart, M. K., Fan, M., & Posner, M. I. (2007). Short-term meditation training improves attention and self-regulation. *Proceedings of the National Academy of Sciences, 104*, 17152–17156.

Tang, Y. Y., Hölzel, B. K., & Posner, M. I. (2015). The neuroscience of mindfulness meditation. *Nature Reviews Neuroscience, 16*, 213–225.

Tops, M., Boksem, M. A., 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, 5:429*.

Tsai, M. H., & Chou, W. L.. (2016). Attentional orienting and executive control are affected by different types of meditation practice. *Consciousness and Cognition, 46*, 110-126.

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, 6:296*.

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

Verhaeghen, P., & Basak, C. (2005). Ageing and switching of the focus of attention in working memory: Results from a modified N-Back task. *The Quarterly Journal of Experimental Psychology Section A, 58*, 134–154.

Vugt, M. K. V., & Amishi P. Jha. (2011). Investigating the impact of mindfulness meditation training on working memory: a mathematical modeling approach. *Cognitive Affective & Behavioral Neuroscience, 11*, 344–353.

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*, 597–605.

Zhang, W., Sjoerds, Z., & Hommel, B. (2020). Metacontrol of human creativity: The neurocognitive mechanisms of convergent and divergent thinking. *Neuroimage, 210:*116572.

Ziegler, D. A., Simon, A. J., Gallen, C. L., Skinner, S., Janowich, J. R., Volponi, J. J., Rolle, C. E., Mishra, J., Kornfield, J., Anguera, J. A., & Gazzaley, A. (2019). Closed-loop digital meditation improves sustained attention in young adults. *Nature human behaviour, 3*, 746–757.