Sleep-dependent learning: a nap is as good as a night

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The learning of perceptual skills has been shown in some cases to depend on the plasticity of the visual cortex[1] and to require post-training nocturnal sleep[2]. We now report that sleep-dependent learning of a texture discrimination task can be accomplished in humans by brief (60– 90 min) naps containing both slow-wave sleep (SWS) and rapid eye movement (REM) sleep. This nap-dependent learning closely resembled that previously reported for an 8-h night of sleep in terms of magnitude, sleep-stage dependency and retinotopic specificity, and it was additive to subsequent sleep-dependent improvement, such that performance over 24 h showed as much learning as is normally seen after twice that length of time. Thus, from the perspective of behavioral improvement, a nap is as good as a night of sleep for learning on this perceptual task.

A wide variety of learning processes in both humans and animals requires extended, post-training sleep (for review, see ref. 3). Depending on the nature of the task, differing stages of sleep contribute to this sleep-dependent consolidation process. For the most part, studies in humans have investigated the benefits of nocturnal sleep[3]. Research on behavioral effects of napping has found improvement in alertness, productivity and mood[4,5], as well as restoration of perceptual deterioration[6]. But whether relatively brief daytime naps can produce learning is not known.

Improvement on visual perceptual tasks can occur over periods of minutes to hours[7], as well as over extended periods of days[2], and remain stable for months[8]. For a visual texture-discrimination task in which subjects must rapidly discriminate the orientation of a target embedded in distractors[9], initial improvement is seen over the first few minutes of training[10], and slower improvement is seen over subsequent nights of sleep[2,11].

Both SWS[12] and REM[13] are implicated in a two-stage model of nocturnal consolidation, with overnight improvement being retinotopically specific and highly correlated with the product of the amount of early-night SWS and late-night REM sleep[11]. Repeated testing within a day on this task leads to a retinotopically specific deterioration in performance[6], which is reversed by 60-min midday naps rich in SWS. But these naps have relatively little REM sleep, and fail to produce significant improvement over baseline performance. Similar deterioration without sleep is also seen at night[12].

We now report that 60- and 90-min naps containing both SWS and REM facilitate learning on this texture-discrimination task, in a manner similar to that seen after nocturnal sleep.

Subjects were trained on the texture discrimination task at 9:00 in the morning on day 1, tested at 19:00 that evening, and then retested at 9:00 the next morning. In the task, a target screen is briefly flashed, consisting of a 19 × 19 grid of horizontal bars containing three diagonal bars and a central fixation target. Then, after a variable-length interstimulus interval (ISI), a mask consisting of both horizontal and diagonal bars appears. The diagonal bars, located in the lower-left visual quadrant, form either a horizontal row or vertical column. After each trial, subjects report whether the diagonal bar array was in a row or column arrangement, as well as whether the central fixation target was an "L" or "T." Performance is defined as the threshold ISI required for a subject to be 80% accurate in the row/column discrimination. Two experimental groups took naps at 14:00 (group 1: total sleep time, 59.3 ± 6.4 (mean ± s.d.); SWS, 20.2 ± 2.0; REM, 4.2 ± 2.2 min; group 2: total, 96.3 ± 6.3; SWS, 47.2 ± 5.8; REM, 25.6 ± 4.1 min), while 'no-nap' control subjects went about their normal day without midday sleep. All subjects reported sleeping an average of 7.6 ± 2.1 h on the night before day 1 and 7.5 ± 1.2 h on the night before day 2. Improvement was measured as a decrease in threshold ISI from each subject's baseline threshold (at 9:00 on day 1)[9].

No-nap control subjects showed the expected deterioration in performance at 19:00 (13.7 ms longer ISI threshold, $P = 0.06$, **Fig. 1**), and performed significantly worse than the nap groups ($P = 0.02$). The deterioration in performance from training to first retest in this group, measured over an 8-h interval, was similar to that seen in our prior

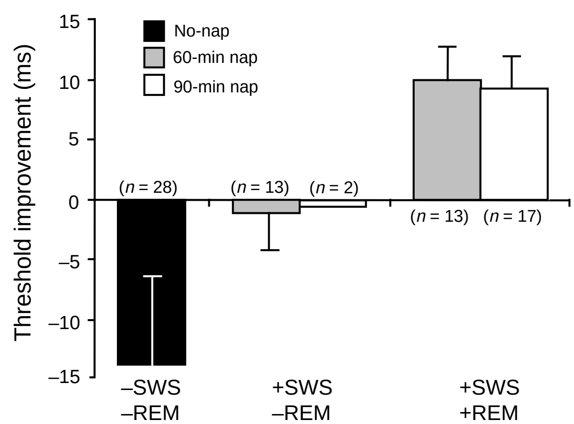

Figure 1 Same-day improvement in no-nap, 60-min nap and 90-min nap groups, with and without REM and SWS. Left, no-nap group shows deterioration at 19:00 from baseline test at 9:00. Center, performance after naps with SWS but without REM shows neither deterioration nor improvement. Right, naps with SWS and REM led to significant improvement. Only two subjects in the 90-min nap group showed no REM. Experiments were approved by the Committee on the Use of Human Subjects of Harvard University. Informed written consent was obtained from all subjects.

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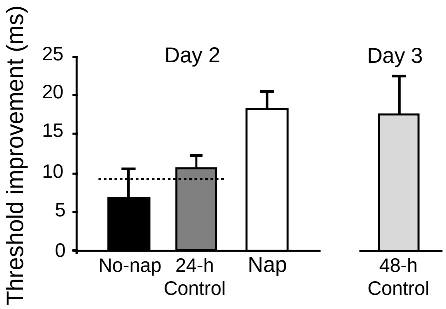

Figure 2 Improvement for nap and no-nap groups. Left, improvements 24 h after training for the no-nap group's second retest, the 24-h control group's first retest, and the 90-min nap group's second retest, all at 9:00 on day 2. Dotted line shows nap group's improvement on day 1. Right, improvement 48 h post-training with no nap. Data for 48-h controls are from ref. 2. Data for 24-h controls were combined with previously published data[2], which were not significantly different from the present sample.

study, which showed 13.8 ms deterioration over a 2-h interval[6]. This suggests that stimulus exposure rather than inter-test interval produces deterioration in texture discrimination, and that sleep, rather than time, is required to reverse this perceptual deterioration[6].

When tested at 19:00, the 90-min nap group showed significant improvement (8.4 ms, $P = 0.008$), whereas the 60-min nap group showed marginal improvement (4.4 ms, $P = 0.07$). Mindful of our hypothesis that both SWS and REM may be necessary for learning in naps, we divided the 60-min nap group, all of whom had SWS, into subjects with and without REM and found that 60-min naps with both SWS and REM produced significant improvement (10.0 ms, $P = 0.004$, **Fig. 1** right). In contrast, 60-min naps with SWS but not REM showed no improvement (–1.1 ms, $P = 0.72$, **Fig. 1** center) and significantly less than seen in the SWS + REM group ($P = 0.01$). The 90-min nap group showed similar results (**Fig. 1**, white bars). When subjects with SWS + REM naps from the 60- and 90-min groups were combined, improvement correlated significantly with the product of the amount of SWS and REM sleep (stepwise regression, $r = 0.37$, $P = 0.01$), similar to findings for nocturnal sleep[11]. The additive effects of SWS and REM seen in these naps are also similar to those for early and late night sleep reported previously[12]. In addition, the amount of improvement did not differ significantly from that seen in our previous study of overnight improvement[2] (9.7 vs. 11.9 ms; $P = 0.5$). Thus, nap-dependent improvement showed the same magnitude and sleep-stage dependency as did overnight improvement[2,11] (although of lower magnitude than that reported for overnight improvement by others[12,13]). Naps with SWS but not REM reversed the deterioration but did not produce actual improvement, whereas naps with both SWS and REM did both, suggesting that SWS may serve to stabilize performance, and REM may actually facilitate performance improvement.

We tested the retinotopic specificity of nap-dependent learning by training subjects at 9:00 in one visual quadrant (lower left or lower right, counterbalanced) and then retesting them in the contralateral quadrant at 19:00, with a 90-min nap at 14:00. Training plus a nap had no significant effect on the untrained quadrant ($P > 0.2$), indicating that nap-dependent learning has a retinotopic specificity similar to that reported for overnight improvement[9], as well as for same-day deterioration[6], and suggesting that the beneficial effects of a 90-min midday nap are localized to primary visual cortex[9].

Nap-dependent improvement was not at the expense of subsequent nocturnal improvement. On the contrary, when subjects were retested the next morning, the 90-min nap group showed an additional 9.7 ms of improvement (24-h total, 18.1 ms, $P < 0.0001$), and greater improvement than the no-nap group (**Fig. 2**, $P = 0.03$).

The no-nap group showed deterioration at 19:00, but normal levels of improvement on day 2 (7.8 ms; **Fig. 2**, no-nap). This improvement did not differ significantly from a second (24-h) control group trained at 9:00 and retested 24 h later without an intervening test on the evening of day 1 ($P > 0.4$; **Fig. 2**, 24-h control).

The nap group actually showed 50% more improvement over a period of 24 h than the 24-h control group (18.1 vs. 11.8 ms, $P = 0.07$). Indeed, 24-h improvement in the nap group was as great as that previously reported[2] after two nights of sleep (**Fig. 2**, 48-h control; 18.1 ms vs. 17.5 ms; $P > 0.99$). Taken together, these findings indicate that a 90-min nap can produce as much improvement as a night of sleep, and a nap followed by a night of sleep provides as much benefit as two nights of sleep.

These findings show that naps can lead to improved performance on a texture discrimination task similar to previously reported learning after a full night of sleep[2], in terms of magnitude, retinotopic specificity and dependence on both SWS and REM. Similar improvement has been reported after 192 min of early-night sleep[12], where subjects averaged 74 min of SWS and 24 min of REM—an amount of REM similar to the 25.6 min found in our 90-min nap group.

Finally, napping can significantly enhance the improvement that develops over 24 h. Thus, a nap can not only ameliorate experience-dependent perceptual deterioration, but can also facilitate the learning process that results from an hour spent training on a visual texture discrimination task.

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COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

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