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A Computational Model of Focused Attention Meditation and Its Transfer to a Sustained Attention Task

Amir J. Moye and Marieke K. van Vugt

Abstract—Meditation has been shown to aid with the management of affective disorders through improving emotion regulation. Here we begin to develop a theory of meditation by creating a computational cognitive model of focused attention meditation. Our model was created within *Prims*, a derivative of the *ACT-R cognitive architecture*. We implemented a model based on an extensive literature review of how the meditation experience unfolds over time. We then tested the *Prims* model in a sustained attention task, intending to capture a faculty that may be trained with meditation practice. The model was significantly better able to maintain focus after the meditation practice than before. These results agree qualitatively with empirical findings of a longitudinal study on the effects of meditation conducted in 2010. The central mechanism for increasing task relevant focus in the model seems to be a feedback loop. The meditation and mind-wandering processes reinforce themselves and weaken the other. However, this reinforcement is more dispersed in the more elaborate mind-wandering process, which causes it to decrease over time. We speculate that observed improvements in emotion regulation observed after meditation arise from the ability to maintain focus, because it allows the practitioner to avoid emotions spiraling out of control.

Index Terms—Focused attention meditation, mindfulness, sustained attention, SART, Prims, transfer, emotion regulation

◆

1 INTRODUCTION

MEDITATION consists of a set of mental exercises for cultivating a cognitively and emotionally balanced mind that have been developed and practiced reaching as far back as 4000 years [32]. In the last 50 years there has been more and more interest in meditation, in large part because of its effectiveness in improving emotion regulation [11]. The spectrum of empirically examined effects includes some being reasonably well-replicated and of medium to large effects while others have been inconsistent [19], [39]. For example, Kuyken et al. [21] demonstrated that mindfulness-based cognitive therapy (MBCT) was equivalent to maintenance antidepressant treatment in preventing relapse. MBCT is a combination of mindfulness meditation with the restructuring of thought by means of cognitive therapy. A core deficit in depression is ruminative thinking, in which a patient gets stuck in repeated cycles of negative self-focused thinking. It is thought that therapeutic mechanism of MBCT relies on an improvement in attentional control which helps the patient by strengthening their capacity to regulate ruminative thinking (e.g., [5]). In addition, MBCT is thought to facilitate the therapeutic process of decentering—stepping away from intruding thoughts by realizing that it is actually possible to decide to think something else (see [20] for a recent review). Since decentering is a metacognitive assessment of one's mental state and subsequently involves moving this mental state, it requires attention, thereby making attentional control a prime target for computational modeling.

To date there are no comprehensive computational frameworks of meditation[1] and its effects on emotion and cognition (e.g., [48]). To begin to develop such a theory, we first describe the process of meditation practice itself, then how it is thought to affect emotion regulation, and finally we describe our conceptualization of the computational model of meditation.

1.1 Meditation

Meditation is often conceptualized as a family of attentional and emotional regulation exercises (e.g., [46]). Practices can differ greatly concerning the emphasis of the mental faculties used (attention, feeling, reasoning, visualization, etc.), the objects they are focused on (thoughts, images, concepts, internal energy, breath, love, God, etc.; [42]) and lastly with what aim they are employed (relaxation, heightened sense of well-being; attentional balance, insight, etc.; [25], [56]).

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[1] By computational we specifically mean a model implemented as an algorithm or equation that can be simulated on a computer to make quantitative predictions for behavior.

That being said, the common typology to categorize this vast family of practices is based on what meditators are purportedly doing from a first-person perspective: ‘Focused Attention’ (FA) meditation and ‘Open Monitoring’ (OM) meditation [25]. While FA meditation has a clear focus on an object such as the breath, OM practices have no clear focus of attention and the task is to be continuously aware of phenomena appearing and to return to this monitoring when one gets caught up with the content.

In this paper, we begin to develop a computational theory of meditation practices by creating a cognitive model of focused attention (FA) meditation, as this kind of meditation is most amenable to computational modeling. In this practice, the meditator brings her/his attention to an object such as the breath, and then monitors with non-judgmental attention whether attention is still there. As soon as the meditator realizes attention has wandered, s/he brings the attention back to the object of focus, minimizing any further mental elaboration. Of note, this is in contrast to our habitual reaction, in which we often tend to get frustrated with our inability to sustain focus, which then consequently results in aversive emotions. By aversive emotions we are referring to affective states that are experienced as aversive, while pleasurable emotions refer to the converse. Said differently, meditation may reduce the incidence of aversive emotions by developing mental habits that reduce this process of amplification and catastrophizing. This in itself may be one of the most important salutary mechanisms for depressive rumination.

The particular type of FA meditation that was practiced by the subjects relevant for this article was *Samatha* meditation [26]. During meditation, the practitioner trains to monitor whether their attention is still on the object of focus. When monitoring fails, mind-wandering may take over: an unintended shift of focus to a sensory or mental event, which then leads to habitual affective responding, which in turn triggers related mental events such as episodic or procedural memories, that then lead to more habitual affective responses and so on [46]. As these decisions are not conscious the impulses driving them are strongly compelled by affect and mood. A central component of mind-wandering are two recurring “decisions” (if a non-deliberate reaction can be referred to in this way) 1) to start a new train of thought and 2) to elaborate and embellish it. Arguably, more intense moods lead to more passionate mind-wandering content (due to mood-congruent recall, see for example; [30]), which in turn is harder to abstain from (both in regards to steps 1 (starting) and 2 (elaboration)). What is more, an initially mild mood may increase in strength and become a strong mood through ruminative mind-wandering (in the case of aversive mood) or fantasizing (in the case of pleasurable mood). For example, as the meditator is feeling the breath, a memory of a song that was playing in the grocery store earlier might pop up in their mind. As this was perceived as aversive this might trigger thoughts of the smartphone that has been malfunctioning lately (which also has a negative affective valence and is therefore spreading activation that makes other negative chunks more active), leading to angry thoughts about his/her partner who never understands how frustrating this is (also with a negative valence) and so on. The more intense (both aversive or pleasurable) a train of thought becomes the smaller the likelihood of snapping out of it is. Boring or mild thoughts are much more likely to be successfully interrupted by a reminder to come back to the meditation process than exciting ones.

The meditation model was constrained in two ways: (i) qualitatively by comparing model dynamics to first-person accounts of meditation and (ii) quantitatively. For the latter, because meditation itself produces no behavioral output to which one could compare a model output, our model was constrained indirectly by having it predict transfer to a similar task that does produce output. This transfer was compared to empirical data of a three-month FA meditation retreat during which the meditators exhibited improvements in sustained attention [26]. The specific transfer observed was from multiple FA meditation sessions to performance on a *Sustained Attention to Response Task* (SART; [33]). The similarity between the modeled and actual transfer effect is then an indirect measure of how well the model captures the actual meditation process. The rationale here is that an adequate model of meditation would be expected to make reasonably good predictions about transfer to other tasks. One of the main reasons for testing transfer to the SART is its simplicity and relative similarity to the meditation situation. Since affective tasks are typically more complex, we think these have to be left for secondary studies (we have begun to model these outside the context of meditation; see for example [47]).

1.2 Sustained Attention

As mentioned before, a key component of meditation, also crucial for its effect on emotions, is sustained attention. How can we operationalize sustained attention in a computational model? Sustained attention is defined as the ability to focus one’s attention on a given task over an extended period of time and to stay alert while doing so (e.g., [29], [58]). Participants’ performance in various sustained attention tasks is typically quite good at first but quickly begins to decrease. The effect is characterized by a reduction in speed and accuracy as well as reductions in perceptual sensitivity and increases in response bias [57].

We base our mechanism for the decline of sustained attention on previous computational models of performance on the SART, which describe declines of attention as arising from goal decay or increases in lapse probability without saying where that arises from [12], [51].

1.3 Modelling Meditation

A starting point for our model of meditation is a box-and-arrow process model of mindfulness by Vago and Silbersweig [46]. In this model FA meditation begins with the formation of intention and motivation. Next, a so-called executive set is created that contains the practice instructions. This practice instruction is then maintained through working memory processes, while the focus on the intended object is upheld by attentional processes. Mind-wandering is described as an unintended shift of focus to a sensory or mental event, which then leads to habitual affective responding, which in turn triggers related mental events such as episodic or procedural memories, that then lead to more habitual affective responses and so on. In other words, mind-wandering is a process of predominantly memory retrieval [51], consistent with a substantial neuroscience literature [5], [10]. Meditation has been associated with a change in attitude towards your own thoughts—one that is steeped in equanimity [9], [46]. The change in attitude towards thoughts is what allows for the improvement in emotion regulation so often associated with meditation practices. For example, instead of considering a thought of frustration after having made a mistake to be a source for a long train of continued mind-wandering and rumination about this topic, the model could more easily shift back to the intended focus of the task at hand. This breaking of the train of thoughts depends first on decentering, in which the meditator realizes that a thought it merely a thought, and can be dropped. This is then followed by the actual inhibition of the thought, by a process of response inhibition. Sometimes disengaging from the thought also requires emotion regulation, if the thought is highly emotional. While the process of decentering greatly tunes down the intensity of the emotion, additional emotion regulation may be needed to further reduce the strength of the affective response. Finally, executive monitoring is needed to re-engage attention with the meditation object.

As is clear, emotion regulation plays an important role in the meditative process. As far as the modeling of emotion itself goes, one can distinguish between three dominant theoretical frameworks available for computational modeling [16]: discrete/categorical (i.e., focusing on a small number of basic emotions), dimensional (two or three underlying dimensions of mood) and componential (emotions resulting appraisal variables). Models relying on appraisal theories are most common and would be a good fit for modeling the emotional processes in meditation, as the cognitive strategies for emotional regulation can be described well with appraisal terminology (e.g., reevaluating a threatening thought or aversive body sensation). Nevertheless, we chose a dimensional approach partially for reasons of parsimony. Like Thagard [45], we only use a single dimension to characterize emotions – valence. Dimensional theorists tend assume that emotion is more of a cognitive label retrospectively attributed to a somatic state, rather than a result of a direct appraisal of the emotion. Affect/mood is not necessarily the result a particular situation or thing (e.g., "I'm happy because of her") but more of an aggregate. Regarding the modeling of the effects of emotion on cognitive processes, we implement Bower's "Network Theory of Affect" [3], which assumes a semantic net of long-term memory. Nodes representing declarative information co-exist with nodes representing emotions. A given emotion spreads activation to associated nodes, which in turn facilitates their recall. This is important, because we have previously shown that MBCT practice changes these memory structures in depressed patients, allowing them to persist less in remembering negative memories and more in remembering positive memories [50].

1.4 Modeling Meditation with *Prims*

The cognitive architecture that was used for modeling meditation is *Prims* (Primitive Information Processing Elements; [44]). It is a recent extension of the well-established *Adaptive Control of Thought – Rational*, or *ACT-R* (Adaptive Control of Thought-Rational; [1]). Like ACT-R, *Prims* is a general symbolic architecture of human cognition, although the architecture also includes sub-symbolic processes such as activation noise, utility calculations, etc. As such the representations of perception, cognition and action are highly abstracted (e.g., the visual input of a bird is just represented as the word "bird"). The execution of a given *Prims* model in a computer program simulates cognition (e.g., memory retrieval) and resulting behavior (e.g., pressing a key) of a human subject. Such a simulation can then be compared to actual human behavior (e.g., speed and accuracy of responses in an experimental task). As in ACT-R, cognitive processing is distributed across specialized modules, which implement computational theories of various aspects of cognition[2] [1]:

- A goal module, which stores active goals and applies their influence.
- An input module, which models perception (e.g., vision).
- An output module, which model outward actions (e.g., button presses).
- A retrieval module, which models declarative memory and memory retrieval processes.
- A working memory module, which stores information that is immediately accessible and intermediate steps in calculations.

Cognitive processing itself takes place in cycles of applying if-then-rules. These rules are called *operators* in *Prims* (and *productions* in ACT-R). In every cycle, the information in the buffers of the modules is compared to the conditions of the operators. If multiple operators have conditions that fit the information in the system, a competition between them occurs and the operator with the highest activation – which depends among other factors on a baseline activation plus a random noise variable – is chosen to be executed.

Prims is generally simpler than ACT-R. There is for example no way of modeling low-level perceptual processes. The reason *Prims* was chosen for the modeling in this paper lies in its superior ability to model learning and transfer effects. This is achieved by assuming so-called *primitives*, processes of a very basic nature, which either compare information in respective module buffers (for checking the if-part in the if-then-rules) or copy information from one buffer to another (implementing the then-part). Just as in ACT-R, a cognitive process consists of one or more operators (respectively productions), only that in *Prims* they are further decomposable to condition- and action-primitives, which is necessary for modeling transfer and learning since it allows for the re-use of primitives across tasks. Another difference is that in *Prims* the operator – the sequence of the primitives for a given task (or subtask) – is stored in declarative memory as opposed to procedural memory in ACT-R. For new tasks – i.e., tasks that the model has not 'learned' yet – the necessary primitive actions must be recalled from declarative memory one by one, which makes the process much slower at first. Later on, when the prims begin to be recalled in groups of procedurally connected sequences, the processing speeds up. Ultimately,

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[2] Other theorists such as Brooks [4] would disagree on this point. In his terminology ACT-R/*Prims* might be considered a so-called SMPA model, in which cognition is a process carried out separately from perception and action. Theoreticians such as Brooks conversely maintain that there is no Cartesian cut between the cognitive mind and the body. In this view cognition is embodied and imbedded in the environment. Yet others question the clear-cut modularity and symbolic representations posited by frameworks such as ACT-R and *Prims* (see review by [60]).

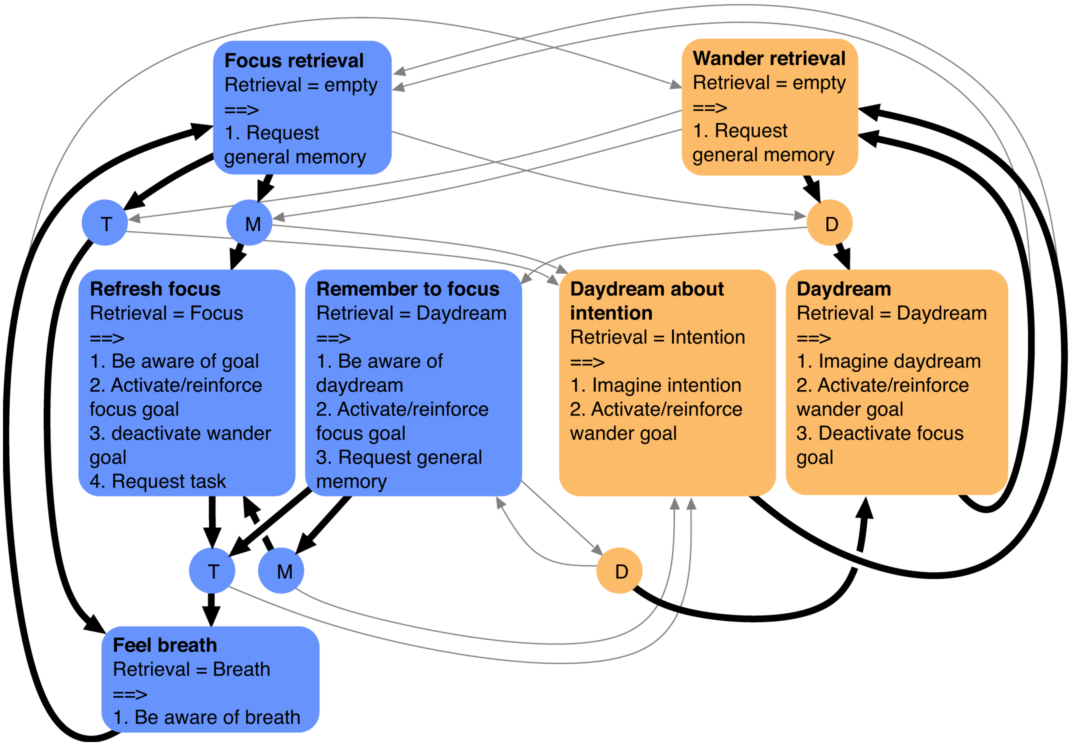

Fig. 1. Meditation model. Blue objects are related to the focus goal, yellow ones are related to the wander goal. The boxes are operators, while the small circles are memories that are retrieved due to a request by an operator. ‘T’ stands for task, ‘M’ stands for meta-task, ‘D’ stands for daydream. The arrows represent possible transitions. Thick black arrows represent high probability, while thin gray arrows indicate lower probability. The represented probabilities always are normalized to the situation in which both goals are active and the memories had similar baseline activations.

when the operator has been performed many times, it can be recalled in one step, as the memories of primitives are all—metaphorically speaking—tightly, procedurally knitted together. The transfer from one task to another is then modeled by allowing for new operators to benefit from chains of already assembled primitives, which leads to steeper learning curves and therefore faster reaction times. Also, in *Prims* operators can send and receive spreading activation (because they are stored in declarative memory), which makes it possible for environmental factors to affect what the model does. Although it was not implemented in the models in this paper, these associations between operators and other declarative memories allow for modeling an influence of mood on the activation of the operators (e.g., only sad memories associated with a given operator). Another advantage of *Prims* is that is has the possibility to model parallel goals, which is a plausible mechanism in meditation, as there is competition between mind-wandering and the meditation task. Future models might also include a goal pertaining to processes such as self-judgment. Presumably, self-judgment would grow less during the practice of meditation. Such decreases in the occurrence of self-judgment would naturally follow if the paying attention goal becomes stronger and thereby crowds out the self-judgment goal. However, for simplicity we have stuck with only modeling task- and mind-wandering goals.

2 METHOD

2.1 Meditation Model

When the model is run for several rounds it simulates roughly four processes that a meditator cycles through:

1. Remembering (or keeping in mind) what is supposed to be done again and again: In this case, this is the task of being aware of the breath.
2. Being aware of breath sensations, which is simulated as copying the perception into working memory.
3. Remembering something else and wandering off into daydreams, worries, etc.
4. Remembering to come back to the task when one has wandered off.

The model does this by assuming two competing goals[3] – focusing on the breath (the focus goal) and mind-wandering (the wander goal) – which each have operators associated with them [51]. Which operator wins depends on three factors in this model: the baseline activation of the operator, the random activation added and the spreading activation from the goal it is associated with. Goals can furthermore be activated or deactivated by operator actions (a unique feature of *Prims* that ACT-R does not have). In the latter case, their activation is automatically 0. This does not mean that operators associated with an inactive goal cannot win a competition; it just makes it a lot less likely.

As can be seen in Fig. 1, all of the operators are triggered by the retrieval (or lack thereof) of the last cycle and as can be seen in Table 1, there are three kinds of memory chunks. Thirty of them are meant to model mind-wandering contents (not necessarily single memories but rather representative instances of narratives or overarching themes). The 31st is the memory of the meta-task, which is the memory of refreshing the goal itself before checking what the low-level

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[3] These goals – especially the goal to mind-wander – are not necessarily explicit/conscious and reportable to the individual.

TABLE 1
The Three Types of Memories in the Declarative Memory of the Meditation Model and Their Slots

Meta-task (n = 1)	Task (n = 1)	Mind-wandering (n = 30)
Memory	Memory	Memory
Intention	Intention	Mind-wandering
Meta-task	Task	Memory-4*
Focus	Breath	Approach*

Note: * *These are examples. The memory slot ranges from 'Memory-1' to 'Memory-30' and the valence slot can contain 'Approach', 'Avoid' or 'Stay'.*

task at hand is. The 32nd is the memory of the low-level task, which entails feeling the breath.

A mind-wandering memory could have the following slot contents: Memory, Mind-wandering, Memory-17, Avoid. The first slot indicates that this chunk is a memory, which is a very general label to allow for general requests. The second slot distinguishes the mind-wandering chunks from the memories of intentions, while the third slot is a placeholder for a specific memory topic (e.g., 'Memory-21' might be a future-oriented and attractive topic – going on vacation). Finally, the fourth slot contains the valence or motivational connotation. Both intention memories have lower activations to begin with, 1.00 as opposed to the mind-wandering chunk's average activation of 3.07. This models the intention memories being less salient and engaging (at first) than the mind-wandering memories. The dichotomy between intentions and mind-wandering memories is necessary, so that retrieval requests associated with both processes can be made separately. An intention request is along the lines of "what was I supposed to be doing?" and a mind-wandering request might be verbalized as "what does this remind me of?".

All memory chunks (including the operators, which—as mentioned before – are chunks in *Prims*) have associations with other chunks, allowing for so called spreading activation to favor the future recall of chunks strongly associated with them. In order to simulate a set of mind-wandering memories/topics and their associations amongst each other, 30 chunks were randomly placed along two axes regarding affect (avoid, neutral, approach) and temporal orientation (past, present, future). As can be seen in Supplementary material: the scripts and models can be found at: https://github.com/amiroquai/meditation_model. Fig. 2, the chunks are on a continuous scale both in regards to affect and temporal orientation. The association magnitude was calculated as the Euclidian distance between chunks in this 2-dimensional space. So, for example mind-wandering about an aversive past event makes it more likely for another aversive past memory to be recalled in the next cycle, while a positive future-oriented memory is least likely to be recalled. An example of a negative past mind-wandering theme is failures in past relationships, which are typically painful memories. These memories might trigger rumination about past failures in the work place (possibly less aversive but still negative) and is very unlikely to trigger daydreaming about pleasurable topics such as promising future job prospects. The closer the mind-wandering topic is to the present and to a neutral affect the higher the association with the memory to come back to the object of focus (in blue in Fig. 2; supplementary material, available online). So even though the affect of the mind-wandering memories is represented discretely in the chunk itself, the associations are based on a dimensional and continuous concept of affect. Though it only relies on one affect dimension, as opposed to the most common dimensional representation of emotions, which prescribes two dimensions: valence and arousal [34], [35], [36]. The labels in the affect slot are therefore not doing anything in the model (they are there for quick diagnostics), it is the underlying continuous association values that make up the actual affective valence of a given memory theme and that determine the sequence of memory retrievals.

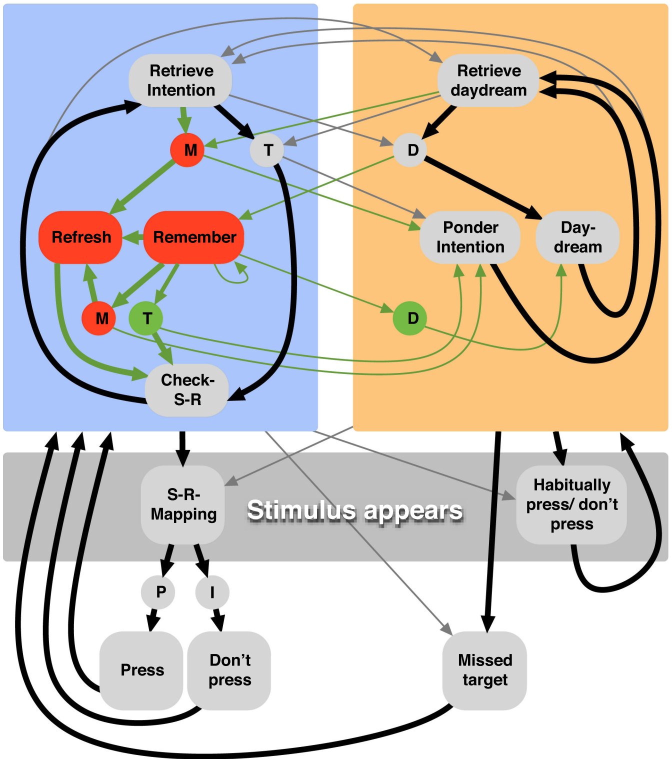

Fig. 2. Model of the SART after transfer. 'T' stands for task, 'M' stands for meta-task and 'D' stands for daydream. The red objects are the transferred operators and the meta-task memory. The green memories and transition lines appear in the diagram as a consequence of this transfer.

The model starts off with the focus goal activated and 'Breath' in the input buffer (which remains there), which reflects the meditator bringing their attention to the breath. As nothing has been retrieved, the retrieval operators of both goals will compete. At this point the focus operator will usually win, as the wander goal is not active yet. If it does, it requests a general memory and since it has associations with the task and meta-task memories, they have a better chance than the daydream memories of being recalled (presuming they have the same baseline activation). If the task memory is remembered this directly triggers being aware of the breath. On the other hand, if the meta-task memory is recalled this first triggers the refresh-focus-operator. It may also trigger the intercepting daydream-about-intention-operator, which diverts the process by imagining the intention (performing the meta-task) instead of putting it into practice and activating the wander goal.

However, if the refresh-focus-operator wins, which is more likely due to the sole activation of the focus goal in this example, this activates the focus goal if it was inactive or reinforcing it if it was already active. Next, the opposing goal is deactivated if it is active and the concrete task at hand is requested, modeling a meta-cognitive process that consists of reinforcing the goal to focus and remembering the task to focus on. As can be seen in Fig. 1, the refresh-focus-operator then proceeds to request the memory of the task at hand (i.e., trying to remember what to focus on after remembering to focus in the first place). If the memory that the feeling the breath is the task at hand is retrieved, this triggers the feel-breath operator. After feeling the breath there is no retrieval request, the retrieval buffer is empty and the retrieval operators are once again triggered.

However, if the wander retrieval operator wins, all memories are equally likely to be retrieved and since there are many more daydream memories, it's usually a daydream topic that is recalled at this point. If the focus goal is still active, there is still a chance of interception on behalf of the focus loop as the remember-to-focus operator is triggered by daydreams just as much as the daydream-operator. The latter models imagining the retrieved daydream content and reinforcing the goal (as well as deactivating competing goals, which in this case is only the focus goal) to mind wander. As there is no retrieval request in this operator, the retrieval buffer is once again empty, which leads to another competition in the next round amongst the retrieval operators of both goals. Once a goal has been activated, its operators tend to go into a stable loop. Yet, as can be seen in Fig. 1, there are multiple interception points to interrupt the stable loop and randomness in the competition further helps to break the loops.

Lastly, a general remark about the meditation models' reliance on randomness. This may be surprising to researchers not acquainted with ACT-R or *Prims*. One way to justify this implementation choice is to refer to it as an aggregate of both facilitating and interfering processes that are not yet understood/known or important enough to explicitly model. These processes are assumed to have a constant effect on the task (e.g., the activation noise stays constant). All things considered, the model is still relatively simple, relying on only 7 operators and 4 modules (input, retrieval, working memory and goal module). We consciously decided to start with such a simple model since simple models are widely recognized to be preferable [31], [55] and because this is to our knowledge the first model of meditation that directly predicts transfer. Future work should model meditation in a more detailed manner.

2.2 SART Model

The model that we chose for simulating participants' SART experience in the experiment is made up of operators for modeling the mind-wandering as well as operators for modeling the execution of the primary task. The operators for mind-wandering are almost identical to their respective copies from the meditation model. In a sense, the model consists of SART operators (identifying the stimulus, pressing, etc.) and a modification of the meditation model missing the primary and secondary focus operators. The model simulates the performance of the meditators in a SART that the participants of the meditation retreat completed before, during, and after the intervention [26]. This task consists of frequent non-targets (long lines, 90 percent chance) and rare targets (short lines, 10 percent chance). The screen switched between the display of a mask (1.55-2.15s) and the display of a stimulus (0.15s). There was a practice block of 120 trials and 4 contiguous test blocks of 120 trials each, which lasted for about 18 min. The main measure of behavior was A' [43], a measure of sensitivity combining hit rates and false alarms. The main finding of this study was that before the retreat, meditators showed a solid decrease in performance over time, while this decline was nearly absent halfway and at the end of the three-month retreat.

Along with the familiar focus and wander goal, there are goals called 'Just-react', 'Check-S-R' (check stimulus-response mapping) and 'missed'. The just-react goal is put in place by a wander operator to model habitual responding during mind wandering. The check-S-R goal has operators to check if the stimulus is a target or not and then to respond adequately. Lastly, the missed goal has operators to respond to the case in which no inhibition or pressing took place – in other words the stimulus was missed. The declarative memory is made up of the same 30 daydreaming memories as in the meditation model. There is a 31st memory, which is the memory of the low-level task: To pay attention to a target. As such, this memory plays a critical role in regulating the mind-wandering dynamics (see also van Vugt & van der Velde, [47], for a similar approach).

In the following section the model will be described in some detail, in Fig. 2. The SART model starts out with 'Focus', 'Check-S-R' and 'Missed' in the goal buffer. The input buffer has four slots that contain 'Breath', 'Mask' or 'Stimulus', 'Longline' or 'Shortline' (the two task stimuli) and 'Not done' or 'Done'. As long as the mask is on the screen it requests a retrieval of the current intention (like in the meditation model it does this by requesting a general memory while having strong associations with the intention chunk, making its retrieval a lot more likely), which usually triggers the reinforce check-S-R goal operator, although one of the wander operators that reacts to intention chunks can interfere here – especially when the wander goal is active. This operator makes sure the 'Check-S-R' chunk is in the goal buffer, so that there is a conscious response to a stimulus when it appears. In contrast to the meditation model, the focus goal has no operators to reinforce itself or to deactivate the wander goal should it become activated. It only deactivates the just-react goal because the habitual and conscious responses are not compatible. The rationale behind modeling the focus operators in this way is to simulate how a lack of meta-cognition and thorough goal management leads to performance that is worse than with such processes after training.

The idea is that the SART task and meditation are like many everyday tasks insofar that there is a constant shift from conscious effortful processing to automated and effortless processing. In other words: it reflects the alternation between system 2 (thinking through details) and system 1 (response based on initial impulse; Kahneman, [18]). Both in the SART as well as in meditation, a lack of effortful system 2 processing leads to lapses and overall decreased performance. The focus operators only constitute a crude version of meta-cognition and goal management.

Nevertheless, it is effortful and requires meta-cognition to regularly check whether the ongoing mental processes are appropriate to the original goal (e.g., feeling the breath sensations, attending to the SART, etc.). The alternative (at least in the model) is to just drift from one habitual pattern to another, both mentally (allowing mood and temporal orientation to direct mental content) and behaviorally (always pressing the same button).

As will be explained in the context of the 'Missed'-operators, this model relies heavily on external cues to bring the attention back in case it has wandered. The fact that the mind-wandering operators have extensive goal management functions even before training reflects the assumption that mind-wandering is a well-established habit that has been optimized over decades (possibly through reinforcement learning as well as trial and error as daydreaming seems to be interesting and rewarding in the short term). When a stimulus does appear the focus operators are blocked, as they have a condition to only react when no stimulus is presented. The check-S-R operators then request what reaction is adequate for the kind of stimulus that appeared and put it into action. The pressing or inhibition of pressing updates the input buffers 'Not done' to 'Done' through an if-then command in the script running the model.[4]

Sooner or later a retrieval of an intention will be intercepted by the wander operator that responds to them, bringing the wander goal and their operators into play or the focus-retrieval-operator retrieves a daydream memory, in which case the primary wander operator responds by deactivating the focus goal and installing the wander goal. This furthermore brings the just-react goal into play. At this point, there is still a slight possibility that an intention is retrieved due to the ambiguous nature of the retrieval requests, which can trigger the check-S-R reinforcing operator and it also sometimes happens that the focus-retrieval-operator wins from the wander-retrieval-operator due to random fluctuations in activation noise. Yet, neither of the operators deactivate the wander goal or activate the focus goal, so the mind-wandering quickly restarts. In a way this models the focus goal not being intrinsically motivating while mind-wandering about passionate concepts is. In summary, the model cycles mostly between retrieving memories, putting them into the imaginal buffer and habitually responding to stimuli that appear. However, every now and then the just-react operators do not react to the stimulus because they must compete with the mind-wandering operators that (in contrast to the focus operators) do not have a condition to block them when there is a stimulus on the screen. When there is no reaction, the operators associated with the missed goal have a high chance of being triggered. These operators press or inhibit at random (although inhibiting is more probable), reactivate the focus goal and deactivate the wander goal. This simulates the experience of daydreaming becoming so absorbing that the task at hand is forgotten altogether, leading to a momentary shock at realizing that the stimulus has been missed, which leads to more focus and less mind-wandering.

The transfer consisted of copying the meta-task memory (the cue that the meta task operator is to be performed) and two meditation model operators into the SART model, transferring the following processes: Reinforcing/activating the focus goal, deactivating the wander goal, reinforcing the focus-related memories and the process of remembering the task at hand when mind-wandering. Importantly, the low-level task and its memory differed from their counterparts in the meditation model: in the SART the low-level task was to check the stimulus-response-mapping in case a stimulus appeared while in the meditation task the low-level task was to experience the breath sensations. In terms of emotion regulation strategies, one could say this transfer reflects a strategy of focusing strongly on the contents of the relevant goals, thereby reducing the risk that processes of ruminative thinking (such as "I am worthless") can proliferate for a long time.

2.3 Prims Parameters

Prims has a vast spectrum of parameters, most of which influence the performance of both models. A majority of them were kept at the default level, while some were adjusted to allow for the models to perform at least somewhat realistically. Specifically, the activation noise was set to 0.4 (default is 0.1), which allowed for slower transitions, more interference and shorter loops. Activation noise refers to the amount or random noise added to the activation value of a given memory chunk. The amount of goal buffer spreading activation was set to 0.75 (the default is 1), which decreases the impact the goal activation/deactivation has, with similar effects as the increased activation noise parameter. The amount of working memory buffer spreading activation was set to 0.3 (the default is 0), which allows for association between daydreams during mind wandering. This is the case because the current daydream, which resides in the working memory needs to affect activation values of other memories in declarative memory. The latency factor was set to 0.15 (the default is 0.2) to make the SART model faster in responding to the stimulus. The learning parameter for production compilation was set to 0.2 (the default is 0.1) to allow the SART model to assemble the prims faster in the training phase.

3 RESULTS

The meditation model was tested for a simulated 18 hours of practice at which point it seemed to have reached a dynamic equilibrium in the process of learning to stay focused on the breath. The analyses reported here pertain to only one run of 18 hours, as there was very little variation between the runs. As can be seen in Supplementary, available online Figure 4, the model starts off with a lot of mind-wandering but slowly begins to shift to more focus and then drops below the rising focus percentage out at

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[4] This was a necessary workaround because there is no module in *Prims* to simulate time perception. The idea here is that the model is blocked from pressing again or initiating the 'Missed' operators because it is clear that not enough time has passed yet. When the trial is over the slot is updated to 'Not done' again, indicating that it is time to be on guard again, which is supposed to approximate a continuous function of readiness. This workaround may or may not be a drawback. As it stands the model functions under the assumption that time perception is not affected in a relevant way by the meditation or the SART. Therefore, assuming time perception to be a constant process it is simplified to a discrete if-then process.

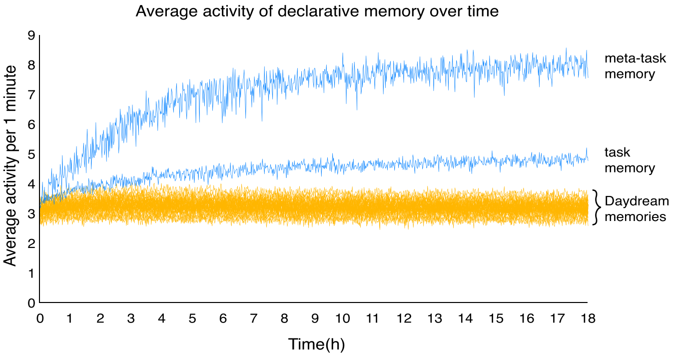

Fig. 3. Average activation of declarative memories over time. The blue lines are task relevant memories, while the yellow lines are daydream memories.

about 5 hours. In the end almost all retrieved memories are focus-related, reflecting the model being fully focused on the breath all the time.

As can be seen in Fig. 3, this shift to being focused is accompanied by increasing activation of the meta-task chunk and the task chunk. Additionally, as can be seen in Supplementary, available online Figure 6, there is an increase in interference by the meta-task chunk over time (this is apparent because the transitions from the wander-retrieval to the primary focus-imaginal-operator increase, which can only mean more meta-task retrieval). In the end almost no more daydreaming chunks are being retrieved by any operators.

The SART model was run for 1 training block and 4 test blocks, just like in the empirical study. The results presented are the average of 30 runs, as the SART model was somewhat variable in its performance, partly due to the relatively short simulated time span (18 min as opposed to 18 hours for the meditation model).

The SART model with transfer was run with a meta-task memory at the low starting activation level of the meditation model: 1.00. As can be seen in Supplementary, available online Figure 7 proportion of time during which the model is mind-wandering decreases, while the proportion of time focused on the task increased. These differences in goal prominence also had consequences for task performance. The hit rate was increased and the false alarm rate was lower (not displayed in the figure), leading to an increased A′. This can be seen in Supplementary, available online Figure 7 as well, where it is shown next to the empirical data of MacLean et al. [26].

We then examined whether the observed patterns were reliable, similar to the empirical data. An independent t-test of the mean sensitivity before and after transfer revealed that the difference was highly significant $(t(58) = 4.49, p < 0.001, d = 1.18)$. Examination of the Q-Q plot and the Shapiro-Wilk test showed no significant deviation from normality $(W(60) = 0.99, \mathrm{p} = 0.85)$. The difference was even more pronounced when the meta-task memory was transferred at above average activation levels $(4.50) : t(47.82) = 14.05, p < 0.001, d = 3.69$. The assumption of normality was rejected $(W(60) = 0.92, p = 0.001)$. Therefore a bootstrap test was conducted. Bootstrap tests rely on resampling with replacement in order to approximate the distribution of a given estimator, which can be useful when assumptions for parametric models are violated. Both cases (meta-task memory at low and high levels) indicate that the transfer notably affected the SART Model. The bootstrap test (1000 samples) corroborated the significance of the effect $(p = 0.001)$.

4 DISCUSSION

This paper set out to explore the cognitive and emotional processes underlying FA meditation by creating a cognitive model to simulate it. To constrain the model and test its plausibility, a cognitive model of a SART was analyzed before and after the transfer of two meditation operators and a memory that prompted them.

The meditation model transitions from mainly mind-wandering to being almost entirely focused on the task at hand. There seem to be two main causes for this development: the increasing dominance of the meta-task memory over the task memory as well as the increasing dominance of both intention memories over the mind wandering memories. The fact that the meta-task memory becomes stronger than the task memory leads to more instances of the following sequence: focus retrieval → refresh focus → feel breath, and less of this sequence: focus retrieval → feel breath. This in turn allows for more reinforcement of the focus goal and the meta-task memory because the refresh-focus-operator involves goal management actions and imagination (which strengthens the memory). The second cause—the domination of the intention memories over the mind-wandering memories—leads to more retrieval of task-related memories and less retrieval of mind-wandering memories. In other words, relatively active intention memories decrease the probability of interference by mind-wandering memories and increase the probability of interference in the wander-retrieval by intention memories (mostly the meta-task memory).

One may wonder why the meta-task and the task memory increase in activation so dramatically over time. The intention memories probably increased in activation because they are retrieved a lot more than any single mind-wandering memory. Even though the mind-wandering memories as a whole are retrieved a lot more frequently at first than the intentions and even though they spread the resulting reinforcement amongst each other to some degree (due to their associations), the reinforcement per single mind-wandering memory is a lot smaller than for the meta-task. What gives the mind-wandering memories the upper hand at first–their numbers–becomes a handicap as the reinforcement they receive is spread too evenly among them. This has interesting implications. It could mean that an important aspect of how FA meditation calms the mind lies in its simplicity and unidirectionality: it only focuses on a small group of memories, while mind-wandering has a broad focus. It could indicate that if the goal management strategy is such that it is sufficient for combating mind-wandering loops and interference–even if only rarely at first–it can reinforce its associated memories, causing it to be more effective as time progresses, which leads to more reinforcement and so on. In other words, if the goal management strategy is effective enough in the beginning (even if only barely) it can create a feedback loop. And while the mind-wandering process creates a feedback loop as well, it is less effective, and therefore less strong, presumably because the loop is a lot more dispersed over different memories.

What is attractive about this loop-competition mechanism is that it is very general and is therefore plausibly implementation-neutral. A *Prims*-independent expression might be the following: two competing feedback loops differing in dispersion and therefore reinforcement per component (in this case, memory chunk) per cycle. In the future it would be interesting to use other architectures (e.g., [22]) with standard parameter settings to corroborate the generality of our proposed mechanism. Lastly, the loop-competition conception allows for specific hypotheses regarding mind-wandering dispersion and its tenacity. For example, we would predict that rumination that is centered strongly around a singular theme (e.g., bereavement) is more disruptive than rumination cycling through multiple themes (e.g., bereavement, job loss, failing economy and what kind of iPhone to buy next). It may therefore be the case that mind-wandering dispersion is inversely correlated with depression symptoms.

When mind-wandering loops are weaker, this is likely to have implications for emotion regulation. In rumination, a core symptom of depression, people get stuck in loops of an extremely “sticky” form of mind-wandering (van Vugt & van der Velde, [47]). We have recently demonstrated that when modelled mind-wandering loops become more sticky, which makes it more difficult to return to the task, this leads to impairments in sustained attention task performance (see also [49], for empirical evidence supporting this idea). In addition, we have demonstrated that a longer period of lingering on negative information during a two-back task can replicate performance impairments of depressed patients [47]. Together, the reduction in the strength of mind-wandering loops could be a mechanism underlying the improvement in emotion regulation observed as a result of mindfulness-based cognitive therapy.

What is interesting about mind-wandering is that it seems to creep up stealthily and is often easy to snap out of, but only for a few moments, which reflects what we think are two core factors in mind-wandering’s longevity: tenacity and momentum. The meditation model explored in this paper suggests that FA meditation functions on the same principles supplemented with the benefits of unidirectionality.

Yet, what this model leaves out is that mind-wandering is typically not a deliberate choice, while a main aspect of FA meditation is the conscious, voluntary and therefore effortful deciding from moment to moment. Not being able to model this asymmetry is a major limitation. The model cannot distinguish between bringing something to mind consciously (“deliberate mind-wandering”) and something appearing on its own (“spontaneous mind-wandering”, [41]). Future work should develop modeling formalisms that can differentiate between deliberate and automatic mind-wandering, for example by separating mind-wandering in response to behavioral goals from mind-wandering associated with habitual thought patterns that are typically not task-related. It is likely that meditation practices specifically reduce spontaneous mind-wandering.

Importantly, we started our paper with the question of how meditation would affect emotion regulation. We demonstrated that in our simulation meditation can improve task focus, which may help to reduce intrusions from rumination [27], but we have not empirically demonstrated that. Future simulations should examine how FA meditation would affect performance on an emotional processing task, such as the emotional N-back modelled in van der Velde, Taatgen & van Vugt [47]. The empirical study that was modelled in that work showed that depression was associated with a reduction in the ability to remove aversive stimuli from working memory (Levens & Gotlieb, [24]). We modelled that phenomenon by assuming that participants with depressive rumination had stronger elaboration on negatively-valenced stimuli (i.e., it was more difficult to disengage from them), and in addition, that they had a stronger perceptual bias towards aversive stimulus information. Meditation practice is likely to reduce this strong elaboration by increasing the importance of task goals and thereby reducing the importance of aversive-elaboration-related operators. In another model of depressive rumination (van Vugt & van der Velde, [47]), we assumed that rumination could be modelled by increasing the connection strength and activations of negative memories relative to non-ruminative thinking. However, in that model we did not explain how these changes in memory structure or “habits of thought” came about. Our meditation model provides a possible theory for this by explaining the reverse process (the reduction in the strength of negative-thought habits that are rumination). Specifically, the strength of habits of thoughts is increased by repeating them. If meditation reduces the tendency to persist in habits of negative thought, due to increased attentional control and increased task focus, this could reduce the strength of negative thought habits.

Consequently, future improvements of our meditation model should include aversive emotions due to frustration arising during the meditation process, which commonly occurs upon realizing that one has once again been distracted. This is important as coping with negative self-judgment is a central aspect of many meditation practices. The current model has an equal chance of mind-wandering about something positive as about something negative when focusing on the intended object fails. Future models would therefore ideally include operators that interfere with the task at hand by modeling judging (i.e., a negatively-biased appraisal; [23]) and ranting. This could be implemented as a specific kind of mind-wandering about particular aversive and self-related topics, which can transition to either regular mind-wandering or a return to the task (similar to van Vugt & van der Velde, [47]). This could be complemented by a metacognition operator that detects such judgmental thoughts as inaccurate and thus returns to the task more quickly. What is more, modeling the formation of new associations between strongly affective memories in general and a metacognitive reaction (e.g., decentering) would be highly interesting. However, this is not currently possible in *Prims* and would need to be developed as a new feature first.

Another approach to take would be to add affective and physiological modules as has been done in ACT-Rϕ [8]. In such a combined physiological-cognitive model the mental processes of mind-wandering and meditation could interact with a more holistic representation of affect, and importantly, the resulting model could make predictions for physiological data on top of the behavioral data. For example: ruminating about negative events from the past might increase noradrenalin levels, which in turn would affect the activation of certain mind-wandering operators via the affective module. Detecting increased levels of agitation (euphoric or fear-based) and applying coping mechanisms (e.g., switching from mind-wandering to feeling the breath) might then constitute a meditative response, which would be modeled so as to increase in activation and speed over the course of simulated meditation training. Another candidate mechanism that could be modelled is Heart-Rate Variability, which has been associated quite specifically with ruminative thinking [28]. There is research indicating enhanced HRV after meditation practice [2]. Furthermore, HRV has been associated with executive functions [15], which are arguably central to the meditation model.

Finally, a remaining question is how plausible the meditation model we presented is. The model was almost entirely constrained by internal consistency considerations and basic assumptions about *Samatha* meditation, which are not very strong constraints. To increase the credibility of the meditation model, assessing the accuracy of predictions of transfer to other tasks than the sustained attention task presented here is necessary. Nevertheless, the positive transfer effect of the goal management operators to the SART give some credence to our model. These results suggest that the mechanisms of the meditation model are at least somewhat generalizable and are not merely artifacts of a specific modeling situation. It furthermore indicates that the method for implementing mind-wandering, which was very similar in both models, is plausible. Furthermore, the transfer was congruent with the kind of change one would predict to arise as a result of meditation. What is more, the meditation model is quite robust, simple, and produces reasonable behavior considering its parsimony. In other words, there is reason to believe that the model captures one important aspect that might underlie FA meditation: a feedback loop effect induced by patient and deliberate application of a goal management strategy. On the other hand, it does not directly capture aspects of meditation that reflect cultivation of a non-judgmental attitude and transformation of mental habits, which are crucial for describing the effect of meditation on emotion regulation.

In short, we have presented the first computational process model of meditation and have shown that it makes predictions for transfer to cognitive task performance. The model suggests that the transfer from meditation to cognitive task performance consists of goal management faculties and that consequently meditation enhances performance through a feedback loop mechanism. These provide some ideas for how meditation could exert salutary effects on emotion regulation that can be tested more explicitly in future simulation studies.

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