

Selective Effects of Sleep on Emotional Memory: What Mechanisms Are Responsible?

Kelly A. Bennion
Boston College

Jessica D. Payne
University of Notre Dame

Elizabeth A. Kensinger
Boston College

Although both nonscientists and scientists alike have long promoted the idea that sleep is beneficial to memory, recent work has shown that the effects of sleep on memory are selective: Sleep ‘selects,’ or preferentially consolidates, the most salient or goal-relevant aspect of an experience, resulting in facilitated retrieval of that information upon waking. In this review, we focus on the selective effects of sleep on emotional memory, highlighting 3 potential mechanisms responsible for these effects. We first discuss how the ‘replaying’ of information during consolidation leads to enhanced memory, with emotionally salient information being preferentially reactivated during sleep. We then discuss how the neurobiology of sleep—specifically, theta oscillations that may enable prefrontal-limbic connections and changing acetylcholine levels—may support the selective consolidation of emotional experiences. Lastly, we provide evidence that information that is preferentially consolidated during sleep may be initially selected during encoding, with endogenous cortisol ‘tagging’ a salient event as important to remember, thus leading to its prioritized consolidation during sleep. In addition to discussing the selective effects of sleep on emotional memory and the potential mechanisms underlying these effects, we emphasize the critical implications of this research for educational and vocational settings.

Keywords: consolidation, emotion, memory, reactivation, sleep

Sleep provides an optimal neurobiological environment for memory consolidation (e.g., Diekelmann & Born, 2010; Marshall & Born, 2007; Stickgold, 2005). Rather than uniformly enhancing consolidation, however, sleep ‘selects’ for consolidation the most salient or goal-relevant information (Stickgold & Walker, 2013, for review; Wilhelm et al., 2011). For example, sleep selectively preserves memory

for only the emotionally salient aspect of an experience (Payne & Kensinger, 2010, 2011; Payne, Stickgold, Swanberg, & Kensinger, 2008). Although emotional stimuli are not the only category of information that sleep preferentially consolidates (Ellenbogen, Hu, Payne, Titone, & Walker, 2007; Fischer & Born, 2009), it is a particularly well-studied example and will be the focus of this review.

Here we highlight three potential neural mechanisms (for discussion of other mechanisms, see Stickgold & Walker, 2007) to explain how this selective consolidation occurs. We first discuss the mechanism of reactivation, in which emotionally salient information may be preferentially reactivated during sleep, thus leading to its enhanced consolidation. We then discuss how the neurobiology of REM sleep, and specifically the prominent theta oscillations and changing levels of acetylcholine (ACh) during sleep, may support the reactivation and preferential consolidation of emotional experiences.

Kelly A. Bennion, Department of Psychology, Boston College; Jessica D. Payne, Department of Psychology, University of Notre Dame; Elizabeth A. Kensinger, Department of Psychology, Boston College.

Preparation of this article was aided by Grant BCS-0963581 from the National Science Foundation (to E.A.K. and J.D.P.). The authors thank Katherine Mickley Steinmetz for her helpful discussion.

Correspondence concerning this article should be addressed to Kelly A. Bennion, 140 Commonwealth Avenue, Boston College Psychology, McGuinn 300, Chestnut Hill, MA 02467. E-mail: kelly.bennion@bc.edu

Further, we propose that sleep's selective consolidation effects may be driven by an encoding-based mechanism: Preferentially consolidated information is "selected" at an earlier time point (during encoding), a concept known as *emotional tagging* (Richter-Levin & Akirav, 2003). We explain the evidence for each of these mechanisms and discuss the translational impact of this line of research.

Consolidation-Based Mechanism: Reactivation

Reactivation is a prominent hypothesis explaining sleep-dependent memory consolidation (alternatively, see the *synaptic homeostasis hypothesis*; Tononi & Cirelli, 2006), in which experienced events are 'replayed' during sleep (e.g., Fuentemilla et al., 2013). Animal studies have shown that within the hippocampus, a region critical for consolidation, the neuronal firing patterns that occur during encoding are spontaneously replayed during sleep (Wilson & McNaughton, 1994). Similarly, in humans, brain areas active during learning are subsequently activated during sleep, reflecting the offline processing of memory traces (Maquet et al., 2000).

Although reactivation is often used to explain sleep-dependent consolidation as a whole, not all past events are reactivated. If reactivation underlies consolidation, then only the subset of events that are reactivated would be consolidated. Thus, reactivation may be both a general mechanism of consolidation and also a mechanism that gives rise to its selectivity. Indeed, studies in humans utilizing a *targeted memory reactivation* paradigm (Rudoy, Voss, Westerberg, & Paller, 2009) corroborate the idea that reactivated information tends to be remembered. Moreover, studies in rats provide direct support for the selective reactivation of motivationally relevant information in the hippocampus and ventral striatum during sleep (Lansink et al., 2008; Lansink, Goltstein, Lankelma, McNaughton, & Pennartz, 2009), demonstrating that important information tends to be replayed.

As far as what determines "importance," Oudiette and colleagues (2013) suggest that this generally has to do with the future relevance of the information: Information that is designated as important to remember or rewarded should be preferentially reactivated (Oudiette et al.,

2013). For example, Oudiette and colleagues (2013) instructed participants to remember the location of objects, while manipulating stimuli importance by assigning each object a low or high value that represented future reward for successful memory. During encoding, each object was accompanied by a characteristic sound (i.e., a cat with a "meow" sound). They then reactivated these low- and high-reward associations by playing the corresponding sounds during a 90-min sleep- or wake-filled delay. Results showed that recall accuracy declined to a greater extent for low- than high-reward objects following sleep.

Another interesting finding specific to sleep was that playing half of the sounds associated with low-reward stimuli "rescued" memory for not only the objects whose sounds were replayed, but for the entire set of low-reward associations (Oudiette et al., 2013). This provides additional evidence that reactivation leads to enhanced consolidation, as it is likely that these low-reward stimuli would have been forgotten in the absence of external cueing. However, the generality of reactivation to enhanced memory for all low-value associations (see also Diekelmann, Büchel, Born, & Rasch, 2011; Rasch, Büchel, Gais, & Born, 2007) requires us to revisit the question of what is selected by sleep: Sleep may not select individual items, but rather categorize what we experience, strengthening whole categories based on future relevance. This is consistent with studies investigating the effects of sleep on the *emotion-induced memory trade-off* (Buchanan & Adolphs, 2002; Reisberg & Heuer, 2004), in which sleep pulls apart, or separately categorizes emotional objects and their neutral backgrounds, selectively consolidating the emotional objects (e.g., Payne, Chambers, & Kensinger, 2012). Emotional stimuli fall under the umbrella of information with 'future relevance' because it is evolutionarily important to remember that which is perceived as threatening, arousing, or negative (Lazarus, 1991). Although no study has investigated the effects of cued reactivation on emotional versus nonemotional stimuli, evidence points toward replay during sleep as a likely mechanism underlying the selective facilitation of emotional memory (e.g., Hu, Stylos-Allan, & Walker, 2006).

Research on memory reactivation has important implications for the treatment and potential prevention of many disorders with a dysfunc-

tion in emotional processing at their core. For example, reactivating traumatic memories during sleep may weaken them. Reexposure of an odor initially presented with faces conditioned to be feared led to a decrease in fear responses and hippocampal activity to those faces relative to those whose corresponding odor had not been reinstated, as well as a reorganization of pattern activity in the amygdala from pre- to postsleep (Hauner, Howard, Zelano, & Gottfried, 2013); this suggests a new association had formed between the odor and safety (akin to exposure therapy; Foa, Hembree, & Rothbaum, 2007). This research has applications for PTSD (Oudiette, Antony, & Paller, 2014; however, see Stickgold, 2007), in that attenuating a fear memory could lead to a decrease in memory intrusions. Moreover, this is applicable in depression, social anxiety, and also nonclinical cases in which negative emotional memories interfere with one's well being. Although the conditions in which reactivation can be used to attenuate emotional memories need to be elucidated, it is a promising area of research from both a clinical and nonclinical perspective.

Although effects of targeted memory reactivation are profound, the aforementioned studies are designed to be a manipulation of the processes that spontaneously occur during sleep: Researchers elicit reactivation by using an external cue (e.g., an odor or tone), thus causally enhancing consolidation (e.g., Rasch et al., 2007). Knowing that reactivation also occurs in the absence of an external cue, we now turn to a discussion of the internal neurobiology that may support consolidation during sleep. We focus on emotional memory consolidation because it is a well-studied example of un instructed selection: Without being told it is important to remember, and without knowledge of a memory test, emotionally salient information is preferentially remembered over sleep-filled delays (Payne & Kensinger, 2011).

Consolidation-Based Mechanism: Theta Oscillations and Changing ACh Levels During Sleep

Reactivation occurs during REM sleep: For instance, several brain areas active during a serial reaction time task are subsequently more active during REM sleep in trained relative to nontrained subjects (Maquet et al., 2000), pro-

viding evidence for the processing of memory traces. Although this is not specific to REM sleep, understanding its neurobiological characteristics may elucidate why reactivation (and similarly, selective consolidation) occurs.

Studying emotional memory consolidation is a particularly fruitful means of better understanding the neurobiological characteristics of REM sleep that may underlie reactivation because REM sleep is strongly associated with emotional memory enhancements (Ackermann & Rasch, 2014). [However, slow-wave sleep (SWS) also has a profound role in consolidation (Gais & Born, 2004), including emotional memory consolidation (Cairney, Durrant, Power, & Lewis, 2014)]. We propose that two features of REM sleep—theta oscillations that may enable prefrontal-limbic connections, and a high cholinergic tone—may make it the ideal neurochemical environment for reactivation and selective emotional memory consolidation. During REM sleep, high-amplitude theta oscillations (4–8 Hz) in the basolateral amygdala (BLA) and hippocampus are observed and highly correlated (Paré, Collins, & Pelletier, 2002), and are proposed to reflect replay of theta activity during waking experiences (Louie & Wilson, 2001). Amygdala and hippocampal theta are also highly correlated during emotional arousal and recall of conditioned fear (Seidenbecher, Laxmi, Stork, & Pape, 2003), likely resulting in a modulation of memory consolidation. Further, theta oscillations also occur within the PFC, and communication between PFC and limbic regions may be critical for optimized consolidation. For example, the degree of theta activity in hippocampus-PFC-BLA networks during REM sleep correlates with the success of fear conditioning in rats (Popa, Duvarci, Popescu, Léna, & Paré, 2010). Similarly, correlations between prefrontal theta during REM sleep and the emotional memory enhancement are suggested to represent cross-talk between the PFC and limbic structures during consolidation (Jones & Wilson, 2005), with the extent of communication predicting the emotional memory enhancement (Nishida, Pearsall, Buckner, & Walker, 2009).

Consistent with the idea that PFC-limbic connections during sleep underlie selective emotional memory consolidation are studies showing that after a night of sleep, activity and connectivity is enhanced in the PFC and amygdala during emotional memory retrieval.

Particularly, [Payne and Kensinger \(2011\)](#) found that consolidation over a night of sleep, relative to a day awake, is associated with enhanced activity in a refined set of regions, including the amygdala and ventromedial PFC (vmPFC) during the retrieval of negative stimuli. After sleep compared with wake, there was enhanced amygdala-hippocampal and amygdala-vmPFC connectivity. These findings parallel those of [Sterpenich and colleagues \(2009\)](#), in which participants either slept or were deprived of sleep after encoding negative and neutral images. After a 6-month delay, those who had slept after encoding showed enhanced amygdala and vmPFC activity and amygdala-vmPFC connectivity during emotional memory retrieval relative to those who were sleep-deprived. Although [Payne and Kensinger \(2011\)](#) and [Sterpenich and colleagues \(2009\)](#) did not focus on REM sleep specifically, the synchronized activity between the amygdala, hippocampus, and neocortical regions that characterizes REM sleep ([Jones & Wilson, 2005](#); [Paré et al., 2002](#)) suggests that REM sleep likely played a role in this selective emotional memory consolidation. As such, the coordination of prefrontal and limbic processes during REM sleep is a likely mechanism underlying selective consolidation.

The second feature of REM sleep that may enable it to be the ideal neurochemical environment to preferentially consolidate emotional information relates to the change in levels of ACh in the transitions from SWS to REM sleep, and the amount of ACh during REM sleep. It is hypothesized that ACh regulates the flow of information between the hippocampus and neocortex, and that shifts in information flow, between the low levels of ACh during SWS to high levels of ACh during REM sleep ([Hobson & Pace-Schott, 2002](#)) are a critical part of long-term consolidation ([Gais & Born, 2004](#); [Hasselmo, 1999](#)). Given the prominent role of ACh in the long-term consolidation of emotionally arousing experiences ([McGaugh, 2004](#); [Power, 2004](#)), the high cholinergic state that characterizes REM sleep provides an ideal environment for selective emotional memory consolidation. ACh enhances amygdala-dependent consolidation, such that infusing muscarinic cholinergic agonists into the amygdala enhances memory across inhibitory avoidance and fear conditioning tasks ([Introini-Collison, Dalmaz, & McGaugh, 1996](#)). Also, blocking cholinergic activ-

ity with scopolamine (an ACh antagonist) during REM sleep impairs consolidation of an avoidance task learned before sleep ([Smith, Tenn, & Annett, 1991](#)). It is important to note, however, that the effects of sleep on emotional memory are not exclusive to REM sleep (e.g., [Cairney et al., 2014](#)), and that low ACh levels that characterize SWS are critical for consolidation of neutral stimuli ([Gais & Born, 2004](#)). Although REM sleep has to date been most strongly correlated with emotional memory consolidation, understanding the chemical and physiological differences between sleep stages, particularly regarding theta rhythms and ACh levels, is essential in elucidating the mechanisms behind observed sleep stage effects.

Because the theta oscillations that characterize REM sleep facilitate interactions between limbic and paralimbic structures (including the hippocampus and amygdala; [Walker & van der Helm, 2009](#)) that support emotional memory consolidation, it is possible that REM sleep deprivation may prevent the selective consolidation of emotional memory (e.g., [Diekelmann, Wilhelm, & Born, 2009](#); [Wagner, Hallschmid, Rasch, & Born, 2006](#); but see [Morgenthaler et al., 2014](#)). This is applicable to both clinical (e.g., depression, anxiety, PTSD) and nonclinical cases in which memory of a negative or traumatic event could theoretically be weakened by selective REM deprivation. Also, as REM sleep has been found to correlate with emotional reactivity to negative stimuli ([Baran, Pace-Schott, Ericson, & Spencer, 2012](#)), it is possible that REM sleep deprivation after a trauma may help attenuate one's emotional response to it. However, there are potential confounds and important considerations to take into account when targeting sleep deprivation (reviewed by [Horne, 2000](#)), including distinguishing between effects attributable to lack of REM sleep versus diminished total sleep time, and accounting for the stress response that can accompany sleep deprivation (e.g., [Leproult, Co-pinschi, Buxton, & van Cauter, 1997](#)).

Encoding-Based Mechanism: Emotional Tagging and the Role of Cortisol

Having discussed two consolidation-based mechanisms that result in the reactivation and preferential facilitation of emotional memory, it is still unclear what provides the signal that this

information should be selectively replayed and strengthened during sleep in the first place. Here we suggest that information that is preferentially consolidated during sleep is “selected” at an earlier time point—during encoding. This concept, known as *emotional tagging* (Richter-Levin & Akirav, 2003), suggests that the arousal generated by an emotional experience “tags” a salient event at encoding, leading to its prioritized consolidation during sleep.

The ‘emotional tag’ is related to the better known concept of synaptic tagging, which is widely used to explain how events become stored in long-term memory: Synapses activated by a learning experience are “tagged” with a molecular marker, ensuring that the plasticity-related proteins necessary for long-term memory are captured by these synapses and not others (e.g., Frey & Morris, 1997). This process ensures the specificity of long-term potentiation. Relatedly, a tagging mechanism is thought to underlie why typically forgotten information (e.g., the weather on this date five years ago) is remembered when associated with an emotional event (e.g., the weather on your graduation day five years ago): The encoding of an arousing event activates the amygdala, resulting in long-term plasticity in the synapses marked by the tag (Bergado, Lucas, & Richter-Levin, 2011; Wang & Morris, 2010). However, what exactly is this emotional tag?

It has long been known that emotional experiences activate the amygdala during encoding (LeDoux, 2000), and that the amygdala modulates hippocampal-based learning (Buchanan & Adolphs, 2002). Specifically, epinephrine and corticosterone (cortisol in humans) activate adrenergic receptors in the BLA, which modulate the effect of these hormones on consolidation (McGaugh, 2004; McGaugh & Roozendaal, 2002). It is possible that the amygdala-hippocampal interaction (not only the activation of the amygdala during encoding, but also subsequent amygdala-hippocampal connectivity) is the emotional tag, and that certain circumstances, such as an optimized level of cortisol, must be met to ensure that this tag is set during the initial experiencing of the event.

Building on the concept that emotional arousal potentiates the preferential consolidation of the emotional aspects of an experience, recent work has shown that endogenous cortisol may help set these emotional tags (Bennion,

Mickley Steinmetz, Kensinger, & Payne, 2015). Specifically, elevated cortisol at encoding works with the arousal generated by the emotional stimuli themselves, thus setting a tag that essentially selects this information for preferential processing. A study by van Stegeren and colleagues (2007) aligns with this idea, in which participants with higher endogenous cortisol levels exhibited stronger amygdala responses to emotional images than those with lower endogenous cortisol levels (van Stegeren et al., 2007). Critically, administration of the noradrenergic antagonist propranolol blocked this cortisol-dependent amygdala activation, suggesting that interactions with arousal-induced noradrenergic activation in the amygdala (Roozendaal, Bars-egyan, & Lee, 2007) and perhaps the consequent strengthening of connections among the amygdala, hippocampus, and prefrontal regions (van Stegeren, 2009) may be necessary for cortisol to have an enhancing effect on emotional memory consolidation.

Knowing that elevated cortisol during encoding, combined with arousal and noradrenergic activation associated with viewing negative stimuli (Abercrombie, Speck, & Monticelli, 2006; Roozendaal, Okuda, van der Zee, & McGaugh, 2006), may be critical for setting an emotional tag, it then becomes important to clarify whether sleep subsequently uses this tag to select which information to preferentially consolidate. Bennion and colleagues (2015) collected salivary cortisol samples from participants before an encoding task in which they viewed emotional and neutral scenes while their eyes were tracked. The scenes were composed of a negative (e.g., taxi accident) or neutral (e.g., taxi) item superimposed on a plausible neutral background (e.g., an avenue). Encoding took place either in the evening, followed by a night asleep, or in the morning, followed by a day awake. After a 12-hr delay, participants took a recognition test during fMRI that assessed object and background memory separately.

Elevated cortisol at encoding led to enhanced memory for the emotional items, but only if participants slept during consolidation. This suggests that cortisol interacts with sleep to enhance, and perhaps even enable, consolidation benefits, as such benefits are not observed following a delay containing wakefulness. In addition, elevated cortisol led to a stronger re-

lation between looking time at encoding and subsequent memory for negative items following sleep relative to wake. This suggests that cortisol facilitates memory for negative stimuli by strengthening the relation between how long participants look at the items during encoding and their ability to later remember them, especially when sleep occurs during the retention interval. Furthermore, those with higher cortisol at encoding showed a stronger relation between the time spent looking at negative items during encoding and intensified activity in emotional processing regions (particularly the amygdala and vmPFC) during successful retrieval of those negative items following sleep but not wake (Bennion et al., 2015). This unique state of encoding resulted in activity in the same smaller set of limbic regions that supports successful emotional memory retrieval after sleep relative to wake (Payne & Kensinger, 2011; Sterpenich et al., 2009), suggesting a possible attentional mechanism for this selective emotional memory benefit.

Although there still is much to be understood about how an emotional tag created at encoding leads to the strengthening of the “tagged” information during sleep (including what the optimal level of cortisol is for this tagging to occur; e.g., see Sandi, 2013), this suggests that selective consolidation during sleep depends not only on informational content, but also on the state of the individual experiencing the event. Indeed, elevations in both cortisol (Bennion et al., 2015) and physiological arousal (see Cunningham et al., 2014) during the time of encoding provide the optimal state for downstream sleep-based memory consolidation (and particularly emotional memory consolidation). As such, encoding emotional information in the presence of elevated cortisol (and likely other arousal-related neuromodulators), perhaps whether intentionally encoding (e.g., watching news coverage of a tragedy) or unintentionally encoding (e.g., being involved in a tragedy), may lead to greater emotional memory following sleep compared to if encoding while cortisol levels are lower.

Conclusions and Broader Implications

Here we have discussed three related mechanisms—each selecting aspects of experiences to preferentially strengthen, while allowing

other information to decay. This selection process may first occur at encoding, with cortisol and other arousal-related neuromodulators aiding in ‘tagging’ an emotionally salient event as important to remember. Then, this information is prioritized during sleep, through reactivation, and likely enabled by theta oscillations and high ACh levels during REM sleep. Although we have focused on the selective effects of emotional memory consolidation, this research suggests a more general conclusion, in that sleep is smart: It does not consolidate all information equally, but rather selectively preserves memory for information of future relevance (whether that be rewarded, emotional, instructed to be remembered, etc.). Here we outline concrete recommendations to allow educators, students, and employers to utilize what we know about sleep as a tool to enhance functioning in educational and vocational settings.

Information we prioritize during the day is more likely to be reactivated during sleep (Oudiette & Paller, 2013), suggesting that information that is rewarded, valued, or salient is preferentially facilitated during sleep. What this means for educators is that it is critical to highlight important information so that it is clear what should be salient during a class period or when completing a long reading assignment. Emphasizing what information should be remembered, and also giving assignments that require students to review (i.e., reactivate) the most pertinent material, is likely to lead to a preferential strengthening of that information during sleep. Further, because sleep tends to enhance information encountered relatively recently (only a few hours prior to sleep; Gais, Lucas, & Born, 2006), such homework or reading exercises may be most effective when completed close to bedtime.

Given the positive consequences of strengthening memory during sleep, this also provides evidence for why sleep deprivation, a pervasive problem in today’s society, should be avoided. Even mild sleep deprivation can be pernicious because REM sleep occurs in increasing percentages over the course of a night, and tends to be lost during chronic sleep restriction (i.e., 4–7 hours of nightly sleep; Banks & Dinges, 2007). Thus, losing just a few hours of sleep each night can disrupt the ability for selective consolidation, leading to less efficient memory systems. Although some steps can be taken at home to

combat sleep deprivation, educators and employers should consider a shift in start times to better align with circadian rhythms and sleep needs. For instance, even a 30-min delay in school start time is sufficient to result in improvements in alertness, mood, and health in adolescents (Owens, Belon, & Moss, 2010), an age group particularly at-risk for sleep deprivation because their circadian rhythms naturally cause them to feel alert at night and therefore have difficulty maintaining an early bedtime. Additionally, *flex-time*, which involves not a reduction in work hours, but simply a rearrangement or shift in schedule that is mutually agreed on by the employer and employee, has been shown to result in an average increase of 52 minutes of nightly sleep, as well as enhanced sleep quality, energy levels, self-report health, and decreased personal distress (Moen, Kelly, Tranby, & Huang, 2011). In addition to these health benefits, better sleep would lead to employees being able to extract important information for preferential consolidation, thus leading to more efficient work. If it is not feasible to implement such a shift, allowing employees to take daytime naps may be a helpful alternative, as the effects of a nap on strengthening memory are comparable with that of overnight sleep (e.g., Alger, Lau, & Fishbein, 2010; Backhaus & Junghanns, 2006).

Although sleep is smart, selectively preserving memory for information of future relevance, we as rememberers can take steps to make it smarter. Sleep already helps us preferentially remember these experiences, but understanding the mechanisms behind its selectivity may have powerful consequences—not only in science, but also in education, work, health, and everyday life.

References

- Abercrombie, H. C., Speck, N. S., & Monticelli, R. M. (2006). Endogenous cortisol elevations are related to memory facilitation only in individuals who are emotionally aroused. *Psychoneuroendocrinology*, *31*, 187–196. <http://dx.doi.org/10.1016/j.psycheneu.2005.06.008>
- Ackermann, S., & Rasch, B. (2014). Differential effects of non-REM and REM sleep on memory consolidation? *Current Neurology and Neuroscience Reports*, *14*, 430. <http://dx.doi.org/10.1007/s11910-013-0430-8>
- Alger, S. E., Lau, H., & Fishbein, W. (2010). Delayed onset of a daytime nap facilitates retention of declarative memory. *PLoS ONE*, *5*, e12131. <http://dx.doi.org/10.1371/journal.pone.0012131>
- Backhaus, J., & Junghanns, K. (2006). Daytime naps improve procedural motor memory. *Sleep Medicine*, *7*, 508–512. <http://dx.doi.org/10.1016/j.sleep.2006.04.002>
- Banks, S., & Dinges, D. F. (2007). Behavioral and physiological consequences of sleep restriction. *Journal of Clinical Sleep Medicine*, *3*, 519–528.
- Baran, B., Pace-Schott, E. F., Ericson, C., & Spencer, R. M. (2012). Processing of emotional reactivity and emotional memory over sleep. *The Journal of Neuroscience*, *32*, 1035–1042. <http://dx.doi.org/10.1523/JNEUROSCI.2532-11.2012>
- Bennion, K. A., Mickley Steinmetz, K. R., Kensinger, E. A., & Payne, J. D. (2015). Sleep and cortisol interact to support memory consolidation. *Cerebral Cortex*, *25*, 646–657. <http://dx.doi.org/10.1093/cercor/bht255>
- Bergado, J. A., Lucas, M., & Richter-Levin, G. (2011). Emotional tagging—A simple hypothesis in a complex reality. *Progress in Neurobiology*, *94*, 64–76. <http://dx.doi.org/10.1016/j.pneurobio.2011.03.004>
- Buchanan, T. W., & Adolphs, R. (2002). The role of the human amygdala in emotional modulation of long-term declarative memory. In S. Moore & M. Oaksford (Eds.), *Emotional cognition: From brain to behavior* (pp. 9–34). London, UK: Benjamins. <http://dx.doi.org/10.1075/aicr.44.02buc>
- Cairney, S. A., Durrant, S. J., Power, R., & Lewis, P. A. (2014). Complementary roles of slow-wave sleep and rapid eye movement sleep in emotional memory consolidation. *Cerebral Cortex*. Advance online publication. <http://dx.doi.org/10.1093/cercor/bht349>
- Cunningham, T. J., Crowell, C. R., Alger, S. E., Kensinger, E. A., Villano, M. A., Mattingly, S. M., & Payne, J. D. (2014). Psychophysiological arousal at encoding leads to reduced reactivity but enhanced emotional memory following sleep. *Neurobiology of Learning and Memory*, *114*, 155–164. <http://dx.doi.org/10.1016/j.nlm.2014.06.002>
- Diekelmann, S., & Born, J. (2010). The memory function of sleep. *Nature Reviews Neuroscience*, *11*, 114–126.
- Diekelmann, S., Büchel, C., Born, J., & Rasch, B. (2011). Labile or stable: Opposing consequences for memory when reactivated during waking and sleep. *Nature Neuroscience*, *14*, 381–386. <http://dx.doi.org/10.1038/nn.2744>
- Diekelmann, S., Wilhelm, I., & Born, J. (2009). The whats and whens of sleep-dependent memory consolidation. *Sleep Medicine Reviews*, *13*, 309–321. <http://dx.doi.org/10.1016/j.smrv.2008.08.002>

- Ellenbogen, J. M., Hu, P. T., Payne, J. D., Titone, D., & Walker, M. P. (2007). Human relational memory requires time and sleep. *PNAS Proceedings of the National Academy of Sciences of the United States of America*, *104*, 7723–7728. <http://dx.doi.org/10.1073/pnas.0700094104>
- Fischer, S., & Born, J. (2009). Anticipated reward enhances offline learning during sleep. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*, 1586–1593. <http://dx.doi.org/10.1037/a0017256>
- Foa, E., Hembree, E., & Rothbaum, B. O. (2007). *Prolonged exposure therapy for PTSD: Emotional processing of traumatic experiences therapist guide*. New York, NY: Oxford University Press.
- Frey, U., & Morris, R. G. (1997). Synaptic tagging and long-term potentiation. *Nature*, *385*, 533–536. <http://dx.doi.org/10.1038/385533a0>
- Fuentemilla, L., Miró, J., Ripollés, P., Vilà-Balló, A., Juncadella, M., Castañer, S., . . . Rodríguez-Fornells, A. (2013). Hippocampus-dependent strengthening of targeted memories via reactivation during sleep in humans. *Current Biology*, *23*, 1769–1775. <http://dx.doi.org/10.1016/j.cub.2013.07.006>
- Gais, S., & Born, J. (2004). Low acetylcholine during slow-wave sleep is critical for declarative memory consolidation. *PNAS Proceedings of the National Academy of Sciences of the United States of America*, *101*, 2140–2144. <http://dx.doi.org/10.1073/pnas.0305404101>
- Gais, S., Lucas, B., & Born, J. (2006). Sleep after learning aids memory recall. *Learning & Memory (Cold Spring Harbor, N. Y.)*, *13*, 259–262. <http://dx.doi.org/10.1101/lm.132106>
- Hasselmo, M. E. (1999). Neuromodulation: Acetylcholine and memory consolidation. *Trends in Cognitive Sciences*, *3*, 351–359. [http://dx.doi.org/10.1016/S1364-6613\(99\)01365-0](http://dx.doi.org/10.1016/S1364-6613(99)01365-0)
- Hauer, K. K., Howard, J. D., Zelano, C., & Gottfried, J. A. (2013). Stimulus-specific enhancement of fear extinction during slow-wave sleep. *Nature Neuroscience*, *16*, 1553–1555. <http://dx.doi.org/10.1038/nn.3527>
- Hobson, J. A., & Pace-Schott, E. F. (2002). The cognitive neuroscience of sleep: Neuronal systems, consciousness and learning. *Nature Reviews Neuroscience*, *3*, 679–693. <http://dx.doi.org/10.1038/nrn915>
- Horne, J. A. (2000). REM sleep - by default? *Neuroscience and Biobehavioral Reviews*, *24*, 777–797. [http://dx.doi.org/10.1016/S0149-7634\(00\)00037-3](http://dx.doi.org/10.1016/S0149-7634(00)00037-3)
- Hu, P., Stylos-Allan, M., & Walker, M. P. (2006). Sleep facilitates consolidation of emotional declarative memory. *Psychological Science*, *17*, 891–898. <http://dx.doi.org/10.1111/j.1467-9280.2006.01799.x>
- Introini-Collison, I. B., Dalmaz, C., & McGaugh, J. L. (1996). Amygdala β -noradrenergic influences on memory storage involve cholinergic activation. *Neurobiology of Learning and Memory*, *65*, 57–64. <http://dx.doi.org/10.1006/nlme.1996.0006>
- Jones, M. W., & Wilson, M. A. (2005). Theta rhythms coordinate hippocampal-prefrontal interactions in a spatial memory task. *PLoS Biology*, *3*, e402. <http://dx.doi.org/10.1371/journal.pbio.0030402>
- Lansink, C. S., Goltstein, P. M., Lankelma, J. V., Joosten, R. N., McNaughton, B. L., & Pennartz, C. M. (2008). Preferential reactivation of motivationally relevant information in the ventral striatum. *The Journal of Neuroscience*, *28*, 6372–6382. <http://dx.doi.org/10.1523/JNEUROSCI.1054-08.2008>
- Lansink, C. S., Goltstein, P. M., Lankelma, J. V., McNaughton, B. L., & Pennartz, C. M. (2009). Hippocampus leads ventral striatum in replay of place-reward information. *PLoS Biology*, *7*, e1000173. <http://dx.doi.org/10.1371/journal.pbio.1000173>
- Lazarus, R. S. (1991). *Emotion and adaptation*. New York, NY: Oxford University Press.
- LeDoux, J. E. (2000). Emotion circuits in the brain. *Annual Review of Neuroscience*, *23*, 155–184. <http://dx.doi.org/10.1146/annurev.neuro.23.1.155>
- Leproult, R., Copinschi, G., Buxton, O., & Van Cauter, E. (1997). Sleep loss results in an elevation of cortisol levels the next evening. *Sleep: Journal of Sleep Research & Sleep Medicine*, *20*, 865–870.
- Louie, K., & Wilson, M. A. (2001). Temporally structured replay of awake hippocampal ensemble activity during rapid eye movement sleep. *Neuron*, *29*, 145–156. [http://dx.doi.org/10.1016/S0896-6273\(01\)00186-6](http://dx.doi.org/10.1016/S0896-6273(01)00186-6)
- Maquet, P., Laureys, S., Peigneux, P., Fuchs, S., Petiau, C., Phillips, C., . . . Cleeremans, A. (2000). Experience-dependent changes in cerebral activation during human REM sleep. *Nature Neuroscience*, *3*, 831–836. <http://dx.doi.org/10.1038/77744>
- Marshall, L., & Born, J. (2007). The contribution of sleep to hippocampus-dependent memory consolidation. *Trends in Cognitive Sciences*, *11*, 442–450. <http://dx.doi.org/10.1016/j.tics.2007.09.001>
- McGaugh, J. L. (2004). The amygdala modulates the consolidation of memories of emotionally arousing experiences. *Annual Review of Neuroscience*, *27*, 1–28. <http://dx.doi.org/10.1146/annurev.neuro.27.070203.144157>
- McGaugh, J. L., & Roozendaal, B. (2002). Role of adrenal stress hormones in forming lasting memories in the brain. *Current Opinion in Neurobiology*, *12*, 205–210. [http://dx.doi.org/10.1016/S0959-4388\(02\)00306-9](http://dx.doi.org/10.1016/S0959-4388(02)00306-9)
- Moen, P., Kelly, E. L., Tranby, E., & Huang, Q. (2011). Changing work, changing health: Can real

- work-time flexibility promote health behaviors and well-being? *Journal of Health and Social Behavior*, 52, 404–429. <http://dx.doi.org/10.1177/0022146511418979>
- Morgenthaler, J., Wiesner, C. D., Hinze, K., Abels, L. C., Prehn-Kristensen, A., & Göder, R. (2014). Selective REM-sleep deprivation does not diminish emotional memory consolidation in young healthy subjects. *PLoS ONE*, 9, e89849. <http://dx.doi.org/10.1371/journal.pone.0089849>
- Nishida, M., Pearsall, J., Buckner, R. L., & Walker, M. P. (2009). REM sleep, prefrontal theta, and the consolidation of human emotional memory. *Cerebral Cortex*, 19, 1158–1166. <http://dx.doi.org/10.1093/cercor/bhn155>
- Oudiette, D., Antony, J. W., Creery, J. D., & Paller, K. A. (2013). The role of memory reactivation during wakefulness and sleep in determining which memories endure. *The Journal of Neuroscience*, 33, 6672–6678. <http://dx.doi.org/10.1523/JNEUROSCI.5497-12.2013>
- Oudiette, D., Antony, J. W., & Paller, K. A. (2014). Fear not: Manipulating sleep might help you forget. *Trends in Cognitive Sciences*, 18, 3–4. <http://dx.doi.org/10.1016/j.tics.2013.10.003>
- Oudiette, D., & Paller, K. A. (2013). Upgrading the sleeping brain with targeted memory reactivation. *Trends in Cognitive Sciences*, 17, 142–149. <http://dx.doi.org/10.1016/j.tics.2013.01.006>
- Owens, J. A., Belon, K., & Moss, P. (2010). Impact of delaying school start time on adolescent sleep, mood, and behavior. *Archives of Pediatrics & Adolescent Medicine*, 164, 608–614. <http://dx.doi.org/10.1001/archpediatrics.2010.96>
- Paré, D., Collins, D. R., & Pelletier, J. G. (2002). Amygdala oscillations and the consolidation of emotional memories. *Trends in Cognitive Sciences*, 6, 306–314. [http://dx.doi.org/10.1016/S1364-6613\(02\)01924-1](http://dx.doi.org/10.1016/S1364-6613(02)01924-1)
- Payne, J. D., Chambers, A. M., & Kensinger, E. A. (2012). Sleep promotes lasting changes in selective memory for emotional scenes. *Frontiers in Integrative Neuroscience*, 6, 108. <http://dx.doi.org/10.3389/fnint.2012.00108>
- Payne, J. D., & Kensinger, E. A. (2010). Sleep's role in the consolidation of emotional episodic memories. *Current Directions in Psychological Science*, 19, 290–295. <http://dx.doi.org/10.1177/0963721410383978>
- Payne, J. D., & Kensinger, E. A. (2011). Sleep leads to changes in the emotional memory trace: Evidence from fMRI. *Journal of Cognitive Neuroscience*, 23, 1285–1297. <http://dx.doi.org/10.1162/jocn.2010.21526>
- Payne, J. D., Stickgold, R., Swanberg, K., & Kensinger, E. A. (2008). Sleep preferentially enhances memory for emotional components of scenes. *Psychological Science*, 19, 781–788. <http://dx.doi.org/10.1111/j.1467-9280.2008.02157.x>
- Popa, D., Duvarci, S., Popescu, A. T., Léna, C., & Paré, D. (2010). Coherent amygdalocortical theta promotes fear memory consolidation during paradoxical sleep. *PNAS Proceedings of the National Academy of Sciences of the United States of America*, 107, 6516–6519. <http://dx.doi.org/10.1073/pnas.0913016107>
- Power, A. E. (2004). Slow-wave sleep, acetylcholine, and memory consolidation. *PNAS Proceedings of the National Academy of Sciences of the United States of America*, 101, 1795–1796. <http://dx.doi.org/10.1073/pnas.0400237101>
- Rasch, B., Büchel, C., Gais, S., & Born, J. (2007). Odor cues during slow-wave sleep prompt declarative memory consolidation. *Science*, 315, 1426–1429. <http://dx.doi.org/10.1126/science.1138581>
- Reisberg, D., & Heuer, F. (2004). Remembering emotional events. In D. Reisberg & P. Hertel (Eds.), *Memory and emotion* (pp. 3–41). New York, NY: Oxford University Press. <http://dx.doi.org/10.1093/acprof:oso/9780195158564.003.0001>
- Richter-Levin, G., & Akirav, I. (2003). Emotional tagging of memory formation—In the search for neural mechanisms. *Brain Research Reviews*, 43, 247–256. <http://dx.doi.org/10.1016/j.brainresrev.2003.08.005>
- Roosendaal, B., Barsegyan, A., & Lee, S. (2007). Adrenal stress hormones, amygdala activation, and memory for emotionally arousing experiences. *Progress in Brain Research*, 167, 79–97. [http://dx.doi.org/10.1016/S0079-6123\(07\)67006-X](http://dx.doi.org/10.1016/S0079-6123(07)67006-X)
- Roosendaal, B., Okuda, S., Van der Zee, E. A., & McGaugh, J. L. (2006). Glucocorticoid enhancement of memory requires arousal-induced noradrenergic activation in the basolateral amygdala. *PNAS Proceedings of the National Academy of Sciences of the United States of America*, 103, 6741–6746. <http://dx.doi.org/10.1073/pnas.0601874103>
- Rudoy, J. D., Voss, J. L., Westerberg, C. E., & Paller, K. A. (2009). Strengthening individual memories by reactivating them during sleep. *Science*, 326, 1079. <http://dx.doi.org/10.1126/science.1179013>
- Sandi, C. (2013). Stress and cognition. *Wiley Interdisciplinary Reviews: Cognitive Science*, 4, 245–261. <http://dx.doi.org/10.1002/wcs.1222>
- Seidenbecher, T., Laxmi, T. R., Stork, O., & Pape, H. C. (2003). Amygdalar and hippocampal theta rhythm synchronization during fear memory retrieval. *Science*, 301, 846–850. <http://dx.doi.org/10.1126/science.1085818>
- Smith, C., Tenn, C., & Annett, R. (1991). Some biochemical and behavioural aspects of the paradoxical sleep window. *Canadian Journal of Psy-*

- chology/Revue Canadienne de Psychologie, 45, 115.
- Sterpenich, V., Albouy, G., Darsaud, A., Schmidt, C., Vandewalle, G., Dang Vu, T. T., . . . Maquet, P. (2009). Sleep promotes the neural reorganization of remote emotional memory. *The Journal of Neuroscience*, 29, 5143–5152. <http://dx.doi.org/10.1523/JNEUROSCI.0561-09.2009>
- Stickgold, R. (2005). Sleep-dependent memory consolidation. *Nature*, 437, 1272–1278. <http://dx.doi.org/10.1038/nature04286>
- Stickgold, R. (2007). Of sleep, memories and trauma. *Nature Neuroscience*, 10, 540–542. <http://dx.doi.org/10.1038/nn0507-540>
- Stickgold, R., & Walker, M. P. (2007). Sleep-dependent memory consolidation and reconsolidation. *Sleep Medicine*, 8, 331–343. <http://dx.doi.org/10.1016/j.sleep.2007.03.011>
- Stickgold, R., & Walker, M. P. (2013). Sleep-dependent memory triage: Evolving generalization through selective processing. *Nature Neuroscience*, 16, 139–145. <http://dx.doi.org/10.1038/nn.3303>
- Tononi, G., & Cirelli, C. (2006). Sleep function and synaptic homeostasis. *Sleep Medicine Reviews*, 10, 49–62. <http://dx.doi.org/10.1016/j.smrv.2005.05.002>
- van Stegeren, A. H. (2009). Imaging stress effects on memory: A review of neuroimaging studies. *The Canadian Journal of Psychiatry / La Revue canadienne de psychiatrie*, 54, 16–27.
- van Stegeren, A. H., Wolf, O. T., Everaerd, W., Scheltens, P., Barkhof, F., & Rombouts, S. A. (2007). Endogenous cortisol level interacts with noradrenergic activation in the human amygdala. *Neurobiology of Learning and Memory*, 87, 57–66. <http://dx.doi.org/10.1016/j.nlm.2006.05.008>
- Wagner, U., Hallschmid, M., Rasch, B., & Born, J. (2006). Brief sleep after learning keeps emotional memories alive for years. *Biological Psychiatry*, 60, 788–790. <http://dx.doi.org/10.1016/j.biopsych.2006.03.061>
- Walker, M. P., & van der Helm, E. (2009). Overnight therapy? The role of sleep in emotional brain processing. *Psychological Bulletin*, 135, 731–748. <http://dx.doi.org/10.1037/a0016570>
- Wang, S. H., & Morris, R. G. (2010). Hippocampal-neocortical interactions in memory formation, consolidation, and reconsolidation. *Annual Review of Psychology*, 61, 49–79. <http://dx.doi.org/10.1146/annurev.psych.093008.100523>
- Wilhelm, I., Diekelmann, S., Molzow, I., Ayoub, A., Mölle, M., & Born, J. (2011). Sleep selectively enhances memory expected to be of future relevance. *The Journal of Neuroscience*, 31, 1563–1569. <http://dx.doi.org/10.1523/JNEUROSCI.3575-10.2011>
- Wilson, M. A., & McNaughton, B. L. (1994). Reactivation of hippocampal ensemble memories during sleep. *Science*, 265, 676–679. <http://dx.doi.org/10.1126/science.8036517>

Received March 24, 2014

Revision received November 3, 2014

Accepted November 5, 2014 ■