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Strengthening Individual Memories by Reactivating them During Sleep

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Abstract

While asleep, people heard sounds that had earlier been associated with objects at specific spatial locations. Upon waking, they recalled these locations more accurately than other locations for which no reminder cues were provided. Consolidation thus operates during sleep with high specificity and is subject to systematic influences through simple auditory stimulation.

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 prior to a nap (Fig. 1A). Each object was paired with a characteristic sound delivered over a speaker (e.g., cat/meow, kettle/whistle). For the entirety of the nap, white noise was presented at an unobtrusive intensity (~62dB sound-pressure level), and during non-REM sleep the sounds for 25 of the objects were presented, with white-noise intensity lowered so that overall 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 ($1.07 \text{ cm} \pm 0.08 \text{ SE}$ vs. $1.23 \text{ cm} \pm 0.10 \text{ SE}$, respectively, $t_{11} = 2.6$, $p < .05$). Forgetting occurred between the final stage of learning and the post-nap test, with a smaller decline for cued compared to uncued objects (Fig. 1C). An advantage for cued-object locations computed in this manner was evident in 10 of the 12 participants.

EEG recordings provided information for determining sleep stages (6). Additionally, EEG responses to sound cues were sorted into 2 conditions via a median split on the difference between pre- and post-nap accuracy: (1) in the less-forgetting condition, mean accuracy was superior post-nap (placements $0.51 \text{ cm} \pm 0.1 \text{ cm SE}$ closer to correct); (2) in the more-forgetting condition, mean accuracy was superior pre-nap (placements $0.60 \text{ cm} \pm 0.1 \text{ cm SE}$ farther from correct). Average EEG amplitudes measured over the interval from 600-1000 ms after sound onset were $15.3 \text{ } \mu\text{V}$ greater when there was less forgetting ($t_{11} = 3.2$, $p < .$

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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).

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 (1.15cm from target $\pm 0.07\text{ SE}$ vs. $1.32\text{cm} \pm 0.14\text{ SE}$, for cued vs. 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.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

References and Notes

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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 $\pm$ SE). (B) Sleep-staging data are shown for a representative participant, including the 3.5-min sequence of 25 sound cues. Vertex EEG responses 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 to uncued objects was reflected by a smaller change in error ($t_{11} = 3.2$, $p < .01$).