Strengthening Individual Memories by Reactivating Them During Sleep

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Initially fragile memories can gain stability via consolidation, but the extent to which sleep contributes to this process is unresolved (*1*, *2*). Sleep between encoding and retrieval, relative to wakefulness, promotes memory storage in some circumstances, perhaps from internally generated memory reactivation (*3*, *4*). Moreover, reinstating a learning context (an odor) during slow-wave sleep enhances retrieval of spatial information learned in that context (*5*). It remains unclear whether exposure during sleep to cues associated with newly learned information can selectively enhance the storage of individual memories.

We taught people to associate each of 50 unique object images with a location on a computer screen before a nap (Fig. 1A). Each object was paired with a characteristic sound delivered over a speaker (e.g., cat with meow and kettle with whistle). For the entirety of the nap, white noise was presented at an unobtrusive intensity (about 62 dB sound-pressure level). During non–rapid eye movement (non-REM) sleep, the sounds for 25 of the objects were presented, with white-noise intensity lowered such that overall sound levels were approximately constant (Fig. 1B).

After waking, individuals viewed all 50 objects and attempted to position each one in its original location. Absolute distance measures showed that object placements were more accurate for objects that were cued by their sounds during sleep than for those not cued [1.07 ± 0.08 cm (SE) versus 1.23 ± 0.10 cm (SE), respectively; t_{11} = 2.6; $P < 0.05$]. Forgetting occurred between the final stage of learning and the postnap test, with a smaller decline for cued compared with uncued objects (Fig. 1C). An advantage for cued-object locations computed in this manner was evident in 10 of the 12 participants.

Electroencephalographic (EEG) recordings provided information for determining sleep stages (*6*). Additionally, EEG responses to sound cues were sorted into two conditions via a median split on the difference between pre- and postnap accuracy: (i) less-forgetting accuracy was superior postnap compared with prenap [placements 0.51 ± 0.1 cm (SE) closer to correct]; (ii) more-forgetting accuracy was superior prenap compared with postnap [placements 0.60 ± 0.1 cm (SE) closer to correct]. Average EEG amplitudes measured over the interval from 600 to 1000 ms after sound onset were 15.3 μV greater when there was less forgetting (t_{11} = 3.2, $P < 0.01$). Thus, the degree of recall improvement or decline appeared to have been influenced by sound-induced memory processing during sleep, as indexed by brain potentials.

Participants professed no knowledge that sounds were presented during sleep. Moreover, they performed at chance when forced to guess which sounds were presented during sleep (*6*).

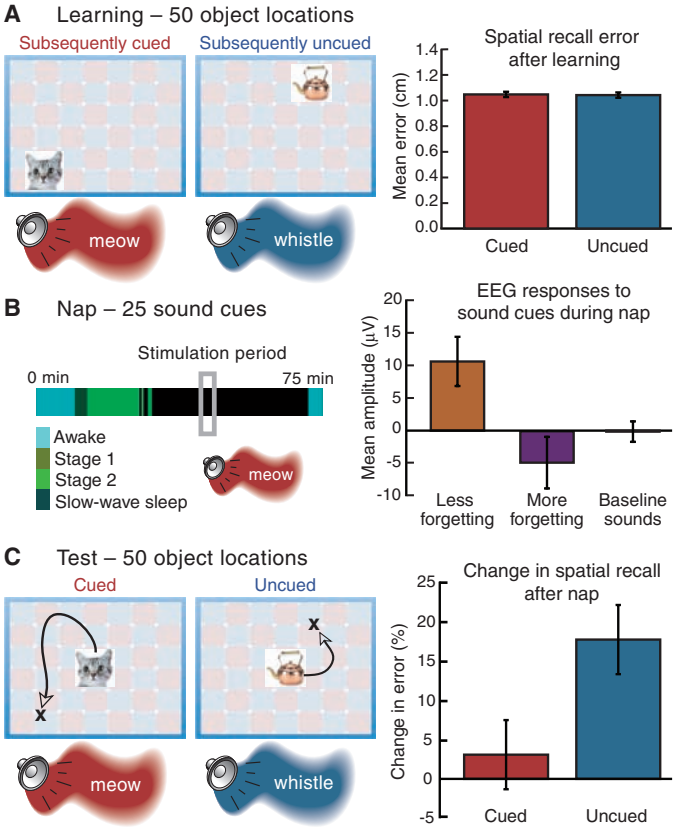

Fig. 1. (**A**) Individuals learned object-location associations while hearing object sounds. Accuracy at the final stage of learning was matched for objects subsequently cued or not cued by the sounds (mean ± SE). (**B**) Sleep-staging data are shown for a representative participant, including the 3.5-min sequence of 25 sound cues. Vertex brain potentials differed according to level of forgetting for corresponding object locations. (**C**) After the nap, individuals attempted to place each object in its correct location (arrows simulate motion of objects as individuals complete the task). Better spatial-location retention for cued compared with uncued objects was reflected by a smaller change in error (t_{11} = 3.2, $P < 0.01$).

These results show that information presented during sleep can influence subsequent retrieval during waking. In an additional control experiment with 12 other participants who remained awake, sounds presented after learning did not reliably influence recall accuracy [1.15 cm from target ± 0.07 (SE) versus 1.32 cm ± 0.14 (SE) for cued versus uncued items, respectively; t_{11} = 1.4; P = 0.18].

The extent to which cues affect consolidation in waking subjects may depend on how strongly individuals attend to the cues (*6*). Regardless, we propose that sound cues presented during sleep prompted preferential processing of corresponding object-location associations. The hippocampus has previously been implicated in sleep-mediated consolidation (*3*, *5*). Memory storage in our study likely depends on representations of objects, sounds, and locations in multiple cortical regions, along with hippocampal networks capable of linking these representations together (*2*). Although some sleep theories emphasize general plasticity mechanisms that could benefit all information learned before sleep (*7*), our results show that memory processing during sleep can be highly specific. Certain associations may be preferentially reactivated during sleep as a normal part of memory stabilization and consolidation.

Whereas opportunities for enhancement of memory storage may be available every time we sleep, reminders during sleep can be used to target the reactivation and strengthening of individual memories.

References and Notes

1. J. L. McGaugh, *Science* **287**, 248 (2000).
2. K. A. Paller, in *Encyclopedia of Neuroscience*, L. R. Squire, Ed. (Academic Press, Oxford, 2009), pp. 741–749.
3. J. Born, B. Rasch, S. Gais, *Neuroscientist* **12**, 410 (2006).
4. R. Stickgold, J. A. Hobson, R. Fosse, M. Fosse, *Science* **294**, 1052 (2001).
5. B. Rasch, C. Büchel, S. Gais, J. Born, *Science* **315**, 1426 (2007).
6. Materials and methods are available as supporting material on *Science* Online.
7. G. Tononi, C. Cirelli, *Brain Res. Bull.* **62**, 143 (2003).
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Supporting Online Material

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Materials and Methods
Tables S1 to S3

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