Between persistence and flexibility: the neuromodulation of cognitive control

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Chapter 3

Metacontrol of event-file management: More selective handling after Focused-Attention than after Open-Monitoring Meditation

Abstract

Features of perceived and produced events (actions) are integrated into episodic event files. Whereas the creation of event files occurs more or less automatically, their retrieval can be controlled in principle, but considerable intra- and inter-individual variability exists with respect to the efficiency of this control. We hypothesize that efficiency depends on the current metacontrol state (bias towards persistence or flexibility) of the perceiver/actor and that a bias towards persistence (which is known to increase the focus on relevant information) should render the retrieval of event files more selective or prevent it altogether. We induced biases towards persistence and flexibility by having meditation-naive participants undergo either focus attention meditation (FAM) or open monitoring meditation (OMM), respectively. Experiment 1 A showed that trial-to-trial stimulus-induced retrieval of event files was modulated by meditation: while trial-to-trial effects of bindings of the two task-relevant features (stimulus shape and response location) were the same under both meditation conditions, the effect of the binding involving the irrelevant stimulus feature stimulus color and the response was more pronounced after OMM than after FAM. This effect was mainly driven by OMM as demonstrated in Experiment 1B and was replicable yet limited to the first experimental session in a within-participant design, as demonstrated in Experiment 2. These results suggest that engaging in OMM leads to less efficient filtering of information in WM, which fits with theoretical claims and empirical observations suggesting that OMM can induce a metacontrol state that weakens top-down control of information processing.

Keywords: Focused attention meditation (FAM), open monitoring meditation (OMM), event-file, feature binding

Introduction

More than twenty-five years have passed since Kahneman, Treisman and Gibbs (1992) introduced the concept of "*object files"* to address one of the most intriguing problems in psychology: how different features (shape, color, size, orientation, location, etc.) belonging to a given object are related to each other across cortical feature maps – the binding problem (Treisman, 1996). Object files are assumed to consist of integrated episodic memory traces that are created automatically when attending a perceptual object and to contain perceptual, perhaps even semantic information about the object (Kahneman, Treisman & Gibbs, 1992). Hommel (1998, 2004, 2005; Hommel et al., 2001) extended the concept to also include action-related information (the event file), and various studies demonstrated that object features are more or less automatically bound to the response they are associated with (Müsseler & Hommel, 1997; Stoet & Hommel, 1999, Hommel, 1998; Hommel et al., 2001; Hommel, 2004). In short, event files are assumed to consist of integrated networks of codes representing both perceived and produced features of a given event (Hommel, 1998; Hommel et al., 2001; Hommel, 2004). These networks are created while being exposed to the event and retrieved if and when at least one of the features included in the network is repeated. Evidence for the spontaneous creation of event files and their retrieval based on feature repetitions has been reported from studies in which various stimulus and/or response features were repeated alternated from one trial (the prime) to the next (the probe). Such studies have revealed two very consistent and widely replicable patterns.

First, repeating only some, but not all features of a perception-action episode (e.g., shape but not location, or color but not the response) produces a performance cost (the "partial-repetition cost"; cf. Hommel, 1998), as compared to the conditions in which all features are either repeated (i.e., complete repetitions) or alternated (i.e., complete alternations, Hommel, 1998; Hommel & Colzato, 2004). Partial repetition costs have been attributed to the retrieval of the previously-created (but no longer valid) episodic binding and the consequent activation of feature codes that are inconsistent with, and thus compete with the feature codes representing the actual current stimulus-response combination (Hommel, 1998; Hommel, 2004). Indeed, fMRI studies have revealed that repeating a particular stimulus feature leads to the reactivation of cortical areas coding for the feature that has accompanied the repeated feature in the previous trial (Kühn, Keizer, Colzato, Rombouts, & Hommel, 2011; Keizer, Nieuwenhuis, Colzato, Theeuwisse, Rombouts & Hommel, 2008).

Second, there is evidence that binding effects are moderated by the task context. Statistically speaking, binding effects are indicated by two-way interactions. For instance, if the repetition versus alternation of the shape feature interacts with the repetition versus alternation of the response (due to that performance is better with complete repetition or alternation than with partial repetition of one feature but not the other), this suggests that shape and response have been bound in the previous part of the trial and that this binding has now been retrieved. Binding is based on the integration of binary relations between feature codes. Importantly, however, not all of the possible two-way interactions are equally strong. For instance, if participants are instructed to carry out manual responses to stimulus shape, strong interactions between shape and response repetition are obtained, indicating very substantial partial-repetition costs, whereas interactions involving task-irrelevant stimulus features, like color (if shape is relevant), are commonly less pronounced (Hommel, 1998). This pattern suggests a certain degree of control over how event files are managed, but it is not yet clear on which particular aspect of event-file management this control is exerted. Note that the standard event-file task with stimulus and response repetitions or alternations can produce partial-repetition costs (i.e., two-way interactions) only if two conditions are met: For one, the codes of the particular features in the prime trial must have been integrated, bound into an event file. Without this binding process, repeating a feature in the probe trial could only lead to the retrieval of the codes of the features that actually occurred in the prime trial, but not to the retrieval of codes that accompanied the repeated feature in the prime trial but no longer occurs in the probe trial. For another, successful binding of the features presented in the prime trial can only affect performance in the probe trial if feature repetition actually retrieves the previously created event file. It follows that the presence of significant partial-repetition costs is a valid indicator for previous binding in the prime trial and retrieval in the probe trial, but the absence or reduction of partial-repetition costs is more difficult to attribute: that could be due to less effective or absent binding, or retrieval, or both (Frings et al., 2020; Hommel, 2021). Accordingly, the observation that the size and probability of significant partial-repetition costs depends on task-relevance and instructions might be due to an effect on binding, on retrieval, or both.

There is preliminary evidence that favors retrieval over binding as the target of control processes (Hommel, 2021). As for binding, research has found that object features are bound to each other even when binding is neither necessary nor useful, and that binding processes are not restricted to task-relevant features but also involve task-irrelevant features (Hommel, 1998; Hommel & Colzato, 2004; Hommel, Memelink, Zmigrod, & Colzato, 2014). Moreover, evidence exists that binding processes are not sensitive to distraction and attentional demands (Hommel, 2005), although they are more pronounced for object features that match features binding stored in the long-term memory (i.e., for real-life objects; Colzato, Raffone, & Hommel; 2006; Hommel & Colzato, 2009), probably because these features are more likely to receive attentional top-down support (Hommel & Colzato, 2009). More evidence for an impact of control processes comes from studies looking into individual differences. The general pattern of these studies is that individuals characterized by less efficient or sub-optimal cognitive control functioning (e.g., individuals low in fluid intelligence: Colzato, van Wouwe, Lavender & Hommel, 2006; individuals who are less accurate in working memory monitoring and updating: Colzato, Zmigrod & Hommel, 2013; children and elderly: Hommel, Kray & Lindenberger, 2011; people suffering from autistic spectrum disorders: Zmigrod et al., 2013; and people prone to rumination: Colzato, Steenbergen & Hommel, 2020) show larger partial-repetition costs than more optimally functioning individuals. Interpreting these observations in terms of binding would make little sense: if anything, more intelligent individuals, those with a more efficient working memory, young adults, and other healthy non-ruminators would be expected to show more efficient binding, and thus larger partial-repetition costs, than individuals with less efficient control abilities. Hence, from a binding perspective, one would have expected the exact opposite outcome in all of these studies. From a retrieval perspective, however, all these observations make perfect sense (Hommel, 2021). Note that the prime-probe task does not require, or provide any reward for retrieval, so that one might consider it a useful strategy to not retrieve any event file in probe trials. While this does not seem to be possible, as the partial-repetition costs indicate, smaller costs could be taken to indicate more selectivity, especially with regard to bindings including task-irrelevant features, and thus better cognitive control. This conclusion also fits with the observation that undergoing a neurofeedback training aimed at increasing cortical gamma synchronization reduced partial-repetition costs due to bindings involving the irrelevant feature (Keizer, Verschoor, Verment & Hommel, 2010; Keizer, Verment &

Hommel, 2010) and improved memory retrieval of relevant features in a memory recollection task (Keizer, Verment & Hommel, 2010).

The aim of the present study was to provide a more direct test of the assumption that efficiency of event file management depends on the current metacontrol state (bias towards persistence or flexibility. More specifically, we tried to induce two different control styles that we assumed to increase and reduce the selectivity of event-file retrieval, respectively. According to the metacontrol state model (MSM; Hommel, 2015; Hommel & Colzato, 2017), cognitive processing can be affected by metacontrol states that vary between two poles: extreme persistence and extreme flexibility. While the former is characterized by a strong top-down influence of the current action goal(s), high selectivity and goal maintenance, and strong mutual competition between alternative representations that compete for a selection, the latter is characterized by a weak top-down influence of the current action goal, low selectivity and goal maintenance, and weak mutual competition between alternative representations. Therefore, it is reasonable to expect a bias towards persistence to reduce or eliminate retrieval (as visible in smaller partial-repetition costs) of bindings. Preliminary evidence supporting this possibility comes from Colzato et al. (2007b), who showed that visuomotor partial-repetition costs are increased under conditions that are known to be associated with a higher activation of the striatal dopaminergic system (which is suspected to drive cognitive flexibility: Dreisbach & Goschke, 2004; Hommel, 2015), such as induced positive mood and medium spontaneous eye blink rates (Jongkees & Colzato, 2016). Along the same lines, inducing moderate stress levels (which have been suggested to boost cognitive control, up to a certain stress level; e.g., Steinhauser, Maier, & Hübner, 2007) was found to reduce visuomotor partial-repetition costs (Colzato et al., 2008). Hence, biasing metacontrol towards persistence should reduce, and biasing metacontrol towards flexibility should increase partial-repetition costs, especially those including task-irrelevant features.

A procedure that can be assumed to induce particular metacontrol state biases is meditation (for reviews, see Hommel, 2015; Hommel & Colzato, 2017a,b). According to Lutz, Slagter, Dunne and Davidson (2008), meditation techniques can be divided in two categories: Focused Attention meditation (FAM) and Open Monitoring meditation (OMM). While FAM requires the meditator to focus the attention on a single thought or event and to avoid any sort of distraction, OMM requires the meditator to open up and accept any possible upcoming thought (see also Lippelt et al., 2014). Previous research has shown that these two different forms of meditation can have an immediate, differential and systematic impact on an individual's metacontrol state, by biasing it towards either persistence or flexibility, respectively. Specifically, FAM has been found to facilitate dynamic modulation of cognitive control (Chan et al. 2020), to enhance motor sequence learning (Chan et al., 2017; Chan et al., 2018; Immink et al., 2017) and to improve the ability to suppress task-irrelevant information (Colzato et al., 2016). In contrast, OMM has been found to promote divergent thinking (Baas et al., 2014; Colzato et al., 2012a; Colzato et al., 2014, for a review, see Hommel & Colzato, 2017). As elaborated elsewhere (e.g., Hommel & Colzato, 2017b), FAM can thus be assumed to enhance top-down control, so to focus more strongly on relevant information and/or induce more competition between relevant and irrelevant information (Duncan, 2001), whereas OMM weakens top-down control and thus impairs selectivity and reduces competition (Hommel, 2015). In other words, FAM biases metacontrol towards persistence and OMM towards flexibility.

If so, it might be possible to enhance people's ability to control event-file retrieval by inducing a metacontrol bias towards persistence, which in turn should be achieved by engaging in FAM, while undergoing OMM should be less effective for that purpose. We expected the standard interactions between feature-repetition effects indicative of feature binding but were particularly interested in testing two more specific hypotheses. First, we predicted that partial-repetition costs should be reduced or eliminated after FAM as compared to OMM. To test these hypotheses, we had participants naive to meditation engage in brief bouts of either FAM or OMM before performing an event file task designed to assess partial-repetition costs produced by bindings of relevant features (stimulus shape and response location in our case) and bindings involving irrelevant features (stimulus color). Given that people's current or default metacontrol state cannot (yet) be objectively determined, our hypothesis was necessarily relative: partial repetition costs should be smaller under FAM than under OMM, but whether this would be due to an increase of selectivity under FAM, or a reduction of selectivity under OMM, or both was impossible to predict.

In the follow-up manipulation, we did use a more neutral non-meditation condition for comparison purposes, but as long as the exact cognitive components of meditation remain uncharted, there is no objective way to assess the true neutrality of any other condition. The goal of the FAM and OMM manipulation was to induce two different control styles employing audio instructions prompting participants towards differential attentional engagement during the exercise. As for the control condition, we needed a comparable task (e.g. audio and similar duration), yet with no specific demands on attentional control. The choice of listening to instrumental music as a control condition fulfilled such requirements and further allowed for more direct comparisons of the possible mediating effect of mood and arousal. More specifically, previous research shows that music listening can induce relaxation and improve mood, similar to meditation. Hence, here we attempted to isolate such an effect of relaxation by means of employing relatively passive music listening condition, without claiming that our control condition necessarily falls exactly in between the two experimental conditions.

Crucially, in the event-file task we predicted that possible changes in partial-repetition costs should be more visible with regard to bindings including task-irrelevant features (Keizer et al., 2010a,b), as they would be the most obvious targets of control operations. However, given previous findings, we concentrated on stimulus-response bindings with task-irrelevant features (color-response bindings in our task) but more or less neglected the corresponding stimulus-stimulus feature binding (shape-color bindings in our task), even though we will present the outcomes for comparison purposes. The reason is twofold. For one, partial-repetition costs for stimulus-stimulus feature bindings are commonly very small, often not significant, so that statistics would be unlikely to provide the operation space needed to demonstrate a significant moderation of this effect by meditation. For another, the binding of stimulus features does not seem to rely on the exact same neural mechanisms as the binding of stimulus and response features. Not only do the effects fail to correlate (Colzato, Warrens & Hommel, 2006), but they have also been dissociated by manipulations targeting neurotransmitter systems (Colzato, Erasmus & Hommel, 2004; Colzato, Fagioli, Erasmus & Hommel, 2005). Accordingly, our main comparisons will be between the binding of shape and response, which in our task will be the binding that includes only task-relevant features, and the binding of color and response, which will include a task-irrelevant feature.

Experiment 1A and 1B

The aim of **Experiment 1A** was to test whether partial-repetition costs in a standard event-file task (modeled after Hommel, 1998) would be smaller after FAM than after OMM—where meditation varied between participants. The outline of the task is shown in Fig. 2. We manipulated the shape and the color of the stimulus, and the location of the response. In the event-file task, participants are anticipated to respond faster to complete repetitions or alternations of stimulus and response features and react slower when presented with partial-repetition, i.e., the repetition of one but not all features. Such partial-repetition costs would indicate a conflict between the previously generated, now retrieved (S1-R1) binding and the new (S2-R2) binding. Accordingly, there were repetitions and alternations of stimulus shape, the task-relevant stimulus feature dimension, stimulus color, the task-irrelevant stimulus feature dimension, and of response location, the task-relevant response feature dimension.

This task allows examining the retrieval of episodic bindings as a function of the combination of the two visual stimulus features (shape and color) and the response feature, which could either repeat or alternate independently of each other. These combinations correspond to complete repetitions, complete alternations, and partial repetitions involving 2 or 3 features. We expected partial-repetition costs for all three binary interactions (shape/color, shape/response, and color/response), with a particularly strong impact of meditation on the colour-response interaction. Weak or non-significant effects were expected for stimulus-stimulus feature binding (shape-color binding in our case), because these kinds of bindings are generally very small and differentially affected by meditation styles that stimulus-response bindings (Lippelt et al., 2014).

To anticipate, Experiment 1A did produce the expected interaction between meditation type and partial-repetition costs for the color-response interaction. To see whether this effect was more reflecting the impact of FAM or the impact of OMM, we ran **Experiment 1B,** which included a non-meditation control condition, in which another group of participants listened to instrumental music. To avoid redundancies, we will present the two experiments together.

Methods

Participants

Sample size for Experiment 1A was chosen based on previous experience with the task and its effects, and on power calculation (please see Supplement) that indicated that around 40 participants per group were necessary in order to detect a significant interaction with a moderate effect size (ηp^2 = .06), given alpha =0.05 and power = 0.80. In order to attain the power ninety-four Dutch students of Leiden University were recruited via the university's online system and offered course credit or a financial reward of 6.50 euros for participating. Once recruited, all participants were screened for demographics, psychiatric illness and drug use. Fourteen participants had to be excluded from the analyses: Six because of the very high error rates (around 50%), one because of too slow reaction times (RTs) relative to the other participants (more than three standard deviations from the sample mean), three participants reported a history of psychiatric illness, two participants failed to comply with the experimental instructions, and two participants because of a software failure. The final sample included 80 healthy, drug free and meditation-naive participants (66 females, 14 males, mean age = 21.45 years, range 18–28). Participants were randomly and equally distributed in two experimental groups. Forty participants (7 males, mean age = 21.52 years, SD = 2.5) underwent a FAM session and 40 other participants (7 males, mean age = 21.38 years, SD = 2.1) underwent to an OMM session.

For Experiment 1B, 52 Leiden University students were recruited and screened the same way as in Experiment 1A. Nine participants were excluded due to very high error rates (around a chance level 50%) and one because of very slow reaction times (more than two standard deviations from the sample mean), one participant had to be excluded due to extensive meditation experience prior to the experiment and one because of software error. Forty healthy, drug-free and meditation naive participants were included in the final sample (30 females, 10 males, mean age = 22.92 years, range 18–30). The distribution of males and females in the control Group was comparable with the FAM and OMM groups, ($\chi 2$ (1, N =120) = 0.71, p = 0.702, *Cramer's V* = 0.007). A significant difference was found for age, (F (1,76) = 6.65, p = 0.012, η^2_p = 0.08), as participants in control group were approximately 1.47 year older than in the meditation groups. However, as participants were randomly selected, this difference can be interpreted as a random sampling effect. Informed consent was signed by all participants and the protocol was approved by the local ethical committee (Leiden University) and conformed to the ethical standards of the Declaration of Helsinki.

Procedure

The study employed a double-blind, between-participant design consisting of a single session of about one hour. Upon arrival, participants read and signed the informed consent, filled out a short screening questionnaire and rated their mood on a 9 x 9 grid (i.e., the Affect Grid; Russell, Weis, & Mendelsohn, 1989) designed to assess two dimensions of affect: pleasure and arousal, both with values ranging from 1 (low pleasure/arousal) to 9 (high pleasure/arousal). Immediately thereafter, participants performed a short practice block of the event-file task consisting of 32 trials, which was followed by a second mood measurement. Next, in Experiment 1A participants were asked to put on their headphones and to listen to a 17-min guided meditation audio file of either FAM or OMM, both developed and validated by Baas et al. (2014). The recorded audio files were presented in Dutch and participants were instructed to relax and to follow the audio instructions, given by the same male voice, as best as possible. During FAM, participants were instructed to focus and maintain their attention on their own breathing, to avoid mind wondering and to bring their attention back to their breathing whenever this happened. During OMM, participants were instructed to focus on the “here and now” and to continuously monitor their awareness of feelings, thoughts, and bodily sensations, without judging and emotionally reacting to them. In Experiment 1B we recruited an additional control group. The procedure closely mirrored the procedure of Experiment 1A, except that participants did not engage in meditation but listened to relaxation music instead (See Figure 1)**.** Specifically, participants were instructed to simply relax while instrumental music was played for the duration of 17 minutes. The music consisted of flute sound and other instrumental sounds and was published a free online archive as a royalty-free track (to download the specific music audio please see OSF data link). This exercise did not require specific attentional focus during the practice, yet changes in affect and arousal were anticipated. In both experiments (1A and 1B) participants were aware ahead of the session that they will participate either in meditation or relaxation exercise, respectively.

Event-file task

The task, originally developed by Hommel (1998), was adopted from Colzato et al (2012b). The E-Prime 2.0 software system (Psychology Software Tools, Inc., Pittsburgh, PA) was used to generate the task and collect the responses. Responses were executed by pressing the “z” or the “m” key of a QWERTY keyboard with the left and right index fingers, respectively. Figure 2 provides a schematic representation of the sequence of events of each trial of the event file task. On each trial, participants were instructed to carry out two consecutive responses (R1 and R2), one upon the presentation of the first stimulus (S1) and the other after the presentation of the second stimulus (S2). S1 and S2 consisted of images of an apple and a banana, presented in two possible colors, yellow or green. The response to S1 was signaled in advance by means of a response cue, presented for 1500 ms, and consisting of a left- or right-pointing arrowheads that pre-instructed the participant to prepare a left (“z”) or a right (“m”) key-press, respectively. The response cue was presented 1000 ms before S1, but the pre-cued response had to be emitted only upon S1 presentation, which lasted for 1000 ms, based on the direction of the preceding arrowhead. Note that, even though the identity of S1 was irrelevant for the R1, it varied in terms of both shape (banana vs. apple) and color (yellow vs. green). S2 appeared 1500 ms after the offset of S1 to signal R2 and lasted on the screen for 2000 ms. Participants were instructed to respond to the shape of S2 by pressing the left (“z”) key if S2 depicted an apple or the right (“m”) key if it depicted a banana. S2 could be presented in either yellow or green, just like S1, but its color was irrelevant to the task. Consecutive trials were separated by an intertrial interval (ITI) of 1000 ms. Participants were asked to respond as quickly and accurately as possible to both S1 and S2.

This task allows to examine retrieval of episodic bindings as a function of the combination of the two visual stimulus features (shape and color) and the response feature, which could either repeat or alternate independently of each other, thereby creating a 2 × 2 × 2 factorial design resulting in 8 possible combinations reflecting complete repetitions, complete alternations, and partial repetitions involving 2 or 3 features. The experimental block consisted of 192 trials, equally distributed across the 8 aforementioned conditions and presented in random order.

Figure 1.

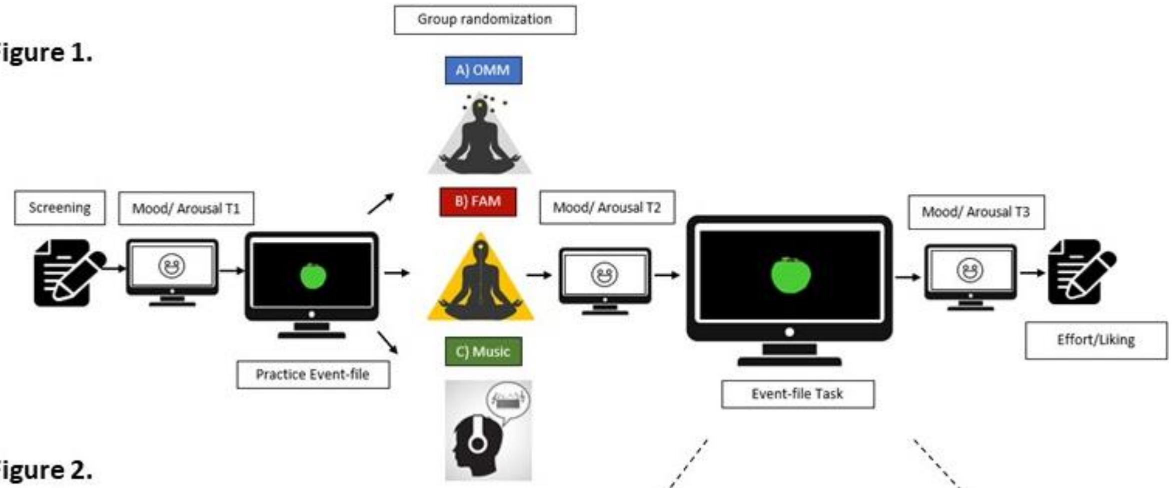

Figure 2.

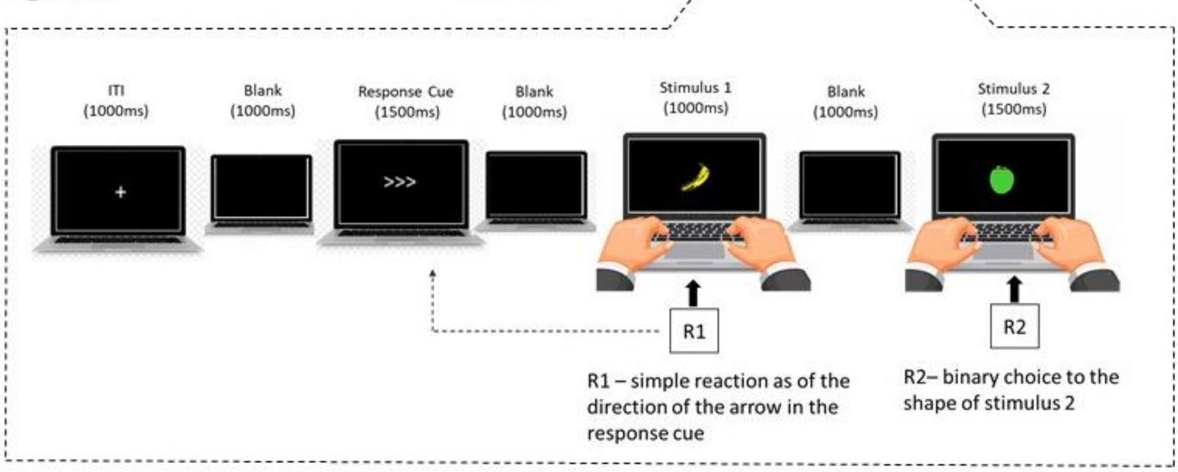

Figure 1. Shows outline of tasks in Experiments 1A and 1B. Participants were randomly assigned to either the FAM or OMM condition in Experiment 1A and all assigned to Music listening in Experiment 1B. **Figure 2.** Shows time sequence of an example trial in the event-file task. Each trial began with the presentation of an arrowhead, which signaled a left or right response (R1) that was to be delayed until presentation of the first stimulus (S1). Participants were instructed to press the left ("z") key if the arrowhead preceding the prime stimulus pointed to the left, and the right ("m") key if the arrowhead pointed to the right. The second stimulus S2 appeared 1,000 ms after S1 and participants were instructed to respond to the shape of the stimulus: the presentation of an "apple" required them to press the left ("z") key, whereas the presentation of a "banana" required them to press the right ('m") key. Participants were asked to respond as quickly and accurately as possible to both S1 and S2. Please note that the shape was a task relevant stimulus while color was task irrelevant stimulus.

Statistical analysis

One-way ANOVAs were performed to compare experimental groups in terms of age, and to assess whether the two forms of meditation and control group were comparable in terms of likability, difficulty and efforts. A chi-squared test was used to compare the three groups in terms of gender distribution. Mood data, in terms of Pleasure and Arousal, were analyzed by means of two separate repeated-measures ANOVAs with experimental group (FAM, OMM, and Music) as between-participants factor and time (first vs. second vs. third measurement) as within-participants factor.

For the event file task, R2 responses were analyzed by submitting RTs and percentage of errors (PEs) to two separate repeated-measures ANOVA with group (FAM, OMM, and Music) as between-participants factor and response (repetition vs. alternation), shape (repetition vs. alternation), and color (repetition vs. alternation) as within-participants factors. For the RTs and ERs analysis, we excluded anticipation responses (<150 ms) and missing responses (> 1500 ms). For the RTs analyses, the incorrect responses to S1 and S2 were further excluded. Additionally, participants with an average RT deviating more than 3 standard deviations from the sample's mean were removed from all analyses as well as those with very high error rates (around chance level 50%).

For the RT analysis, we also excluded incorrect and missing responses to either S1 or S2. Note that effects reflecting the binding and subsequent retrieval of visual stimulus features (shape and color) are indexed by a statistical two-way interaction between shape and color, whereas visuomotor bindings between stimulus and response features are indexed by interactions between shape and response and between color and response (Hommel et al., 1998).

Partial-repetition costs (PRCs) for a given interaction were calculated by computing the difference between RTs (or PEs) for partial repetitions (i.e., trials in which only one of two features repeated) and the RTs for complete repetitions and complete alternations. For instance, PRCs in RT for the binding between shape and response were computed as follows: (RT shape repeated/response alternated + RT shape alternated/response repeated)/2 – (RT shape repeated/response repeated + RT shape alternated/response alternated)/2. Values larger than 0 indicate PRCs do the retrieval of a no longer valid episodic binding. A significance level of $p < 0.05$ was adopted for all statistical tests.

Results

Subjective effects

The three groups were comparable in terms of likability (F (2,117) = 0.141, p = 0.868, η^2_p = 0.002), difficulty (F (2,117) = 1.271, p = 0.284, η^2_p = 0.021), but a significant difference was found for ratings of effort (F (2,117) = 12.54, p < 0.001, η^2_p = 0.177). Specifically, as shown in Figure 3C, participants reported to find meditation exercises (FAM, OMM) significantly more effortful as compared to more passive music listening ($t_s \geq 3.48$, $p_s < 0.001$). This result indicates that the experimental manipulation was successful as meditation priming required participants to actively engage their attentional resources.

Secondly, ANOVAs performed on pleasure and arousal scores revealed significant main effects of time for both pleasure (F (2,1.7 = 20.28, p < 0.001, η^2_p = 0.058), and arousal (F (2,1.5) = 87.3, p < 0.001, η^2_p = 0.24). Moreover, post-hoc tests indicated that pleasure levels were significantly higher and arousal levels significantly lower at the third measurement (i.e., after the meditation) as compared to the first two measurements (ps ≤.007). More crucially, no main effects of group or interactions between time and group were found (*Fs* ≤ 2.11, ps ≥ 0.07), indicating a comparable effect of group on mood and arousal across time (see Table 1 for means). Yet, as shown in Figure 3D in Experiment 1B mood ratings significantly dropped from baseline in the control group after the music presentation (p < 0.001, d = 0.67). This effect suggests that the music presentation lowered participants' mood, potentially because the lack of engagement during music listening or a mismatch with their music preferences.

Table 1. Arousal and pleasure ratings as a function of meditation (FAM vs. OMM) and Time (T1 vs. T2 vs. T3) for Experiment 1A (FAM and OMM) and Experiment 1B (Music). Standard errors of the means are shown in parentheses.

		Experiment 1A		Experiment 1B
		FAM	**OMM**	**Music**
Arousal				
	T1	5.0 (0.2)	5.7 (0.2)	5.1 (0.2)
	T2	5.4 (0.3)	5.5 (0.3)	5.1 (0.2)
	T3	3.3 (0.2)	3.3 (0.2)	3.6 (0.2)
Mood				
	T1	6.4 (0.2)	6.5 (0.2)	6.4 (0.2)
	T2	6.5 (0.2)	6.3 (0.2)	5.7 (0.2)
	T3	7.0 (0.2)	6.9 (0.2)	6.9 (0.2)

Event-file task

After excluding trials with missing or anticipatory responses, mean RTs for correct responses and proportions of errors for R2 were analysed, for a complete overview, see **Table 2 and Table 3.** As the Tables show, there was no group effect in RTs, suggesting that the three groups are roughly comparable in principle. The analyses revealed a significant main effect for color and significant two-way interaction between shape-response and color-response, where repetitions produced faster RTs than alternations *and* significant three-way interaction between shape, color, and response.

Of particular importance for our purposes, the three-way interaction involving response, color, and group was significant, indicating that the effect of color-response binding differed between the groups. As Figure 3 shows, FAM had a very similar effect as Music, but the effect color-response binding was significantly larger after OMM than in both of these conditions. A separate analysis of the two meditation groups (Experiment 1A) also revealed a significant three-way interaction between response, color, and group suggesting that the two types of meditation affected the color-response bindings differently. Interestingly, a group effect of this sort was only obtained for the color-response binding. The error analysis showed main effects for shape, color and response *and* interactions between shape-color, shape-response and color-response indicating that repetitions produced faster RTs than alternations. Importantly, no significant three-way interaction involving PRCs and group.

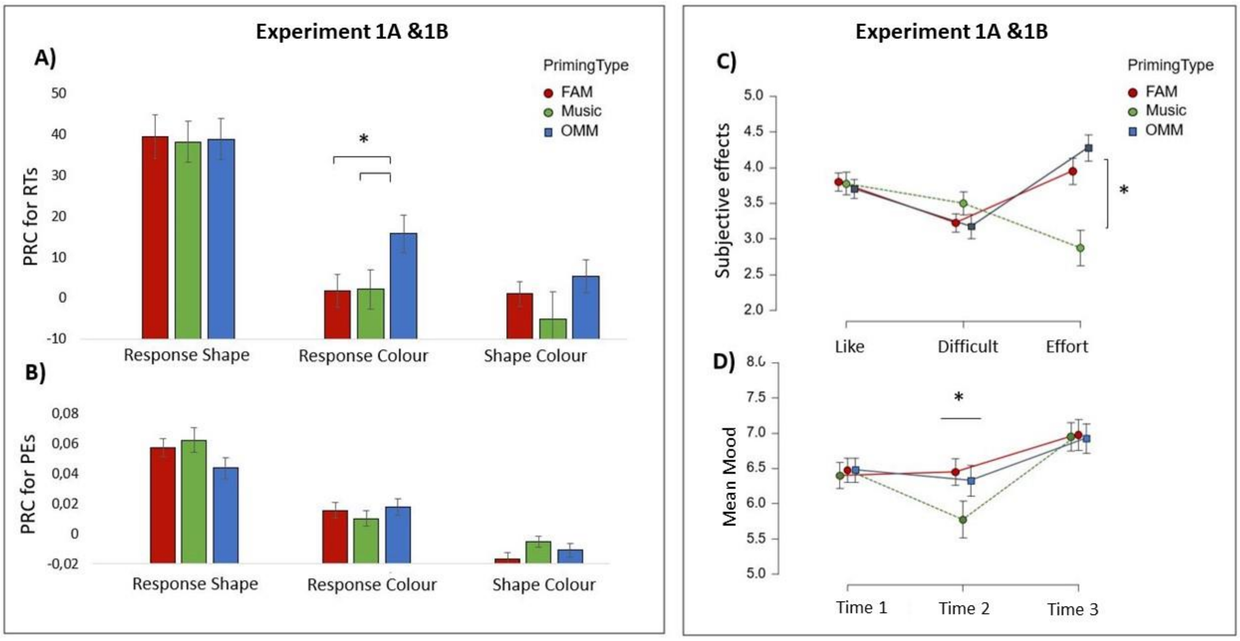

Figure 3. Partial repetition cost in Reaction time (RTs) and Percentage error (PEs) for the event-file task. Error bars represent standard errors, an asterisk indicates an es significance level of $p < .05$. As indicated in the side panel (C-D) significant group differences were found for the ratings of effort and pleasure.

Exploratory control analyses

Additional control analyses were carried out to account for the possible mediating effect of mood and ratings of effort on Event-file task, considering that significant group differences were found. We carried out Pearson's correlation between the significant outcome measure (e.g., partial repetition cost for response color) and the ratings of effort and mood (change of mood from baseline). The results from correlations were not significant ($Rs \leq 0.06$, $Ps \geq 0.485$) suggesting that the subjective effects did not significantly mediate the observed effect.

Table 2. Results of analysis of variance on mean reaction time of correct responses (RT) and percentage of errors (PE) for Experiment 1.

Experiment 1

	RT		PE	
	MSE	F	MSE	F
Group (G)	85148	1,025	0,01	1,189
Shape (S)	3088	1,24	0,022	7,622 **
Color (C)	7073	5,282 *	0,009	4,968 *
Response (R)	5744	1,92	0,024	5,538 *
S x G	2433	0,977	0,001	0,144
C x G	807	0,602	0,001	0,605
R x G	5813	1,943	0,003	0,775
S x C	36	0,02	0,029	19,452 ***
S x C x G	2154	1,195	0,003	1,803
S x R	362333	171,577 ***	0,709	177,414 ***
S x R x G	33	0,015	0,007	1,831
C x R	10244	6,385 *	0,05	23,043 ***
C x R x G	5064	3,156 *	0,001	0,548
S x C x R	25613	13,54 ***	0,011	6,84
S x C x R x G	2501	1,322	0,002	1,138

Table 3. Mean RTs and PEs for responses to R2 as a function of group (FAM vs. OMM vs. Music), the relationship between the responses (R1 and R2), and the relationship between the stimulus features (S1 and S2) for shape and color. Standard deviation of the mean are shown in parentheses.

Group						
Groups	FAM		Music		OMM	
	RT (SD)	*PE (SD)*	*RT (SD)*	*PE (SD)*	*RT (SD)*	*PE (SD)*
Neither	508 (77)	1,9 (3,6)	548 (136)	1,9 (3,3)	543 (113)	1,7 (3,9)
Response	542 (99)	6,8 (8,1)	565 (120)	7,4 (6,6)	582 (115)	6,8 (7,8)
Color	503 (78)	2 (4,1)	530 (114)	2 (3,2)	539 (108)	2,3 (3,6)
Shape	544 (95)	6,5 (6,6)	569 (130)	7,3 (8,5)	561 (101)	5,5 (5,9)
CxR	545 (95)	4,9 (4,5)	560 (113)	7,9 (7,7)	580 (112)	4,4 (4,9)
SxR	511 (99)	1,2 (2,8)	527 (108)	2,8 (3,9)	556 (133)	2,4 (3,9)
SxC	549 (93)	11,2 (8,4)	579 (133)	10,9 (8,6)	580 (121)	8,8 (8,4)
SxCxR	500 (101)	1,6 (3,3)	515 (111)	1,9 (3,9)	510 (112)	1,6 (3,3)

Discussion

Experiment 1 A showed that trial-to trial stimulus-induced retrieval of event files was modulated by meditation: while trial-to-trial effects of bindings of the two task-relevant features (stimulus shape and response location) were the same under both meditation conditions, the effect of the binding involving the irrelevant stimulus feature stimulus color and the response was more pronounced after OMM. The result for color-response binding is interesting as previous research shows that feature retrieval is systematically affected by the degree to which a particular stimulus dimension is attended to (e.g., Hommel, 2005, 2007). Given previous evidence suggesting that FAM strengthens, and OMM weakens top-down support for relevant information and/or increases local competition between relevant and irrelevant information (Lippelt et al., 2014), our finding suggests that OMM-induced weakening of top-down regulation (and/or the resulting loss in competition) increased the impact of bindings including task-irrelevant feature codes. Importantly, there was no evidence that mood or arousal accounted for this observation. Hence, OMM opened the door for the creation and/or retrieval of not strictly relevant bindings, which in turn fits with the assumption that OMM facilitates distributed and flexible attention allocation and thus promotes a more inclusive information processing style. In line with this idea, previous research demonstrated that OM meditators performed better at sustaining attention on paradigm than FAM but only when the target stimulus was unexpected (Valentine & Sweet, 1999). Similarly, meditation was previously shown to impact the way people distribute their attention over a rapid stream of events in the attentional-blink paradigm. Specifically, OMM showed smaller attentional blink, indicating that they could detect briefly presented target stimuli more efficiently, possibly through more parallel information processing (Slagter et al. 2007).

Experiment 2

Experiment 1 provided first evidence that meditation might have a selective impact on task-irrelevant feature bindings, especially by boosting the effect of such bindings after OMM. However, the effect was small, and so we sought to replicate the effect in a within-participants study, which we expected to provide a stricter test because of the reduced impact of between-participant variability. Our second aim was related to a recent study by Ulrich et al. (2021), who also examined the effects of a brief (15 minutes) FAM on S-R bindings using a standard event file task. The authors found reduced partial overlap costs for relevant feature codes after FAM. In principle, this observation is fully consistent with our approach and our conclusions so far: FAM would be expected to promote goal-maintenance for, and focus on relevant information, to the expense of irrelevant information. Hence, in some sense, the findings of Ulrich et al. represent the mirror image of our findings from Experiment 1 and could thus be seen as simply the other side of the same theoretical coin.

One may wonder why we did not find any corresponding effects after FAM. That might have to do with the character of the control group, which was active (i.e. listening instrumental music) in the present Experiment 1 but passive in the Ulrich et al. study, where participants only engaged in the event-file task without a previous priming manipulation. Secondly, it may also have to do with the sample. In previous studies on meditation in our lab, we often found asymmetric effects of the two meditation types, with a stronger impact of OMM but small or absent effects of FAM (see Lippelt et al. 2014). Given that we commonly tested students directly coming from, were going to academic lectures or related exercises, it makes sense to assume that these participants might already have a strong bias towards persistence. This explanation seems valid considering that cognitive control states are proposed to be relatively inert (Allport et al., 1994) and thus take time to change. As such, this would leave little operation space for interventions seeking to further increase persistence, but leave much more space for interventions seeking to increase flexibility. Depending on the specific acquisition of the tested participants, and corresponding pre-experimental biases towards persistence or flexibility, studies may thus differ with respect to the more potent type of intervention and yet fit with the general theoretical idea.

Another concern was the fact that the effect reported by Ulrich et al. turned out to be rather sensitive to context conditions: it required some experience of the participants with the task and showed up only in the earlier phases of the particular session. While the fact that we found significant effects in Experiment 1 suggests that task experience was sufficient for our purposes, a within-participants design is more vulnerable to context conditions, as transfer effects from the first to the second meditation manipulation are possible. We thus did not only balance the order in which we exposed participants to FAM and OMM, but also tested whether the sequence of the two meditations had an impact. Otherwise, our expectations were as in Experiment 1.

Methods

Participants

Forty-seven Leiden University students recruited via the online university system attended both experimental sessions in good order for course credit or a financial compensation of 13 euros. After screening, 5 participants were excluded due to very high error rates (around a chance level 50%), 1 participant had to be excluded due to history of psychiatric illness, and 1 because he/she had extensive prior meditation experience. The final sample included 40 drug free and meditation-naive participants (33 females, 7 males, mean age = 21.82 years, range 18–32). In the first session, 20 participants were randomly assigned to start with the FAM meditation (17 females, 3 males, mean age = 22.45 years) and the remaining 20 were assigned to start with the OMM meditation (16 females, 4 males, mean age = 21.16 years). Informed consent was given by all participants and the protocol was approved by the local ethical committee (Leiden University, Faculty of Social and behavioural Sciences) and conformed to the ethical standards of the Declaration of Helsinki.

Procedure

The task comprised of identical procedure as in Experiment 1A, with the difference that here we implemented a within-participant cross-over design. This study thus involved two experimental appointments with 7 days in between. The procedure of each experimental session was identical to the procedure in Experiment 1A (See

Figure 4), yet this time participants engaged in FAM meditation in one session and in OMM meditation in the other session. The order of FAM and OMM sessions was randomly counter-balanced across participants. Participants were again asked to perform the Event-file task, rated their mood, arousal, and impressions from the meditations.

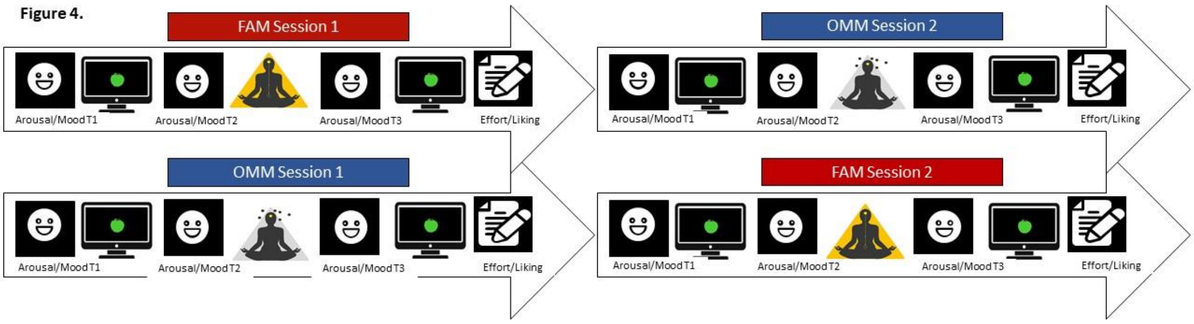

Figure 4. The experimental outline for Experiment 2. Each participant underwent one session of FAM and OMM meditation, counter-balanced across participants, with 7 days in between.

Statistical Analyses

Ratings of liking, difficulty, and effort were analysed with repeated-measures ANOVAs with meditation (FAM, OMM) as the within-participants factor and session order (FAM or OMM first) as the between-participants factor. Similarly, participants' affective state (mood and arousal) was analyzed by a repeated-measures ANOVA, with time (first vs. second vs. third measurement) and meditation (FAM, OMM) as a within-participants factor and session order as between-participants factor. Before the RTs and ERs analysis, we performed the identical pre-processing steps as in Experiment 1 during which anticipatory and missing responses were excluded.

The binding-related effects were again assessed by submitting R2 correct RTs and PEs to separate repeated measures factorial ANOVAs with 2 levels for response, 2 levels for shape, and 2 levels for color (corresponding to the repetion vs. alternation). However, in contrast to Experiment 1, meditation (OMM vs. FAM) was entered as within-participant factors and session order (session 1 and session 2) as between participant factor. For a complete overview of means and the ANOVAs output please see **Table 4** and **Table 5.**

Results

Subjective effects

Participants' ratings of liking and difficulty were comparable across the session order (t_s ≤1.7, $p_s \geq 0.09$) as well as the meditation, (t_s ≤0.2, $p_s \geq 0.375$). However, in the second experimental session participants reported to find FAM meditation significantly more effortful than OMM, ($t(37)= 2.29$, $p = 0.027$, d =0.736) (see Figure 5D). This is not surprising considering that participants in the second session could compare OMM and FAM more effectively. The difference in perceived effort could be interpreted in line with the metacontrol theory proposing that FAM requires higher top-down control to steer attention to a single focal point.

The *rm*ANOVA performed on participants' mood ratings showed non-significant main effects of session order (F = 0.092, p =0.763) and group (F = 0.08, p =0.779) and no significant interactions ($Fs \leq 1.44$, $p \geq 0.234$), thus indicating that affective states were comparable across experimental sessions. However, analyses of arousal ratings showed a significant main effect of session order (F = 5.58, p = 0.024), and an interaction between session order and meditation (F = 0.048, p = 0.048). As shown in Figure 5C, ratings of arousal were significantly higher after OMM than after FAM in the first session. The ratings of arousal significantly dropped in the last measurement regardless of meditation, which can be explained by fatigue (for means see Table 4).

Table 4. Arousal and pleasure ratings as a function of meditation (FAM vs. OMM) and Time (T1 vs. T2 vs. T3) for Experiment 2 for each session.

	Experiment 2				
		Session 1		**Session 2**	
		FAM	**OMM**	**FAM**	**OMM**
Arousal	T1	4.8 (1.3)	5.2 (1.4)	5.6 (1.3)	5.8 (1.4)
	T2	4.9 (1.6)	6.0 (1.3) *	5.6 (1.2)	5.6 (1.1)
	T3	3.1 (1.2)	3.7 (1.6)	4.1 (1.3)	3.9 (1.4)
Mood	T1	6.3 (1.0)	6.1 (1.3)	6.4 (1.3)	5.8 (1.4)
	T2	5.8 (1.3)	5.7 (1.5)	6.1 (1.3)	5.7 (1.3)
	T3	6.4 (1.3)	6.4 (1.9)	6.3 (1.8)	6.2 (1.3)

Note: *$p < .05$, ** $p < .01$,*** $p < .001$.

Event-file task

As the tables show, the RTs analyses revealed no main effect of meditation or session order. Significant main effects were found for color and significant two-way interaction between color-response. Importantly, three-way interaction involving response, colour and meditation was non-significant. However, we did find a significant four-way interaction of these factors with session order: as shown in Figure 5A, PRCs for response-colour binding varied with meditation, but only in the first experimental session. The PRCs for shape-colour and shape-response binding were comparable among meditation, as indicated by lack of significant three-way and four-way interactions. In PEs, the main effects of meditation or session order were not significant. Significant main effects were found for color and shape but no significant interactions except for the standard shape-by-response to-way interaction were obtained.

Exploratory control analyses

Additional control analyses were carried out to see whether arousal and effort might account for some effect. Given the group difference in the first session, we ran Pearson correlations between the significant outcome measures (i.e. Color-Response RT) and the change in arousal in the first session (baseline corrected arousal after meditation). The correlation was non-significant, ($r(37) = 0.036$, p = 0.365), indicating that arousal did not mediate response-color binding. Pearson correlations between the outcome measures and subjective ratings of effort were also not significant ($Rs \leq 0143$, $Ps \geq 0.216$).

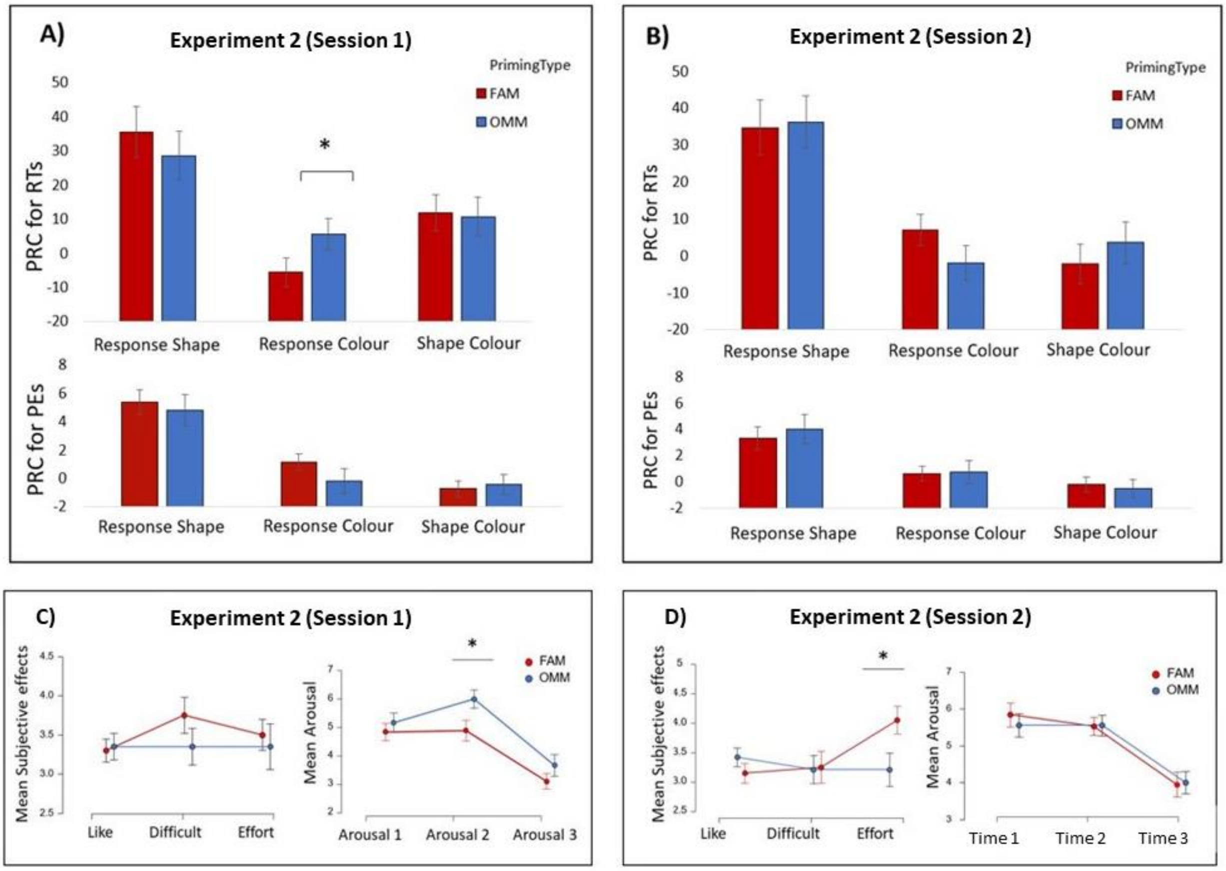

Figure 5. Partial-repetition-cost (PRC) in Reaction time (RTs) and Percentage error (PEs) for the event-file task of Experiment 2 in two experimental sessions. OMM resulted in an increase of binding costs between response and colour for the RTs as compared to FAM group. No significant effects were found for the PE analyses. Lower panels show mean ratings of arousal as well as mean ratings of liking, difficulty and effort in each of the two experimental sessions. Error bars represent standard errors, asterisk indicates significance level of $p < .05$.

Table 5. Results of analysis of variance on mean reaction time of correct responses (RT) and percentage of errors (PE) for Experiment 2.

RT			**Error**	
Factors	SEM	F	SEM	F
Meditation (M)	13574	0,934	0,225	0,006
Session Order (O)	42928	0,339	459,006	3,7
Shape (S)	329	0,166	250	8,822**
Color (C)	8462	6,222 *	10	0,429
Response (R)	70	0,034	102,4	4,613*
M x O	306	0,021	99,225	2,544
S x O	1109	0,559	18,225	0,643
C x O	777	0,571	0,4	0,017
R x O	14	0,007	0,025	0,001
M x S	1094	1,109	0,756	0,046
M x S x O	3237	3,28	0,156	0,01
M x C	47	0,039	0,056	0,004
M x C x O	385	0,324	8,556	0,546
S x C	5765	3,523	17,556	0,917
S x C x O	4453	2,721	0,156	0,008
M x R	536	0,378	6,806	0,489
M x R x O	2939	2,075	29,756	2,137
S x R	182097	55,939***	3,285,156	54,296***
S x R x O	487	0,15	110,556	1,827
C x R	250	0,351	37,056	1,051
C x R x O	255	0,385	8,556	0,243
M x S x C	203	0,252	2,5	0,133
M x S x C x O	465	0,578	0,225	0,012
M x S x R	278	0,287	1,225	0,064
M x S x R x O	708	0,732	30,625	1,612
M x C x R	53	0,061	5,625	0,366
M x C x R x O	4027	4,653 *	10	0,652
S x C x R	4020	2,62	4,225	0,184
S x C x R x O	359	0,234	24,025	1,048
M x S x C x R	2	0,001	1,056	0,087
M x S x C x R x O	1282	0,756	0,006	5,137e -4

Note: *$p < .05$, ** $p < .01$,*** $p < .001$.

Table 6. Mean RTs and PEs for responses to R2 as a function of meditation group (FAM vs. OMM) and experimental Session. Match represents the relationship between the responses (R1 and R2), and the relationship between the stimulus features (S1 and S2) for shape and color. Standard errors of the mean are shown in parentheses.

	Session 1		Session 2		Session1		Session 2	
	FAM	OMM	FAM	OMM	FAM	OMM	FAM	OMM
Match	RT	RT	RT	RT	PE	PE	PE	PE
Neither	525 (89)	515 (74)	517 (116)	503 (86)	1,3 (3,5)	1,8 (2,6)	0,2 (1,1)	0,5(2,5)
Response	561 (109)	562 (107)	557 (122)	537 (87)	6,85 (6,8)	4,8 (4,19)	3,1 (4,3)	5,4 (8,1)
Color	547 (111)	529 (94)	540 (109)	521 (93)	1,3 (3)	1 (2,05)	1,5 (3)	1 (2,1)
Shape	587 (134)	540 (78)	562 (119)	555 (101)	8,2 (10,3)	7,1 (8,7)	4,6 (5,3)	5,1 (8)
C x R	576 (102)	561 (110)	561 (109)	546 (88)	6,4 (6,3)	5,6 (6,2)	2,5 (4,1)	3,9 (7,8)
S x R	534 (99)	517 (72)	537 (103)	503 (78)	2,9 (4,2)	1,7 (2,4)	0,2 (0,9)	1,5 (4,8)
S x C	568 (117)	557 (98)	556 (113)	554 (85)	9,55 (9,2)	8,3 (9,3)	5,7 (5,6)	6,3 (8)
S x C x R	544 (114)	521 (81)	528 (97)	519 (84)	1,95 (2,9)	2,1 (3,6)	0,6 (1,5)	1,4 (2,3)

General Discussion

The present study aimed to provide a more direct test of the assumption that the selectivity of feature-binding and/or retrieval in the event-file task might depend on metacontrol policies. More specifically, we tried to induce two different metacontrol styles through OMM and FAM, which we assumed to increase and reduce the selectivity of feature retrieval, respectively. We expected that partial-repetition costs for the irrelevant feature bindings would be larger after OMM than after FAM.

The results of Experiment 1 provided support for this hypothesis by showing that engaging in OMM, as compared to FAM or listening to music, reduced visuomotor partial repetition costs between the irrelevant stimulus feature color and the response. The partial repetition costs between the relevant stimulus feature and the response were not affected by meditation, suggesting that meditation-induced effects are restricted to the retrieval of task-irrelevant information. Furthermore, mood and arousal did not account for the difference in feature-binding after FAM and OMM as indicated by control analyses. We can thus rule out the possibility that mood and arousal played a significant mediating role in the observed effect. This result fits with Chan et al. (2018), who also found that FAM or OMM's subjective effects did not predict task performance. Such findings contribute to the ongoing debate regarding the locus of meditation practice. Meditation effects may be interpreted as a form of physiological relaxation, where cognition is affected in a bottom-up manner through a parasympathetic response (Melnychuk et al. 2018). However, current results suggest that changes in arousal and mood were not sufficient to account for the observed performance effects, whereas attentional control in meditation had a strong impact.

Crucially, the current result converges well with the metacontrol model. This model proposes that OMM is associated with a more parallel and flexible processing style that weakens top-control and allows for multiple streams of (i.e., both relevant and irrelevant) information to be concurrently processed, which in turn can give rise to insightful/creative solutions (Lippelt et al., 2014). As our present findings suggest, this more relaxed processing style increases the impact of bindings that include task-irrelevant information. This might be interpreted as a lack of control, given that this style allows for the processing of feature codes and bindings that are not strictly necessary for tackling the present task. However, from the more comprehensive control concept that is implied by the metacontrol account, this would be based on a too restricted interpretation of the functions that cognitive control subserve. What looks like an unnecessary processing operation for the task at hand is likely to allow generalizing the experience with this task to other circumstances. While the reactivation of just-created event files in the classical event-file task is actually not necessary, the binding mechanism as such serves the purpose of automatically reactivating available knowledge whenever at least one of the features repeats. Considering task-irrelevant features can thus be assumed to increase the possibility of reactivating the stored bindings, which underlay experimentally controlled conditions may very well turn out to be useful. In other words, while FAM helps individuals to concentrate, if necessary, OMM seems to help individuals to generalize, whenever needed.

Another important observation was that meditation effects were restricted to the first session in Experiment 2. This has important methodological implications and suggests that a within-participant paradigm may not be optimal for assessing meditation effects, at least in individuals with little or no meditation experience. It is possible that experienced meditators are more effective in switching between meditative states of different kinds, as targeted by FAM and OMM, but our findings suggest that this does not apply to non-meditators. Whatever meditation style they experienced first, they apparently did not manage to implement the other style to a sufficient degree. Based on our data, we are unable to say why: it might be that they underestimated the difference between the two styles and reacted to the second instruction by implementing a similar state than in response to the first, but it may also be that our participants did not yet manage to keep the second state sufficiently active to not become overwritten by a reincarnation of the first. More research into the differences between experienced meditators and non-meditators will be useful to better understand these kinds of processes. In any case, our present findings converge with the general observation of Ulrich et al. (2021) that meditation-induced states in non-meditators are very sensitive to context conditions.

Overall, our findings suggest that while the effect of mediation on information processing is relatively subtle, specific and short-lasting, we could replicate this effect, which has promising theoretical and practical implications. For instance, most meditation programs have a one-size-fits-all design and assume that everyone benefits from meditation interventions more or less the same way. Current finding suggests that all meditation techniques are not equal, and that successful intervention should follow the theoretically-guided selection of the best-suited technique. For instance, OMM may be implicated in optimizing cognitive control under stress (Frings et al. 2013) and in a clinical population previously shown to have impairment in the updating of feature bindings (e.g., in Autism Spectrum Disorder, Zmigrod et al. 2013; or Tourette syndrome, Beste et al. 2016), through biasing cognitive processing toward a more parallel processing style.

Limitations and future direction

It is important to keep in mind that we studied completely naïve meditators. While this choice has the benefit of avoiding the typical self-selection artifacts associated with studying long-term meditators, it means that our findings have limited implications for the better understanding of meditation as such. In other words, our findings suggest that giving meditation instructions to naïve participants indeed seems to induce the hypothesized metacontrol state, but this effect may not necessarily exhaust the effects of longer-term meditation. Thus, future research would benefit from recruiting expert meditators, further solidifying our understanding of how FAM and OMM affect the integration of episodic events.

Secondly, the observed effect of OMM on partial-repetition costs relies on successful integration and retrieval of the respective feature combinations, but our design does not allow to disentangle of integration effects from retrieval effects. As explained above, the available evidence favours retrieval over binding, suggesting that the creation of event files occurs automatically and retrieval is more likely to be sensitive to top-down control (Hommel, 2021). And yet, more research will be necessary to characterize the relationship between cognitive control on the one hand and of event-file creation and retrieval on the other (Frings et al., 2020).

Thirdly, we used behavioral measures only. Future studies would benefit from implementing electrophysiological or electromagnetic methods, which are likely to be more sensitive to subtle changes in the handling of event files (Kühn et al., 2011) and more directly related to underlying computational and neural processes in FAM and OMM. Finally, it remains a practical problem that the current metacontrol state of a person cannot be directly estimated. This means that we cannot know the metacontrol state at baseline, before an intervention, which in turn makes it hard to compare findings of studies with different samples beyond a general comparison of differences between FAM and OMM. Possibly, the use of neuroscientific measures will provide a proxy in the future.