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Short-term Focused Attention Meditation Restricts the Retrieval of Stimulus-Response Bindings to Relevant Information

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Abstract

Objectives Goal-direct actions require integrating processing of stimuli and responses, which is why close stimulus-response bindings have to be created. However, the strength of these bindings can be modified. The metacontrol state model (MSM) hypothesizes that this can be achieved through mindfulness meditation. Yet, the cognitive processes underlying possible effects of meditation on S-R bindings remain unexplored.

Methods We examined the effects of a brief bout of focused attention (FA) meditation on S-R bindings using a standard event file task measuring S-R bindings. This was done in a within-subject (crossover) design, where each participant (novice to meditation) was examined at two separate appointments (with and without meditation before the task).

Results We found that 15 min of a single bout of FA meditation was enough to restrict the retrieval of S-R bindings to relevant information as indexed by decreased partial overlap costs.

Conclusion These findings support the MSM framework suggesting that FA meditation induces a top-down biasing of processes toward cognitive persistence. Importantly, however, the effects of FA meditation were only evident when there was prior experience with the task. This shows close similarities to effects in pharmacological and brain stimulation studies and suggests that FA meditation modulates gain control principles in information processing. Moreover, effects of FA meditation were restricted in its duration since FA meditation modulated the retrieval of S-R bindings only in the early phases of the event file task. In novices, effects of short-term FA meditation are thus relatively fragile and only induce some finer adjustments in processing strategy.

Keywords S-R binding · Feature binding · Meditation · Metacontrol state model

The binding problem (Hommel 2004; Treisman 1996), which refers to how different features (shape, color, size, orientation, location, etc.) regarding a given object are integrated in a coherent percept (i.e., "object file"), is one of the most fascinating problems in cognitive psychology. In the last two decades, the concept of "object file" has been broadened to incorporate not only perceptual, but also action-related information (Frings et al. 2020; Hommel 1998, 2004, 2019). That is, visual and motor features are automatically integrated in stimulus-response (S-R) bindings and can be measured by the so-called event file task (Hommel 2004). In this task, the

perception of the same combination of stimulus and response features (i.e., complete repetitions; e.g., both stimulus location and the response) or an entirely different combination (i.e., complete alternations) can promote performance, while the perception of a new combination of the same features can impair it (i.e., partial repetitions; e.g., location but not the response or the response but not the location). This is the case because a "re-binding" process takes place. This process is time-consuming because it produces a conflict between the previously generated S-R binding and the newly established one (Frings et al. 2020; Hommel 2004, 2019; Opitz et al. 2020; Petruo et al. 2016).

Feature binding has been found to be altered in aging (Hommel et al. 2011) and neurological conditions such as Tourette syndrome (Kleimaker et al. 2020a, b; Petruo et al. 2019, 2020), Parkinson's disease (Colzato et al. 2012) and stress (Frings et al. 2013). Against this background, in order to ameliorate these conditions, there is a rising interest for

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enhancing practices aimed on optimizing feature binding. Regarding the issue of cognitive enhancement, in the last few years, meditation practice has become progressively *en vogue* (Davidson and Dahl 2018; Van Dam et al. 2018), and it seems of crucial importance to examine potential enhancing effects of such single bouts on meditation on the updating of S-R bindings. In line with Lutz et al. (2008), focused attention (FA) meditation demands the practitioners to focus on a single event (for example the breath) and to invite them to go back to this focus in case of mind wandering. The research question to assess the short-term effects of a single bout of FA meditation on the retrieval S-R bindings, as indexed by the event file task (Frings et al. 2020; Hommel 1998, 2004, 2019), is theoretically motivated by the metacontrol state model (MSM) (Hommel 2015; Hommel and Colzato 2017). The MSM proposes that these two types of meditation induce particular metacontrol state biases. In line with this model, cognitive processes are impacted by metacontrol states which oscillate between two extremes: persistence and flexibility. The idea is that FA meditation would induce a bias towards cognitive persistence. As such, FA meditation likely entails that more top-down control will support an effective focus on one goal/relevant information and to discharge irrelevant information. Evidence backing this idea comes from a series of studies investing the effect of FA meditation on motor sequence learning and performance (Chan et al. 2017, 2018, 2020; Immink et al. 2017; Tang et al. 2007). First, it has been reported that enhanced top-down control immediately after FA meditation biases the implementation of stimulus-based planning and, by so doing, produces sequence learning benefits (Chan et al. 2017). Second, based on the finding outlined above, Chan et al. (2018) were able to show that after FA meditation, a greater rate of improvement in reaction time (RT) performance was obtained in contrast to a computerized attention task, which also requires focused attention. This result indicates that effect of FA states on increased top-down control during sequence learning relies on the focused attention control component of this specific meditation. Third, level of effort experienced in FA meditation has been found to be linked to significantly greater general sequence performance improvements (Immink et al. 2017). Last, 21 sessions of FA meditation, compared with a single bout or no FA training, produced a significantly more pronounced N2, an electrophysiological marker for cognitive control during performance monitoring dependent on catecholamines (Ullsperger et al. 2014; Willemssen et al. 2009), over the anterior and central brain regions while performing a motor sequence learning task (Chan et al. 2020).

The idea that FA meditation enhances the attention to one specific aspect, which may support the ability to focus but at the cost of cognitive flexibility, has been supported by Wolff and Beste (2020) where they found a single bout of FA meditation to decrease task switching performance (i.e., impaired cognitive

flexibility). Regarding the integration of visual and motor features, we expect FA meditation to restrict the retrieval of the previously generated S-R binding to the nominally relevant information (i.e., the task-relevant feature codes). If so, the current binding process would be less impacted by the previously generated binding, as the conflict between the previously generated S-R binding and the newly established one would be less pronounced, as indexed by smaller partial-repetition costs. In other words, if FA meditation induces a "persistence" metacontrol bias, performance should be less hampered by partial mismatches between current and former stimulus.

In a nutshell, the aim of the study was to investigate the short-term effects of a single bout of FA meditation on the retrieval S-R bindings. We hypothesized also that the level of familiarity of the task performed and the limited duration of activation of metacontrol state induced by FA meditation in novices will play a role in the exerted short-term effect of a single bout of FA meditation on S-R bindings.

Methods

Participants

Forty participants aged 18 to 35 years (mean age: 25.95 years, SD = ± 4.6; 13 males; 0 left-handed) were recruited to participate in a randomized crossover study design. Beforehand, participants were screened for previous experience in meditation during a phone call to make sure they were novices or had sporadic meditation experience. A total of $N = 23$ participants had experience in meditation in an irregular pattern, whereas $N = 17$ reported having no experience in meditation at all. All participants were free of medication, had normal or corrected-to-normal vision and hearing, and reported no neurological or psychiatric disorders.

Procedure

The within-subject crossover study comprised two appointments with 11 (SD = 12) days in between. Participants were randomly assigned to one out of two groups. Group A ($N = 20$) listened through headphones to a 15-min FA meditation using a smartphone App "Die Achtsamkeit App - Meditation für Jeden" (English: "The Mindfulness App") during the first appointment, right before performing the S-R task. This group did not meditate during the second appointment. For group B ($N = 20$), the order of FA treatment was reversed (first appointment: no FA meditation; second appointment: FA meditation). Both groups did not further listen to the App (https://themindfulnessapp.com/) between the two appointments. The App, evaluated by Mani et al. (2015), was installed on a smartphone (Samsung Galaxy J3) and can be downloaded in the Google play store (https://play.google.com/store/apps/

Following Wolff and Beste (2020), the study protocol remained the same for both appointments except for listening of meditation or not. First, participants were welcomed and seated in the EEG lab, then the informed consent was signed, followed by preparing the EEG cap. Group A did then listen to the FA meditation before performing the S-R paradigm, whereas group B skipped the FA meditation during the first appointment and vice versa. The FA meditation started with a gong sound, followed by instructions given by a calm, male voice. First, the participants had to find a comfortable sitting position and were asked to focus on their breath. Participants were instructed to return to the breath when their mind wandered on something else. Then, the focus of their attention was extended to the whole body. After a few minutes, participants were asked to notice the breath once again, focusing on the "here and now". Three gong sounds ended the 15-min FA meditation. The background sounds, which the App offers (e.g., sea, forest), were not turned on.

Measures

Following Takacs et al. (2020a, b)), a S-R paradigm was employed to test the effects of a single FA meditation on stimulus-response bindings. The outline of the task is shown in Fig. 1.

The participants sat about 60 cm away from a screen. During each trial of the task, three vertically connected boxes (each 2.4 cm × 0.9 cm) were presented on the black screen. The participants were shown one arrowhead and two bars one after the other. First, the arrowhead was shown for 1500 ms in the middle of the three boxes. Participants had to remember the direction and wait until the first bar, stimulus 1 (S1), was presented. When the arrow disappeared, the screen turned black for 1000 ms. As soon as the S1 was shown for 500 ms, participants were asked to press a key button on a QWERTZ keyboard and decide in which direction the arrow was pointed. If the arrow was pointed to the left, participants had to press the left key with their left index finger. If the arrow was pointed to the right, participants were asked to press the right key with their right index finger. If the participant did not react to the direction of the arrow within time limit of 500 ms, the arrow will be presented again until response. Both presented bars (S1, S2) varied by color (red or green), shape (horizontal or vertical) and location (upper or lower box). Although the first response (R1) should be performed independently of color, shape and location of S1, due to the proximity of S1 and R1, the stimulus characteristics were nevertheless bound to the response (automatic S-R binding). When the participants' response (R1) was within the 500 ms, the screen turned blank for 2000 ms. While the participants saw the second bar, stimulus 2 (S2), for 2000 ms or until the participant reacted, they had to indicate by pressing a

key, whether the second bar was horizontally oriented (left key) or vertically oriented (right key). Therefore, it was possible that R1 and R2 were either repeated or alternated. The paradigm comprised 384 trials in total, but it could include up to 395 trials if R1 was not given within 500 ms. The factorial combination of S2 features determined the number of trials as follows: color (2) × shape (2) × location (2), the repetition versus alternation of color (2) × repetition versus alternation of shape (2) × repetition versus alternation of location (2) × response (2), while each combination was applied three times. Thus, four different feature components can be differentiated between S1 and S2 for each trial: identical (three/full features overlap condition), completely different (zero/no feature overlap condition), or partly similar (partial features overlap conditions: one feature and two features overlap).

Data Analyses

Repeated measures ANOVAs (Greenhouse-Geisser-corrected, if necessary) were used to analyze mean reaction times (RTs) and mean accuracy (hit percentage of correct responses) for each participant and condition for R2. The factor "half" (first vs. second half of task performance), "meditation" (with vs. without), "response" (repeat vs. alternate) and "feature overlap" (zero vs. one vs. two vs. full) was used as within-subject factor. The factor "group" (FA meditation at appointment 1 vs. 2) was used as a between-subject factor. For the descriptive statistics, the mean and standard deviation (SD) are given. Statistics were calculated using IBM SPSS Statistics 25.0.0.2. All data are available at the Open Science Framework (https://osf.io/wur48/).

Results

Reaction Times

The ANOVA for RTs revealed a main effect of feature overlap, $F(2.05, 77.95) = 6$, $p = .004$, $\eta^2 = .136$. Participants showed the fastest reaction in the no feature overlap condition (453.157 ms ± 11.659), compared with one feature overlap (460 ms ± 10, $p = .026$) or the two features overlap condition (463.554 ms ± 10.757, $p < .001$). There was no significant difference between the three features overlap condition (460.517 ms ± 10.722) and any of the other conditions, $p > .05$. Further, the ANOVA revealed two two-way interactions: meditation by group, $F(1, 38) = 4.335$, $p= .044$, $\eta^2 = 0.102$, and feature overlap by response, $F(1.79, 67.9 = 48.48$ $p < .001$, $\eta^2 = 0.561$. Interestingly, the first two-way interaction was modified by a four-way interaction involving half and feature overlap, $F(3, 114) = 2.72$, $p = .048$, $\eta^2 = .067$, and a five-way interaction involving half, feature overlap and response $F(3, 114) = 3.01$, $p = .033$, $\eta^2 = .073$.
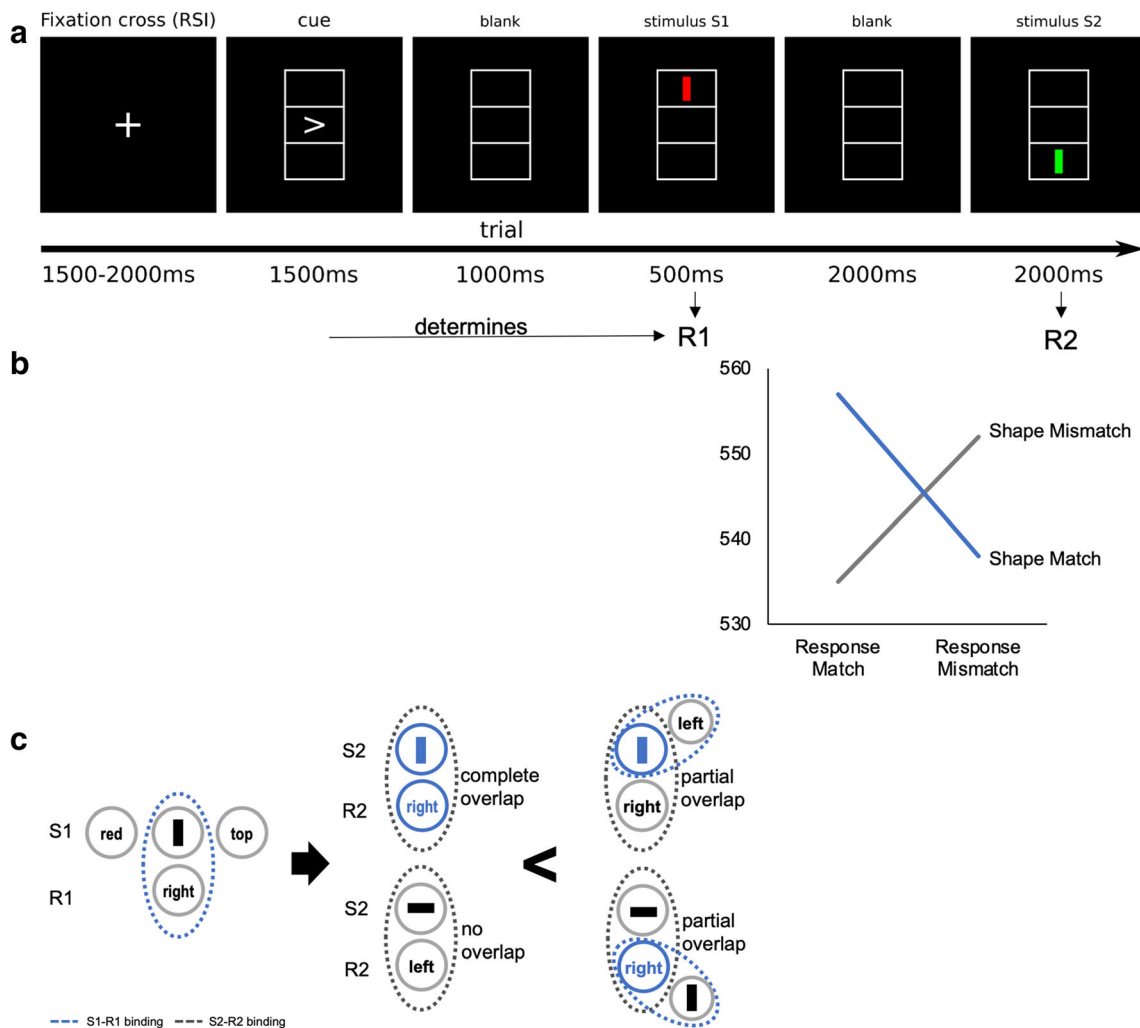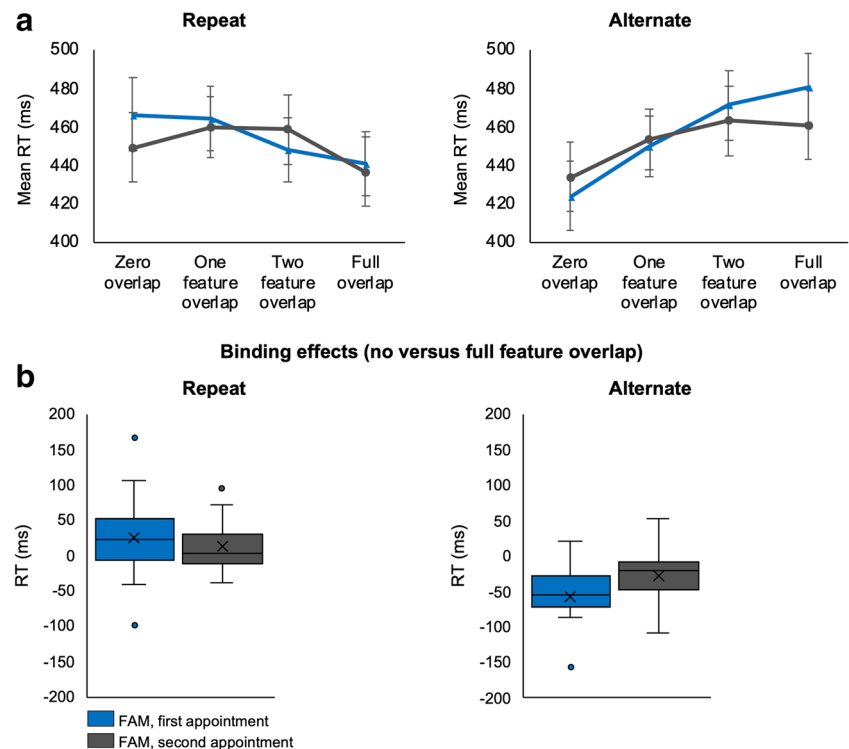
Fig. 1 **a** Schematic illustration of the sequence of events during a trial. The cue determines R1 (right vs. left keypress depending on the direction of the arrow) which is triggered by S1. R2 is triggered by S2 which requires a binary choice reaction to its shape (horizontal vs. vertical). **b** Typical patterns of results obtained for R2. In the case of the illustrated example, people are faster when facing the repetition of stimulus shape and response features (i.e., complete repetitions; e.g., both stimulus shape and the response) or when facing an entirely different combination (i.e., complete alternations). In contrast, people are slower when facing a new combination of the same features (i.e., partial repetitions; e.g., shape but not the response or the response but not the shape). **c** Theoretical explanation of the costs associated to the "re-binding" process. In the case of the illustrated example, given that the vertical line is bound to the right response (S1-R1 binding), a time-consuming process takes place when the same right response (R2) needs to be "re-bind" to the new horizontal line (S2) or when the same horizontal line (S2) needs to be "re-bind" to the new left response (R2) creating two new S2-R2 bindings. This process is time-consuming because it produces a conflict between the previously generated S-R binding (S1-R1 binding) and the newly established one (S2-R2 binding)

In order to understand this five-way interaction, repeated-measures ANOVAs were conducted for the first and the second half separately. Only the first, but not the second half, $F \leq 1.38$, $p \geq .251$ showed a significant effect of meditation × feature overlap × response × group, $F(3, 114) = 3.54$, $p = .017$, $\eta^2 = .085$. Given that this four-way interaction was significant for the first but not the second half, separate ANOVAs were calculated for the condition "with" and "without" meditation when considering only the first half of trials. Only for condition "with", but not for the condition "without" meditation, $F \leq .53$, $p \geq .663$, there was a significant three-way interaction involving feature overlap × response × group, $F(3, 114) = 3.76$, $p = .013$, $\eta^2 = .09$. Given that this three-

way interaction was significant for "with" but not "without" meditation, separate ANOVAs were calculated for group (receiving FA meditation at the first or at the second appointment) when considering only the condition "with" meditation. For both groups, the response by feature overlap interaction was significant, but for the group who received FA meditation at the second appointment, the strength of this interaction was smaller, $F(1.98, 37.63) = 5.06$, $p = .012$, $\eta^2 = .21$, compared with the group who received FA meditation at the first appointment, $F(1.78, 33.82) = 20.47$, $p < .001$, $\eta^2 = .519$, see Fig. 2. For the latter group, the average RT tended to decrease from the no feature overlap to the full feature overlap condition when response had to be repeated (449 ms ± 19 vs.

Fig. 2 The RTs for the first half regarding the "with" meditation data are displayed. **a** RT results across feature overlap and response type for the group who received FA meditation at the first appointment (blue) and for the group who received FA meditation at the second appointment (dark grey). The mean RT is shown as a function of overlapping features for repeated and alternated responses. **b** The binding effects are displayed. Differences of mean RTs between (i) response repetition at no overlap versus full overlap and (ii) response alternation at no overlap versus full overlap. Error bars denote standard error of the mean

437 ms ± 17, p = .188). In contrast, responses became slower from the no feature overlap (434 ms ± 19) to the one feature overlap (454 ms ± 18, p = .006), the two features overlap (463 ms ± 19, p = .001) and the full feature overlap conditions (461 ms ± 17, p = .006) when response had to be alternated. Regarding the former group, the average RT tended to decrease from the one feature overlap to the full feature overlap condition when response had to be repeated (466 ± 19 vs. 441 ms ± 16, p = .062). In contrast, responses became slower from the no feature overlap (424 ms ± 17) to the one feature overlap (450 ms ± 13, p = .003), the two features overlap (471 ms ± 17, p < .001) and the full feature overlap conditions (480 ms ± 19, p < .001) when response had to be alternated.

In sum, as expected, following FA meditation, we found decreased partial overlap costs when performing the task for the second time as compared with the first time as indication that the level of familiarity of the task performed affects the strength of S-R bindings. Further, we found that this effect was reliable only for the first half of the trials pointing out limited duration of activation of metacontrol state induced by meditation in novices.
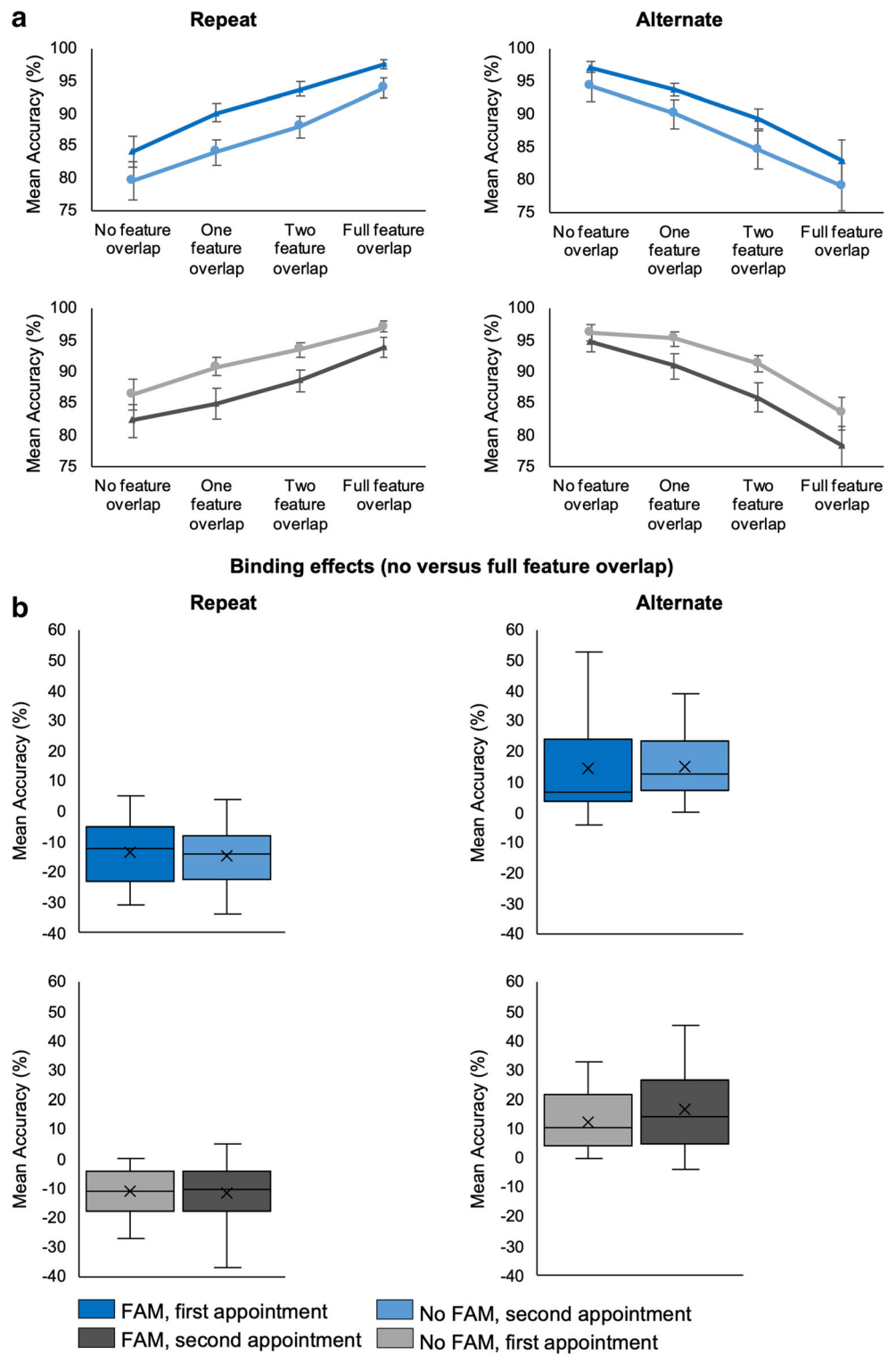
Accuracy

The ANOVA for mean accuracy revealed a two-way interaction involving response × feature overlap, $F(1.59, 60.41) = 84.71$, $p < .001$, $\eta^2 = .69$. This interaction was modified by meditation × feature overlap × response × group ($F[3, 114] = 4.25$, $p = .007$, $\eta^2 = .101$). In order to understand the four-way

interaction, we conducted repeated-measures ANOVAs separately for the condition "with" and "without" meditation, but yielded no significant three-way interaction involving feature overlap × response × group ($F[3, 114] = .24$, $p = .871$, $\eta^2 = .006$; $F[3, 114] = 1.22$, $p = .308$, $\eta^2 = .031$). The same was true when we tried to disentangle the four-way interaction by carrying out separate ANOVAs for group, response, and feature overlap, $F \leq 3.48$, $p \geq .07$. Then, we carried out four separate ANOVAs considering the different combination of factors for meditation (with vs. without) and group (FA meditation at appointment 1 vs. 2). For the condition "with" meditation for both groups, the strength of the response by feature overlap interaction was smaller ($F[1.55, 29.52] = 24.25$, $p < .001$, $\eta^2 = .561$, $F[1.82, 34.64] = 24.64$, $p < .001$, $\eta^2 = .565$ for the group who received FA meditation at the first appointment and the group who received FA meditation at the second appointment, respectively) compared with the condition "without" meditation ($F[1.94, 36.8] = 32.31$, $p < .001$, $\eta^2 = .63$, $F[1.6, 30.47] = 40.35$, $p < .001$, $\eta^2 = .68$ for the group who received FA meditation at the first appointment and the group who received FA meditation at the second appointment, respectively), as indication that, as expected, FA meditation did decrease the partial overlap costs, see Fig. 3.

Discussion

The aim of the current study was to examine the short-term effects of a single bout of FA meditation on the retrieval of S-

Fig. 3 The mean accuracy data are displayed. **a** Mean accuracy results across feature overlap and response type for the group who received FA meditation at the first appointment (red), for the group who received FA meditation at the second appointment (green), for the group who did not receive FA meditation at the first appointment (dark red), and for the group who did not receive FA meditation at the second appointment (dark green). The mean accuracy is shown as a function of overlapping features for repeated and alternated responses. **b** The binding effects are displayed. Differences of mean accuracy between (i) response repetition at no overlap versus full overlap and (ii) response alternation at no overlap versus full overlap. Error bars denote standard error of the mean

R bindings. When we perceive the same combination of stimulus and response features or an entirely different combination, performance is improved in contrast to when we perceive a partially new combination of the same feature which hampers performance (Frings et al. 2020; Hommel 2004, 2019). Responsible for this impairment is a conflict between the previously generated S-R binding and the newly established one which calls for a time-consuming "rebinding" process. Our theoretical hypothesis was based on the MSM (Hommel 2015; Hommel and Colzato 2017) which proposes that FA meditation induces a specific metacontrol state with a bias towards cognitive persistence. This idea has been recently

supported, on the one hand, by a series of studies investing the effect of FA meditation on serial reaction time task showing that enhanced top-down control immediately after FA meditation produces benefits in motor sequence learning and performance (Chan et al. 2017, 2018, 2020; Immink et al. 2017). On the other hand, Wolff and Beste (2020), using the same FA meditation as we did in the current study, found an impairment of task switching performance. Additionally, in the current study, we also considered that effects of FA meditation may depend on prior experience with the specific S-R binding task and may also be limited in the duration of effects.

As expected, we found that the level of familiarity of the task performed and the limited duration of activation of metacontrol state induced by meditation in novices played a key role in the exerted short-term effect of FA meditation on S-R bindings. The idea is that FA meditation induces a bias towards cognitive persistence, that is, more top-down control that sustains an effective focus on one goal and on relevant information and to discharge irrelevant (i.e., not goal-compatible) information. By inducing a persistent metacontrol bias, FA meditation restricts the retrieval of the previously generated S-R binding to the nominally relevant information. Hence, if this is the case, the current binding process would be less impacted by the previously generated binding, as the conflict between the previously generated S-R binding and the newly established one would be less pronounced. Indeed, we found that following FA meditation, performance was less hampered by partial mismatches between current and former stimulus–response relations, indicating restrict retrieval of episodic stimulus–response representations (i.e., decreased partial overlap costs) when performing the task for the second time. It should be stated that the overall interaction obtained a small effect size and that the observed effect of meditation is therefore very specific.

However, the fact that the short-term effect of FA meditation was modulated by the level of familiarity of the task performed is in line with the idea of shared noradrenergic/dopaminergic underpinnings of meditation (Krishnakumar et al. 2015), handling S-R bindings (Verguts and Notebaert 2008, 2009), learning (Harley 2004), and the SNR (Aston-Jones and Cohen 2005). Regarding meditation, several studies have shown that the striatum, the key component of the nigro-striatal dopamine pathway (Palmiter 2008), is active when meditating. Notably, Kjaer et al. (2002) have reported the positron emission tomography (PET) tracer $[^{11}C]$Raclopride to increase the binding to dopamine D2 receptors when the participants where actively meditating. Second, an experienced Buddhist meditator has shown specific increased activity in the anterior cingulate cortex (ACC) and in the striatum during FA compared with other meditative techniques (Hagerty et al. 2013). Third, Knytl and Opitz (2019) have found that FA meditators, as compared with nonmeditators, exhibited attenuated feedback-related negativity, an electrophysiological component known to be affected by dopamine levels in the striatum and ACC. Hence, the studies outlined above imply a crucial activation of the nigro-striatal dopamine pathway when practicing FA meditation.

Regarding the level of familiarity of the task performed, besides the possibility that this effect may arise from better ability to extract salient information (Krueger 1975), several lines of evidence using pharmacological modulations targeting the noradrenergic and dopaminergic system have shown that the effects of the pharmacological modulation depend on learning performance or prior task experience (Adelhöfer et al. 2019; Bensmann et al. 2019; Mückschel et al. 2020a, b). It has been argued that learning/prior task experience and actions of the noradrenergic/dopaminergic system tap into similar mechanisms or principles. This common neural principle likely refers to 'gain control' mechanisms (Bensmann et al. 2019). Gain control is a general working principle in neural networks found at sensory, cognitive (Adelhöfer et al. 2018; Salinas and Thier 2000; Servan-Schreiber et al. 1990; Beste et al. 2016), and motor levels (Greenhouse et al. 2015; Thura and Cisek 2016). Increasing gain control can be viewed as sharpening the responsivity of the neural network and as increasing the signal-noise-ratio (SNR) of information processing. The adjustment of the signal-to-noise ratio, central to gain modulation principles, has also directly been shown to play an important role in learning and experience-dependent neural plasticity effects (Dosher and Lu 1998; Gold et al. 1999). Byers and Serences (2012) note that mechanisms aimed to increase top-down (cognitive) control, like the strengthening of top-down attentional control processes, and processes of learning and plasticity operate by increasing the SNR in neural circuits (Desimone and Duncan 1995; Knudsen 2007; Miller and Cohen 2001). Therefore, prior learning/task experience, as well as FA meditation may both be seen as means to modulating (increasing) SNR in neural circuits and this is why FA meditation effects are modulated by prior task experience as shown in the present data. This is also supported by findings suggesting that experience-dependent changes affect the recruitment of top-down cognitive control (Makino 2019). The interpretation that FA meditation modulates the SNR of neural information processing, which is why there are modulatory effects of learning/prior task experience, is commensurable with the metacontrol theoretical framing of mindfulness meditation (Hommel 2015; Hommel and Colzato 2017). The MSM-hypothesis (Hommel 2015; Hommel and Colzato 2017) proposes that FA meditation induces a specific metacontrol state bias towards cognitive persistence but at the cost of cognitive flexibility. According to MSM, FA meditation induces a top-down biasing of cognitive processes toward cognitive persistence. This is also supposed to happen by increasing the SNR during information processing. However, the finding that FA meditation effects do only

unfold once prior learning experience is evident suggests that the effects induced by short-term FA meditation are relatively fragile and that FA meditation may be seen as mean to induce some finer adjustments in processing strategy. Short-term FA meditation may thus not be useful to induce strong shifts in the cognitive processing strategy but may only be useful to induce some more fine-tuning of information processing.

The finding that short-term FA meditation has only a limited impact fits with the observation that FA meditation effects were restricted to early phases of the event file binding experiment and vanished later in the experiment. Indeed, there is evidence that control states have some degree of inertia, which makes them outlive the task they were created for, but then disappear over time (Allport et al. 1994). The limited temporal stability of FA meditation effects is also in line with previous findings (Chan et al. 2020) and is consistent with the hypothesis put forward by Hommel and Colzato (2017) that novices (as the participants tested in the current study) may be less able than experienced meditators to keep active meditation-induced metacontrol states. It is important to consider that novices exclusively rely on the instruction given by the experimenter to establish a corresponding metacontrol state. Not only may the transformation of the instruction into a corresponding state be suboptimal, due to a lack of understanding or imperfect communication between experimenter and participant, but the established state would also need to be actively maintained to have any impact on cognitive processes. Any distraction of the novice would thus work against this maintenance and, as a consequence, reduce the impact of meditation. In contrast, experienced meditators no longer need to rely on instructions and can thus re-instruct themselves whenever the meditation-induced state is impaired or lost. Along these lines, we would expect experienced meditators to show a more lasting effect of FA meditation in the S-R task.

Limitations and Future Research Directions

A limitation of our study is that we did not use an active control condition. Future and follow-up studies should contrast cognitive performance after FA meditation to cognitive performance after a computerized attention task which also requires focused attention. Using such a control condition, Chan et al. (2018) were able to show that the effects of FA states on increased top-down control during sequence learning relies on the focused attention control component of this specific meditation.

In contrast to FA meditation, open monitoring (OM) meditation, which demands the practitioners to be open and to acknowledge any potential thoughts (but without sticking to them) that pop-up in the mind (Lutz et al. 2008), is supposed to induce a bias towards cognitive flexibility (Hommel 2015;

Hommel and Colzato 2017). It would be interesting for a future study to investigate the effect of OM meditation on S-R bindings. We would expect OM meditation to boost the retrieval of S-R bindings. By so doing, the current binding process would be more impacted by the previously generated binding, as the conflict between the previously generated S-R binding and the newly established one would be more pronounced (Frings et al. 2020; Hommel 2004, 2019). At a neurophysiological level, we believe that the different metacontrol states induced by FA and OM meditation should also be explainable within a SNR framework. Whereas FA meditation supporting a bias towards cognitive persistence is likely to increase the SNR by sharpening gain control mechanisms, OM meditation sustaining a bias towards cognitive flexibility is probable to decrease the SNR by blunting gain control mechanisms. It would be interesting to retrace changes induced by the different types of meditations on the SNR via tracking pupil diameter which can be used as an index of gain control adjustments (Aston-Jones and Cohen 2005).

Declarations

Ethics Statement This study was approved by the institutional review board of the Medical faculty of the TU Dresden and was conducted in accordance with the Declaration of Helsinki.

Informed Consent All participants signed the written informed consent and were remunerated with €70 for their expenditure of time.

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

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