Effect of postlearning meditation on memory consolidation: level of focused attention matters

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Recent studies demonstrate that eyes-closed rest benefits memory consolidation, perhaps due to reduced attention to environmental stimuli. Here, we asked whether focusing attention to *internal* thoughts and feelings after learning similarly blocks memory consolidation. Verbal memory was tested following an eyes-closed consolidation period filled with either focused attention to breath or quiet rest. Although breath-focus did not impair memory relative to quiet rest overall, participants who reported being more successful in maintaining breath-focus during this condition showed increased forgetting. We interpret these findings as incompatible with a simple sensory-interference-based account of rest's effect on memory.

[Supplemental material is available for this article.]

Following encoding, memories are stabilized and transformed over time via a set of processes referred to as "consolidation" (McGaugh 2000; Dudai 2004; Frankland and Bontempi 2005). Delineating the brain states during which consolidation occurs most optimally may help us to discover the mechanisms of this process, which thus far remain incompletely understood.

Numerous studies have established that both sleep (Mednick et al. 2003; Tucker et al. 2006; Nishida and Walker 2007; Payne et al. 2012) and eyes-closed waking rest (Dewar et al. 2012; Brokaw et al. 2016) immediately following encoding benefit memory. These states might promote consolidation due to reduced focused attention to environmental stimuli and/or an associated reduction in hippocampal resource utilization (Mednick et al. 2011). However, there is preliminary evidence that even attending to *internally* generated stimuli, including thought and imagery about the past, present and future, might similarly impair the early stages of consolidation (Craig et al. 2014).

For example, completing an autobiographical memory recall task following encoding has been reported by Craig et al. (2014) to impair consolidation relative to a period of task-free rest, suggesting that this form of inwardly directed attention also inhibits consolidation, much as focused attention to external environmental stimuli does. But like tasks that involve encoding new sensory stimuli, the autobiographical memory task utilized by Craig et al. (2014) is specifically designed to engage the hippocampal memory system. In the present study, we sought to determine whether focusing attention on an internally directed task that places minimal demands on the hippocampal system would similarly impair memory retention.

Mindfulness meditation is a useful manipulation for testing the effect of inwardly directed attention on consolidation because it encourages a high level of focused attention in the context of minimal engagement with the sensory environment. Breath-focus is a simple form of mindfulness meditation where one is directing their attention to not only an internal experience but also to the *present*, rather than to recall the past or imagine the future. This is important because unlike tasks specifically involving recall of past events (Craig et al. 2014), mindful attention tasks such as breath-focus are not thought to engage hippocampal resources (Hasenkamp et al. 2012; Sperduti et al. 2012; Tomasino et al. 2014; Scheibner et al. 2017), instead being associated with activation of frontal regions involved in executive attentional control (Hasenkamp et al. 2012; Tomasino et al. 2014). Thus, the unique nature of breath-focus mindfulness involving internally directed, but hippocampal independent focused attention renders it ideal for testing whether internally directed attention inhibits memory consolidation, even in the absence of hippocampal engagement.

In the present study, we assessed the effect of breath-focus mindfulness meditation on the early stages of memory consolidation, in comparison to a control condition of unconstrained quiet rest. Our goal was to determine whether consolidation is inhibited by focusing one's attention to an internal task that does *not* heavily involve hippocampal resources. We hypothesized that focusing on one's breath would inhibit consolidation relative to a period of unconstrained quiet rest, despite the fact that breath-focus is a very simple inwardly directed task unlikely to heavily tax hippocampal resources. This hypothesis was motivated by past research suggesting that even very simple mental activities that do not obviously involve hippocampal engagement can inhibit consolidation (Dewar et al. 2007), as well as evidence that quiet rest may benefit the early stages of consolidation for a motor-procedural task, for which the relevance of hippocampal activity is unclear (Humiston and Wamsley 2018).

Based on prior research, we also hypothesized that mindful breath-focus meditation would be accompanied by characteristic changes in the EEG, including in the alpha and theta bands (Cahn and Polich 2006; Kakumanu et al. 2018), and that these meditation-induced EEG changes would be associated with subsequent memory performance.

After being prepared for EEG recording, participants ($n=31$) trained on an Icelandic-English word-pairing task (see Supplemental materials), followed by an immediate memory test (Fig. 1). Participants then either focused on their breath or rested quietly for 10 min. During the meditation condition, participants sat

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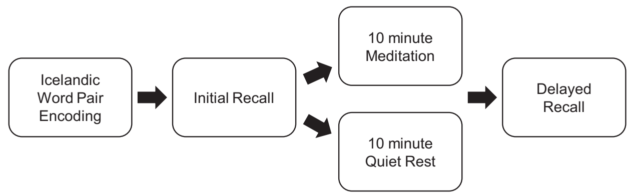

Figure 1. Experimental order of events. Participants first were exposed to the Icelandic word pairs, then immediately tested. Then, they rested or focused on their breath for 10 min. Finally, they were tested on the word pairs again.

quietly with their eyes closed, following a recorded mindfulness breath meditation (Koru Breath Meditation (Greeson et al. 2014)). In the rest condition, participants similarly sat quietly with their eyes closed. To control for the auditory stimulation, a recorded voice reading a recipe was playing in the background. While participants were meditating or resting, EEG was continuously recorded at 400 Hz. After the 10-min quiet rest or meditation, participants waited 30 min before being tested on the Icelandic-English word-pairs task again. Finally, all participants completed a survey assessing their subjective experience during the retention interval, which included rating the amount of time that they actually spent focused on their breath.

Contrary to our hypothesis, the number of items recalled did not change differentially across the meditation ($M = -0.16$ words, SE = 0.13) and quiet rest conditions ($M = -0.52$ words, SE = 0.25) ($t_{(30)} = 1.32$, $P = 0.20$). Participants reported spending significantly more time focusing on their breath in the meditation condition ($M = 46.7\%$; SE = 4.3), compared to during the quiet rest condition ($M = 2.0\%$; SE = 0.8); $t_{(30)} = 9.98$, $P = 4.76 \times 10^{-11}$).

However, in examining the exit questionnaire data, we found there was very wide variability in the extent to which participants reported successfully maintaining focus on their breath during meditation (range during meditation: 0%–90%, compared to 0%–19% in quiet rest). This variability in perceived time spent on breath-focus was highly relevant to memory outcome: Participants who reported successfully focusing on their breath for more time during meditation showed increased forgetting of the Icelandic word pairs across meditation and the following half hour, relative to the rest condition (Pearson's correlation between % time focused on breath vs. [meditation – rest] memory change: $r_{29} = -0.54$, $P = 0.002$, $R^2 = 0.29$; Fig. 2). We therefore conducted additional exploratory analyses of the effect of condition on memory retention, controlling for percent time spent focusing on breath during meditation as a covariate.

Controlling for meditation breath-focus time in a 2 (time: immediate vs. delayed test) × 2 (condition: meditation vs. rest) ANCOVA, there was a significant time × condition × breath-focus time three-way interaction, indicating that the effect of breath-focus time on memory retention differed between the meditation and rest conditions ($F_{(1,29)} = 11.67$, $P = 0.002$; Fig. 3). This was reflected in the fact that across the meditation condition, participants who reported successfully focusing on their breath >50% of the time (*high-breath-focus*) showed significantly more forgetting over time ($M = -0.50$, SE = 0.17), relative to those focusing on their breath ≤50% of the time (*low-breath-focus*, $M = 0.12$, SE = 0.17; $t_{(29)} = 2.53$, $P = 0.017$; Fig. 3). Conversely, the ability to maintain breath-focus in the meditation condition was unrelated to memory retention in the quiet rest condition (memory change across quiet rest for participants with >50% breath-focus in the meditation condition: $M = -0.14$, SE = 0.40 vs. ≤50% breath-focus: $M = -0.82$, SE = 0.29; $t_{(29)} = 1.41$, $P = 0.17$; Fig. 3).

There was additionally a significant time × condition interaction ($F_{(1,29)} = 14.01$, $P = 0.001$) such that accounting for maintenance of breath-focus, meditation led to less forgetting over time (estimated marginal means for recall at training: $M = 8.65$, SE = 0.82 vs. test: $M = 8.48$, SE = 0.80) relative to the quiet rest condition (estimated marginal means for recall at training: $M = 8.90$, SE = 0.84 vs. test: $M = 8.39$, SE = 0.82).

The proportion of time that participants reported maintaining breath-focus during the meditation condition was negatively correlated with mean theta power in both the rest ($r_{29} = -0.37$, $P = 0.04$) and meditation ($r_{29} = -0.35$, $P = 0.052$) conditions. However, after correction for multiple comparisons, this association was not statistically significant at any individual electrode site.

Engaging in attention-demanding tasks after learning impairs consolidation of previously learned information (Dewar et al. 2012; Craig et al. 2014; Brokaw et al. 2016). Recent studies suggest this may occur not via a simple increase in retroactive interference, but instead by inhibiting an active process of memory reactivation and consolidation that would otherwise be unfolding at this time (Carr et al. 2011; Mednick et al. 2011; Dewar et al. 2012; Staresina et al. 2013; Tambini and Davachi 2013; Brokaw et al. 2016; Murphy et al. 2018). Yet the specific features of a postlearning task that facilitate or inhibit early-stage memory consolidation remain unknown. In the current study, we hypothesized that even engaging in a simple breath-focus task after learning would impair memory via the active inhibition of memory reactivation mechanisms, despite the fact that this resting, meditative state involves directing attention to *internally* generated stimuli, rather than the encoding of new information.

Although memory did not differ between the meditation and quiet rest conditions overall, exploratory analyses revealed that within the meditation condition, success in maintaining breath-focus during the postlearning period was negatively associated with subsequent memory. Thus, meditation may have inhibited consolidation when participants were successfully able to maintain focus for the majority of the retention interval. This negative association between breath-focus and memory provides partial support for our hypothesis that following learning, memory consolidation can be inhibited by focused attention that is (1) internally directed, (2) highly dissimilar in content from the previously learned information, yet (3) not strongly engaging the hippocampus.

We had originally hypothesized that quietly resting following learning would lead to the greatest memory improvement. But to the contrary, memory retention was actually superior following low-breath-focus meditation, relative to quiet rest (as shown in Fig. 3). In fact, subjects who reported focusing on their breath

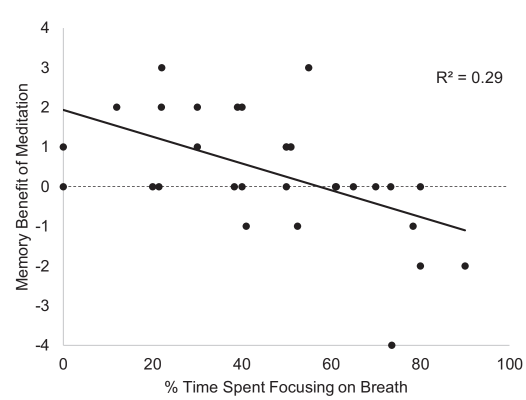

Figure 2. Correlation between breath-focus and memory. More time spent focusing on breath during the meditation condition predicted relatively worse memory following meditation (memory benefit of meditation = memory change across meditation – memory change across quiet rest).

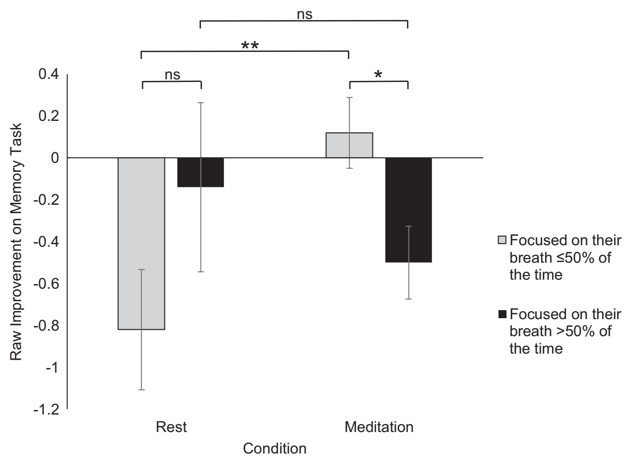

Figure 3. Successful breath-focus during meditation was associated with impaired memory consolidation. In the meditation condition, participants who successfully focused on their breath for the majority of the retention interval showed more forgetting, relative to those who reported spending less time on breath-focus. This was not the case in the rest condition. Error bars ± SEM. ((*) $P < 0.5$, (**) $P < 0.1$).

≤50% of the time during the meditation condition were the only subgroup of participants to show numerical (though nonsignificant) improvement in performance across the retention interval (Fig. 3). This performance benefit of *low*-breath-focus meditation cannot be attributed to a reduction in hippocampal encoding of external stimuli, as sensory processing was similarly minimized in all conditions. Therefore, we must look to other potential explanations for the pattern of results.

One possibility is that hippocampus-dependent memory retrieval processes were more engaged during quiet rest than during low-focus meditation. Although meditation and rest were both characterized by a similar reduction in encoding of new sensory stimuli, quiet rest may have induced relatively greater utilization of hippocampal resources devoted to retrieval of past memory, as participants in this and prior studies report spending the majority of time during quiet rest engaged in thinking about the past and imagining the future. Engagement in these cognitive activities could also have led to increased encoding of participants' subjective experience during rest. These memory-driven cognitive processes are known to engage the hippocampus (Schacter and Addis 2007; Schacter et al. 2012), and could have acted to block consolidation (Mednick et al. 2011), as previously reported following the intentional completion of an autobiographical memory task (Craig et al. 2014). As a result, postlearning quiet rest could benefit memory more than an equivalent duration of active wakefulness (Dewar et al. 2012; Brokaw et al. 2016), but yet may not be the optimal state to facilitate offline consolidation. Alternatively, we may have been incorrect in our assumption that quiet rest would involve less focused attention than breath-focus meditation. It is possible that during quiet rest, participants actually focused intensively on internally generated thoughts and daydreams, engaging frontal executive resources in planning, ruminating and worrying. Low-breath-focus meditation, in contrast, could have benefitted memory as a function of relatively lower focused attention and lower utilization of frontal executive resources.

Either of these scenarios could explain why controlling for reported breath-focus revealed meditation to *enhance* memory relative to rest (time × condition ANCOVA interaction). Equating breath-focus time between conditions, the state of quiet rest appears to be functionally different than the state of meditation, potentially as a result of reduced hippocampal and/or frontal executive resource engagement during quiet rest.

Finally, in our data, low attention to breath-focus may have been indicated by increased theta power. In prior studies, theta activity during sleep has been positively associated with improvement of other types of memory, including emotional memory (Nishida et al. 2009) and auditory learning (Durrant et al. 2015). Here, during quiet wakefulness, increased theta power might similarly be associated with entry into a consolidation-promoting state.

These results add to accumulating evidence that rest benefits consolidation due to active neurobiological processes occurring in "offline" states, and not just because of a simple lack of retroactive interference. The *Opportunistic Consolidation Hypothesis* proposes that any state that reduces the activity of the hippocampus after encoding will allow memory consolidation to occur (Mednick et al. 2011). Such states include sleep, rest and a variety of other "offline" states of consciousness (Mednick et al. 2011; Wamsley 2019). In contrast, the *interference hypothesis* postulates that memory is relatively better following sleep and rest as compared to active wakefulness, simply due to a reduction of retroactive interference in these states. Classically, retroactive interference is defined as resulting from the encoding of specific new learning material that is to some degree overlapping in content with previously encoded information (Wixted 2004). Our current results are not easily explained by a reduction of this form of classically defined retroactive interference. Neither of our quiescent experimental conditions prominently included the encoding of new information during the consolidation period, and whatever new experiences were encoded during these conditions were not overlapping in content with the Icelandic word pairs. Therefore, neither the meditation nor the quiet rest conditions would be expected to induce retroactive interference as classically defined.

The association of breath-focus with forgetting across the meditation condition, therefore, cannot be attributed to a simple reduction in classically defined cue-overload retroactive interference. Instead, this observation is more consistent with the *Opportunistic Consolidation Hypothesis,* in that, relative to low-breath-focus-meditation, generally increased levels of cognitive activity during quiet rest and high-breath-focus meditation could have blocked consolidation due to increased utilization of hippocampal and/or frontal executive attention resources. Of course, our findings cannot be definitely attributed to differences in hippocampal activity or attentional processes between conditions, as the activity of these brain systems was not directly measured in the present study.

A further limitation of this study is that, because degree of breath-focus during meditation was not manipulated, we cannot be confident that memory differences between high- and low-breath-focus individuals were truly caused by variability in breath-focus. Alternatively, this correlation could have been driven by individual differences in metacognitive ability, personality or attention. Additionally, while audio stimulation was matched across conditions, during meditation, participants had to pay attention to the audio, whereas in the quiet rest condition they did not. This differential attention to auditory stimuli is a potential confound.

In summary**,** our results suggest that intentional focus on even a simple, internally directed task may inhibit the early stages of memory consolidation, in the absence of any obvious increase in hippocampal encoding of new experience. Future research should continue to examine the possibility that engagement of frontal executive resources in focused attention may impact the ability of offline consolidation to unfold.

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