Fast Sleep Spindle (13–15 Hz) Activity Correlates with Sleep-Dependent Improvement in Visuomotor Performance

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Study Objectives: The relationship between memory enhancement and fast (13-16 Hz) versus slow (10-13 Hz) spindle activity during sleep was investigated.

Design: Standard polysomnographic recordings were conducted during an adaptation, control nonlearning, and learning night. Automatic spindle detection and measurement was utilized with visual confirmation.

Setting: Participants slept in individual, temperature-controlled bedrooms in a sleep laboratory.

Participants: Twelve healthy student volunteers (9 women and 3 men, mean age: 22.3 years) participated.

Interventions: On the learning night, participants completed a presleep learning session on a modified version of mirror-tracing task followed by a postsleep test session. No learning or test sessions were performed on the adaptation and nonlearning nights.

Measurements and Results: Tracing time was reduced by 6.4 seconds (20.6% ± 2.07%) from the presleep to the postsleep session. Mean amplitude and duration of fast spindles was greater on the learning night than on the nonlearning night (both P values < 0.05). Skill improvement and fast-spindle activity were positively correlated (density [r = 0.76, P < 0.01], amplitude [r = 0.69, P < 0.05], and duration [r = 0.67, P < 0.05]). Significant correlations between fast-spindle activity and mirror-tracing performance were also evident for the nonlearning night. There was no significant relationship between mirror-tracing performance and slow-spindle activity on any night.

Conclusions: The thalamocortical network underlying fast-spindle generation may contribute to or reflect plasticity during sleep.

Keywords: Sleep spindle, procedural memory, motor learning, fast spindle, slow spindle

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MASTERY OF MOTOR SKILLS GENERALLY REQUIRES CONSIDERABLE REPETITION AND PRACTICE OVER EXTENDED PERIODS OF TIME. HOWEVER, prolonged and repeated training sessions can result in short-term performance decrements due to fatigue, decreased motivation, and reduced attention.[1]

One night of sleep has been shown to enhance motor skills,[2,3] suggesting that sleep may facilitate "reconsolidation" of procedural memory. Tamaki et al[2] compared the effects of sleep and wakefulness during the retention period for newly acquired versus preacquired visuomotor skill. Using a modified version of the classic mirror-tracing task, they found that the time taken to perform a newly acquired visuomotor skill improved by approximately 8.4 seconds (24.9%) when practice sessions were followed by sleep. However, no significant improvement was observed in subjects who remained awake following the practice sessions (-0.3 seconds, -2.0%). This suggests that posttraining sleep facilitates the learning a newly acquired visuomotor skill.

Sleep spindles are among the most prominent characteristics of non-rapid eye movement (NREM) sleep. Sleep spindles appear mainly during NREM stage 2 sleep and are one of the defining characteristics of this stage. It has previously been determined that the number of spindles (or sigma power) gradually increases over consecutive sleep cycles within a night, reaching asymptote around the third or fourth cycle.[4–7] Steriade and colleagues have extensively studied the mechanisms underlying sleep spindles and have found that reticular thalamic nucleus, thalamocortical neurons, and cortical pyramidal cells are involved.[8]

Several recent reports have suggested that sleep spindles contribute to memory enhancement during sleep. Schiffelhoz and Aldenhoff[9] demonstrated that rats experience a greater amount of pre-rapid eye movement (REM) sleep (the intermediate sleep stage with high spindle activity) following exposure to a new environment. Several studies have also demonstrated that hippocampal ripple (140- to 200-Hz) activity is temporally correlated with cortical spindle activity (in prefrontal and somatosensory regions) in both mice and rats, further suggesting that sleep spindles may facilitate (or at least reflect) memory-related processes such as plasticity.[10,11] Similarly, it has been suggested that slow waves may somewhat indirectly facilitate memory processes during sleep by virtue of influencing the temporal pattern of spindle activity in a manner that facilitates induction of neural plasticity in the cortex.[12]

Evidence linking spindle activity and memory is substantial. Using an odor-reward association task, Eschenko et al[13] found that spindle density increases after both learning and retrieval in rats. Similarly, in studies on humans, the density of sleep spindles was found to be significantly higher during sleep after a paired-association task than after a nonmemory control task.[14] Clemens et al[15] demonstrated that overnight verbal memory retention after a face-name association test was highly corre-

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lated with number of sleep spindles. Although the studies linking spindle activity and declarative memory are compelling, thus far, few have reported a significant relationship between procedural memory and sleep-spindle activity. One exception is a study by Fogel and Smith,[16] who found increased spindle (12-16 Hz) density (the number of spindles per minute) after the participants had learned 4 types of motor tasks. Together, these various studies suggest that sleep-spindle activity reflects sleep-dependent facilitation of both hippocampus-dependent declarative memory and hippocampus-independent procedural memory processes.

Less clear is the issue of whether sleep-spindle subtypes are differentially associated with memory enhancement. In some studies that have qualitatively and quantitatively analyzed electroencephalogram activity, sleep spindles have been grouped into 2 subtypes. The first is the slow spindle, with a frequency of approximately 12 Hz and a predominantly fronto-central scalp distribution. The second is the fast spindle, with a frequency of approximately 14 Hz and predominantly centro-parietal scalp distribution.[6,7,17,18] Importantly, the temporal distribution of these 2 types of spindles also differs during sleep. Slow spindles tend to predominate in the early part of the night, whereas fast spindles tend to appear later.[6,7,18] For both types of sleep spindles, equivalent dipole sources near the thalamus have been estimated.[19] The orientation of the equivalent dipole of the fast spindle is in the centro-parietal direction, whereas that of the slow spindle is in the frontal direction.

Sleep-spindle types also differ with respect to subsequent EEG activity: Immediately following a fast spindle, activity in the delta-theta band (0.78–7.42 Hz) is enhanced in the centro-parietal areas, while slow spindles tend to be followed by enhanced activity in fronto-central areas.[4]

Given the different spatial and temporal distribution of fast- and slow-spindle subtypes, it is possible that they also play different roles in sleep-related memory processes. To date, there is only 1 study (by Plihal and Born[28]) that suggests (albeit indirectly) that procedural memory may be differentially enhanced by fast spindles, since they found, using a classic mirror-tracing task, that the latter half of nighttime sleep is required for the consolidation of procedural memory. Although they suggested that this may have been associated with increased REM sleep in the latter half of the night, fast sleep spindles also tend to predominate during this portion of the night.

It was therefore hypothesized that slow and fast spindles may differentially reflect enhancement of different types of memory, with fast-spindle activity selectively associated with enhancement of procedural memory. Accordingly, the aim of the present study was to determine whether sleep-mediated facilitation of performance on a mirror-tracing task is differentially associated with fast- versus slow-spindle activity during nighttime sleep.

METHODS

Participants

Twelve healthy student volunteers (9 women and 3 men, 22.3 ± 0.50 years old mean [± SEM]) participated in the study. None had physical or psychiatric diseases that required current medical treatment, and none was suspected of suffering from a sleep disorder. After the purpose and procedure of the study were explained orally, participants provided written informed consent.

Prior to the experiment, participants completed a questionnaire in which their sleep-wake habits were assessed, including typical sleeping and waking times, circadian variation in activity, regularity of sleep habits, nap taking, sleep complaints, and regularity of lifestyle (e.g., mealtimes). They also completed a questionnaire assessing morningness and eveningness[20] and questionnaires designed to characterize and assess physical health, mental health, and the sleep environment.

All participants had regular sleep-wake cycles and slept for 6 to 9 hours daily. None of them took regular naps, drank alcoholic beverages before going to sleep, smoked cigarettes, or took any prescription medications in the month prior to the experiment. Finally, all were right-handed, as assessed by the Edinburgh Handedness Inventory[21] and possessed normal or corrected-to-normal vision.

Stimuli and Apparatus

A 5-point star and 6 irregular figures were used as stimuli. The perimeter of the star was drawn using 2 lines 3 mm apart, forming a path. The star was 400 mm in total length, with each of the 10 angles 50 mm apart. Similar to the star, each of the 6 irregular figures was drawn using 2 lines 3 mm apart. The figures were 600 mm in total length and possessed 11 angles spaced at 50-mm intervals. The participant's right hand was out of view and covered with an open-ended box (width, 300 mm; height, 280 mm; depth, 210 mm) with an 85-mm closed-circuit camera (Akizuki Denshi Tsusho, Saitama, Japan) mounted on top. Stimuli were presented under the box, and the image was projected on a 14-inch display (KV-14AF1, Sony, Tokyo, Japan) placed in front of the participants. The view could be rotated by turning the camera.

Task

A modified version of the classic mirror-tracing task was used. The participants were asked to trace the figures projected on the display from the starting point to the end as quickly as possible with a stylus. They were advised to stay within the path without looking at their hands. During the presleep and postsleep sessions, the star and the 6 irregular figures were alternately presented 6 times each, for a total of 12 presentations. The 6 irregular figures were presented pseudorandomly, with each figure visually rotated by 90° clockwise (rotated image), whereas the visual image of the star was not manipulated (non-rotated image). The order of the images was counterbalanced across the participants and sessions (presleep/postsleep). The duration of each session was approximately 30 minutes.

Procedure

Beginning 1 week prior to the experiment (preparation week), the participants were instructed to maintain their usual sleep-wake schedule. They were also instructed to refrain from excessive alcohol consumption, significantly altering the amount of physical exercise obtained, and napping. Their sleep-wake hab-

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its and compliance were documented subjectively with sleep logs and objectively with wrist actigraphy (Mini-Motionlogger; Ambulatory Monitoring, Inc., Ardsley, NY).

Participants were instructed to refrain from consuming any alcohol and caffeine, performing unusual physical or psychological exercises, and napping on the day prior to the experiment. The order of the learning and nonlearning nights was counterbalanced across participants. When a nonlearning night followed the learning night, the next nonlearning night came at least 1 week later. Considering possible interindividual differences in circadian rhythms, the retiring and waking times were individualized according to each participant's routine. On the learning night, the participants completed the presleep session before retiring and the postsleep session the next morning. These sessions were not performed on the adaptation and nonlearning nights.

Polysomnographic Recordings

EEG was recorded at 28 scalp sites (Fp1, Fp2, F3, F4, FC3, FC4, C3, C4, P3, P4, O1, O2, F7, F8, FT7, FT8, T7, T8, P7, P8, Fpz, AFz, Fz, FCz, Cz, Pz, POz, and Oz) using Ag/AgCl electrodes (EEG1000/9000 ver.03-11, Nihon Koden Inc.), in accordance with the 10-20 system.[22] The scalp electrodes were fixed with collodion. The system reference (mean amplitude between C3 and C4) was used for the recording. The data were rereferenced offline to the linked earlobes. Electrooculograms were recorded at 4 sites: electrodes were placed at the outer canthi of each eye, and 2 were placed 1.5 cm superior and inferior to the left eye. Bipolar submental electromyogram was also recorded. Electrode impedance was maintained below 5 kΩ, and the sampling rate was 500 Hz. The time constants for each recording were as follows: 0.3 seconds for the EEG, 5.0 seconds for the electrooculogram, and 0.003 seconds for the electromyogram. The low-pass filter was set at 120 Hz.

Data Analysis

Perceptual Motor Task

Motor performance was quantified as the time taken to trace each rotated image from the start to the goal (tracing time). The first of the 6 trials for each session were considered adaptation trials and were excluded from the analysis. Performance assessment during the presleep session was based on the tracing time in the last trial of the presleep session (fifth trial), and performance assessment during the postsleep session was based on tracing time in the trial after the adaptation trial (first trial). Improvement in motor-task performance was assessed by dividing the performance of the postsleep session by that of the presleep session for the rotated image (skill improvement: 100 – [first trial in the postsleep session/fifth trial in the presleep session × 100]).

Sleep Parameters

Sleep scoring was completed in accordance with Rechtschaffen and Kales' criteria[23] and the supplements and amendments to these criteria by the Sleep Computing Committee of the Japanese Society of Sleep Research.[24] Sleep staging was manually scored in 20-second epochs. EEG recordings from the C3 electrode were used for this scoring unless contaminated by artifacts, in which case the C4 recordings were used instead. The same EEG sites were used for scoring across individuals and across nights. Sleep efficiency (total sleep time /time in bed × 100), latency to sleep onset, and the percentage of time spent in each sleep stage were calculated. Sleep onset was defined as the time from lights off to the first 2 minutes of continuous NREM stage 2 sleep.

Sleep Spindles

On the learning and nonlearning nights, fast and slow spindles that appeared during NREM stage 2 sleep were confirmed visually, measured, and analyzed. A Butterworth-type zero-phase digital filter (10-16 Hz) (Matlab version 6.5, Mathworks, Inc., Natick, Mass) was applied to the EEG recordings during NREM stage 2 sleep, and spindles were detected automatically. First, the gradient of the wave was analyzed, and the point at which the gradient value changed from negative to positive was defined as the trough. The point at which the value changed from positive to negative was defined as the vertex. The start and end of each spindle was identified by measuring the distance between the troughs of the EEG waves. Difference in voltage was analyzed by subtracting the voltage of the trough from that of the vertex. The trough of the first wave and the vertex of the last wave that fulfilled the criterion were defined as the starting and ending points of each sleep spindle. Spindles that fulfilled the Japanese Society of Sleep Research Society criterion (≥15 µV, ≥0.5 s) were selected for analysis. Spindles with a frequency greater than 10 Hz and less than 13 Hz with a predominant scalp distribution at the frontal regions (Fz > Pz) were classified as slow spindles. Spindles with a frequency greater than or equal to 13 Hz with a predominant scalp distribution at the parietal regions (Pz > Fz) were classified as fast spindles. The indices used to measure spindle activity were as follows: the number, density (total duration of spindles/total duration of NREM stage 2 sleep), mean amplitude (µV), and mean duration (ms) for each cycle. The activity of the slow spindles was calculated at Fz and that of the fast spindles at Pz.

Statistical Analysis

To examine the effects of sleep on motor-skill improvement, a repeated-measures 1-way analysis of variance (ANOVA) was performed across the sessions (presleep/postsleep). To compare the activities of the sleep spindles between the learning and nonlearning nights, 2-way ANOVAs were performed across nights (1 vs 2) and conditions (learning vs nonlearning) for each spindle type. The significant main effect was followed by 1-way ANOVAs for each cycle. Significant interactions were assessed for each night using 1-way ANOVAs. Greenhouse and Geisser ε correction[25] was applied to control for type-I errors. Posthoc tests were performed by multiple comparisons using Shaffer modified sequentially rejective multiple test procedure.[26] This is the improved version of Holm sequentially rejective Bonferroni procedure[27] used to obtain a further increase in power. The relationships between motor-skill improvement and activity in-

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Table 1—Sleep Variables on Learning and Nonlearning Nights

Sleep Variables	Learning		Nonlearning		Analysis of variance	
					$F_{1,11}$	P value
TIB, h	7.6	(0.17)	7.7	(0.19)	1.36	0.268
SE, %	98.2	(0.49)	98.3	(0.48)	0.87	0.372
SOL, min	14.6	(3.05)	12.1	(2.10)	0.69	0.424
% TST						
NREM 1	9.7	(1.31)	8.7	(0.94)	0.69	0.424
NREM 2	49.8	(1.16)	51.1	(1.25)	2.02	0.182
NREM 3	11.0	(0.91)	11.4	(0.59)	0.93	0.356
NREM 4	4.6	(0.72)	3.6	(0.78)	1.99	0.186
REM	21.9	(0.97)	22.5	(1.03)	0.15	0.710
SWS	15.7	(1.54)	15.0	(1.24)	1.63	0.228
MT	2.8	(0.41)	2.7	(0.24)	0.12	0.734

TIB refers to time in bed; SE, sleep efficiency; SOL, sleep-onset latency; NREM, non-rapid eye movement sleep; REM, rapid eye movement sleep; SWS, slow-wave sleep MT, movement time.

dices (number, density, amplitude, and duration) were analyzed for each spindle type using Pearson product-moment correlation coefficient. The significance level was set at $P < 0.05$.

RESULTS

Sleep variables

Results of the analyses of sleep parameters are listed in Table 1. During the learning nights, participants slept for 7.6 ± 0.17 hours, sleep efficiency was 98.2% ± 0.49%, and latency to sleep onset was 14.6 ± 3.05 minutes. During the nonlearning nights, participants slept for 7.7 ± 0.19 hours, sleep efficiency was 98.3% ± 0.48%, and the time to sleep onset was 12.1 ± 2.10 minutes.

Improvement in Motor-Skill Performance

The time taken to trace the rotated images rapidly declined across trials in the presleep session (first trial, 39.8 ± 2.79 s; fifth trial, 30.8 ± 2.79 s). Additional improvement was observed in the postsleep session conducted after 1 intervening night of sleep. Compared to the last trial of the presleep session, the drawing time was 6.4 seconds (20.6% ± 2.07%) shorter in the first trial of the postsleep session (24.4 ± 2.21 s). A 1-way ANOVA demonstrated a significant difference between sessions ($F_{1,11} = 51.06$, $P < 0.0001$).

Fast-Spindle Activity and Motor-Skill Improvement

Because 2 participants did not complete the fifth cycle of NREM stage 2 sleep, only the spindles occurring during the first 4 sleep cycles were analyzed. Table 2 lists the number, mean density, amplitude, and duration of each sleep spindle type for both the learning and nonlearning nights. Figure 1 shows the fast-spindle activity for the learning and nonlearning nights, and, Figure 2, the activity for each sleep cycle. A night × condition ANOVA for the number of fast spindles revealed a significant effect of the conditions ($F_{1,5} = 6.75$, $P = 0.048$). Subsequent 1-way ANOVAs revealed significant differences between the conditions for the first ($F_{1,11} = 8.14$, $P < 0.05$) and fourth ($F_{1,11} = 6.67$, $P < 0.05$) cycles. Posthoc tests revealed that, during these cycles, the spindle number was greater under the nonlearning condition than under the learning condition ($P < 0.05$). With regard to spindle density, neither the main effect nor the interactions were significant. With regard to the amplitude, the night × condition ANOVA revealed significant main effects of condition ($F_{1,5} = 9.05$, $P < 0.005$). Subsequent one-way ANOVAs revealed significant differences between conditions for the third cycle ($F_{1,11} = 6.70$, $P < 0.05$). A post-hoc test revealed that spindle amplitude was greater under the learning condition than under the nonlearning condition ($P < 0.05$). With regard to the duration, the night × condition ANOVA revealed significant main effects of condition ($F_{1,5} = 22.33$, $P = 0.005$). Subsequent one-way ANOVAs revealed significant differences between conditions for all cycles (first: $F_{1,11} = 13.9$, $P = 0.003$; second: $F_{1,11} = 31.9$, $P < 0.001$; third: $F_{1,11} = 17.8$, $P = 0.001$; fourth: $F_{1,11} = 5.57$ $P < 0.05$). Posthoc tests revealed that the spindle duration was longer under the learning condition than under the nonlearning condition ($P < 0.05$).

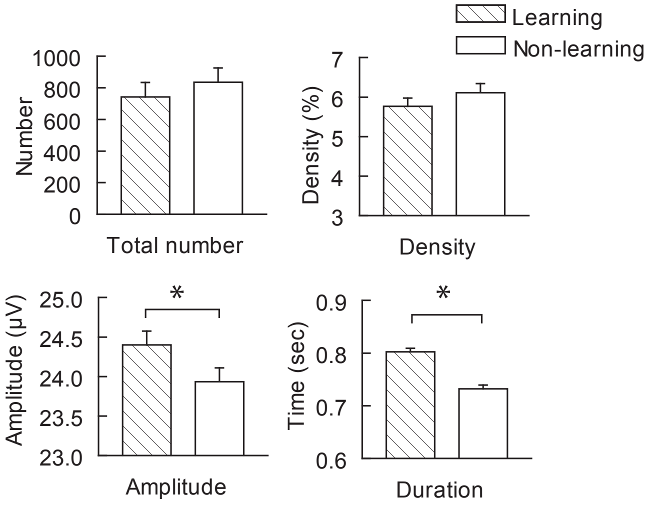

Figure 1—Histogram of the activity of fast spindles (total number, density, amplitude and duration) on the learning and nonlearning nights. * $P < 0.05$

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Table 2—Fast and Slow Sleep Spindles Parameters in 12 Subjects

Variables	Fast Spindle				Slow Spindle			
	Learning Night		Nonlearning Night		Learning Night		Nonlearning Night	
Total number	742.3	(91.50)	835.8	(90.40)	530.4	(92.90)	519.5	(85.98)
Density	5.8	(0.21)	6.1	(0.23)	4.1	(0.83)	3.9	(0.69)
Amplitude	24.4	(0.17)	23.9	(0.17)	23.3	(0.38)	23.9	(0.47)
Duration	0.8	(0.01)	0.7	(0.01)	0.7	(0.02)	0.8	(0.02)

Data are expressed as mean (SEM).

Figure 3 shows a scatter plot of skill improvement and various parameters of fast-spindle activity during learning and nonlearning nights. Significant correlations with performance were evident, except for the total number of spindles (number: r = 0.48, $P > 0.05$; density: r = 0.76, $P < 0.01$; amplitude: r = 0.69, $P < 0.05$; duration: r = 0.67, $P < 0.05$). Table 3 shows the correlation coefficient between the fast-spindle parameters and visuomotor performance. Individual analysis for each cycle revealed a positive trend (P = 0.050) for the number of spindles in the first cycle and a significant relationship between visuomotor performance improvement and spindle activity in the second cycle. Significant relationships were evident in all of the sleep cycles with regard to spindle density, amplitude, and duration except in the first cycle (when fast-spindle duration was not found to be related to performance). Significant relationships were also observed between performance and fast-spindle activity on the nonlearning night, with the exception of the total number of spindles (number: r = 0.40, $P > 0.05$; density: r = 0.65, $P < 0.05$; amplitude: r = 0.69, $P < 0.05$; duration: r = 0.66, $P < 0.05$). Individual analysis for each cycle demonstrated significant relationships except with regard to the number of fast spindles. For spindle density, significant relationships with performance were observed in the first, second, and third cycles ($P < 0.05$ for all) but not in the fourth sleep cycle. Significant relationships were observed in all the cycles for amplitude and duration as well. Subsequently, mean percentage increase in spindle amplitude and duration were calculated for each participant and the correlations of these values with visuomotor performance were determined. These analyses revealed no significant correlations ($P > 0.05$ for all).

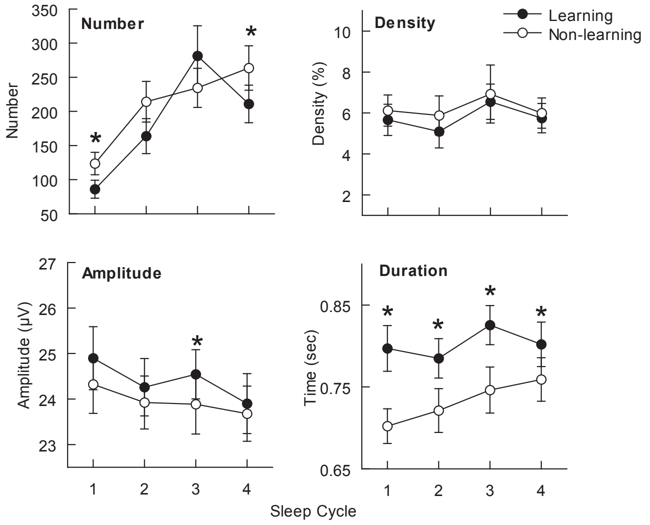

Figure 2—Fast-spindle activity on the learning and nonlearning nights. The y-axis indicates the activity of fast-spindle (number, density, amplitude and duration). The x-axis indicates sleep cycle. Standard errors are shown. * $P < 0.05$

Slow-Spindle Activity and Motor-Skill Improvement

A night × condition ANOVA did not reveal any main effect, and the interaction was not significant for any parameters associated with slow spindles ($P > 0.05$ for all). Figure 4 shows a scatter plot of performance and slow-spindle activity during the learning and nonlearning nights. No significant correlations were observed between slow-spindle activity and visuomotor performance, although the correlation with spindle density approached significance (number: r = 0.39, $P > 0.05$; density: r = 0.52, P = 0.083; amplitude: r = 0.23, $P > 0.05$; duration: r = 0.34, $P > 0.05$). Table 3 shows the correlations between the slow-spindle activity and visuomotor performance. Individual analysis for each cycle demonstrated nonsignificant results

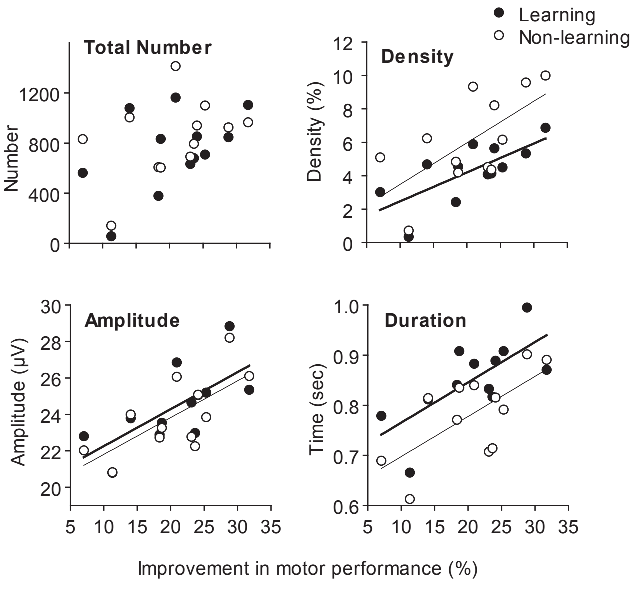

Figure 3—Correlation of fast-spindle activity with improvement in motor performance. The y-axis indicates the activity of fast spindle (total number, density, amplitude and duration). The x-axis indicates the improvement in motor performance (%). Filled circles show the data of the learning-night and open circles show the data of the nonlearning night. Thick line shows the regression line of the learning-night and the thin line shows the regression line of the nonlearning night.

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Table 3—Correlations Between Fast and Slow-Spindle Activity and Motor Performance

	Learning Night				**Nonlearning Night**			
Sleep cycles	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Fast spindle								
Number	0.58[a]	0.67[b]	0.32	0.20	0.40	0.38	0.40	0.21
Density	0.77[c]	0.76[c]	0.68[b]	0.61[b]	0.69[b]	0.61[b]	0.72[c]	0.41
Amplitude	0.71[b]	0.70[b]	0.65[b]	0.61[b]	0.73[b]	0.62[b]	0.67[b]	0.67[b]
Duration	0.35	0.70[b]	0.74[c]	0.62[b]	0.64[b]	0.68[b]	0.67[b]	0.59[b]
Slow spindle								
Number	0.45	0.44	0.22	0.41	-0.12	0.15	0.07	0.22
Density	0.56[a]	0.40	0.44	0.56[a]	-0.01	0.27	0.50[a]	0.28
Amplitude	0.31	0.32	0.13	0.03	0.26	0.13	-0.03	-0.03
Duration	0.27	0.12	0.29	0.51[a]	0.07	-0.07	0.01	-0.18

Values indicate Pearson product-moment correlation (r value).
[a] $P < 0.1$
[b] $P < 0.05$
[c] $P < 0.01$

for each index except for the density in the first (P = 0.057) and fourth (P = 0.058) cycles and the duration in the fourth cycle (P = 0.092), which revealed positive but nonsignificant trends. No measured aspects of slow-spindle activity on the nonlearning night were correlated with visuomotor performance (number: r = 0.10; density: r = 0.25; amplitude: r = 0.09; duration: r = 0.06; all $P > 0.05$). Likewise, individual analysis of each sleep cycle similarly failed to reveal significant relationships with performance, although spindle density in the third cycle revealed a positive trend (P = 0.099) (Table 2).

DISCUSSION

Visuomotor performance was significantly improved by a night of sleep. Fast spindles (13-16 Hz, dominant at Pz) were found to be of greater amplitude and longer duration on learning nights than on nonlearning nights. Although no significant relationship between sleep stages and improvement of visuomotor performance was evident, a significant relationship was observed between performance and fast-spindle parameters, including density, amplitude, and duration. In contrast, no significant relationship was observed between visuomotor performance improvement and the slow-spindle (10-13 Hz, dominant at Fz) activity.

It is notable that the newly acquired motor skill of tracing a rotated image improved overnight by an average of 20.6% (when comparing the last presleep trial against the first postsleep trial on the next day). This result is consistent with previous findings suggesting that sleep enhances motor-skill learning.[2,3] Using a mirror-tracing task similar to the one employed in the present study, Plihal and Born[28] determined that even 3 hours of sleep is enough to positively impact visuomotor learning that involves acquisition of altered relationships between visual inputs and motor outputs. The results of that study are consistent with those of the present study, since both suggest that sleep after training facilitates newly formed visuomotor coordination skills. It is possible that memory traces acquired during the waking period are reconsolidated and reinforced by sleep.

The central goal of the present study was to examine the relationship between memory enhancement and spindle type. Fast spindles had greater amplitude and longer duration on the learning night than on the nonlearning night. In contrast, we did not observe any enhancements in slow-spindle activity during the learning night. Previous studies in which procedural memory was examined along with motor tasks revealed that spindle density is higher on learning nights than on nonlearning nights.[16] However, in those studies, spindles were recorded only from a central site, and slow and fast spindles were not differentiated. Therefore it cannot be determined from that study which spindle type might have accounted for the variance.

As pointed out earlier in this paper, the 2 spindle subtypes differ in frequency and temporal distribution. The present results suggest that there may be value in reclassifying spindles into 2 types to reflect their differential relationships to facilitation of motor (and perhaps other) types of memory and learning.

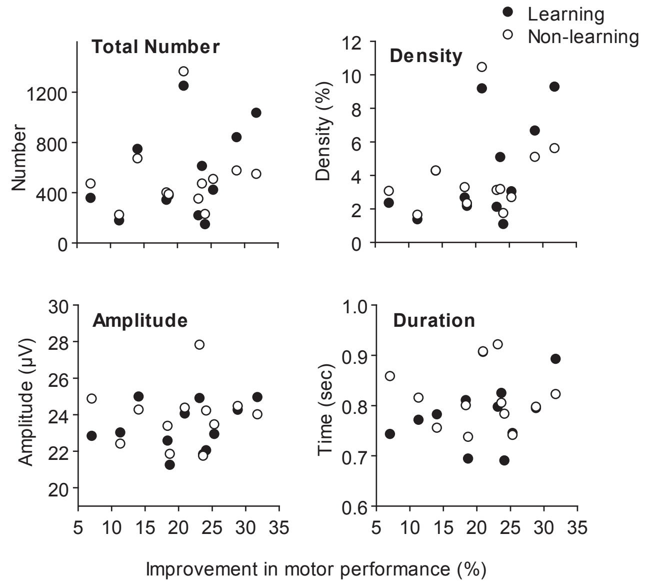

Figure 4—Correlation of slow-spindle activity with improvement in motor performance. The y-axis indicates the activity of fast spindle (total number, density, amplitude and duration). The x-axis indicates the improvement in motor performance (%). Filled circles show the data of the learning-night and open circles show the data of the nonlearning night.

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The present results are consistent with the notion that fast-spindle activity reflects enhancement of procedural memory during sleep. In contrast, there are only minor, if any, relationships between slow spindles and sleep-dependent procedural memory enhancement.

Also evaluated in the present study was the temporal pattern of spindle activity across sleep cycles. Since significant enhancement in the fast-spindle activity (amplitude and duration) on the learning night was evident during all 4 sleep cycles examined, it appears that the fast spindle functions throughout the night to facilitate memory. Significant relationships were observed across all sleep cycles, and the amplitude and duration of fast spindles were found to be larger and longer, respectively, during the learning night than during the nonlearning night.

Although no obvious relationship between slow-spindle activity and procedural-memory enhancement was detected, a prior report suggests an indirect connection between slow spindles and declarative memory. Schmidt et al[29] found that the density (number of sleep spindles per 20-second epoch) in the low-frequency range (11.25-13.75 Hz) increased after performance of a difficult encoding task but not after performance of an easy encoding task. Further, positive correlations were observed between these EEG frequencies during sleep and improvement in declarative memory. It therefore appears that slow and fast spindles might be associated with sleep-dependent enhancement of different types of memory. That is, the slow spindles may primarily reflect declarative memory enhancement, whereas fast spindles may primarily reflect procedural memory enhancement during sleep. Future research should include studies in which spindle parameters are compared following performance of tasks requiring declarative memory and procedural memory in a counterbalanced, crossover design.

It is important to note that in the present study we found significant correlations between fast-spindle activity and improvement in motor skill not only on the learning night, but also on the nonlearning night. Gaillard and Blois[30] reported individual variability in the number of spindles per minute ranging from 3 to 8, with little intraindividual variability. In several reports, it has been suggested that this individual and intraindividual variability is related to learning capacity. For example, Bódizs et al[31] demonstrated that the density of the fast spindles in the frontal lobe was positively correlated with intelligence, as measured by the Raven Progressive Matrices Test. Similarly, Schabus et al[32] reported that cognitive and memory abilities were correlated with both fast (13-16 Hz) and slow-spindle (11-13 Hz) activity. Since only the fast-spindle activity in the present study was associated with motor-skill improvement during the nonlearning night, it is possible that the fast sleep spindle is particularly important for motor-learning ability. We should add that, thus far, no study has been focused on the ability of motor learning and sleep variables. The present study is the first to demonstrate a clear relationship between sleep-spindle parameters (especially fast spindles) and the potential for motor learning. This suggests the possibility that innate motor learning ability may be predicted by determining fast-spindle activity.

Moreover, it is also important to point out that accurate, objective methods for detecting and classifying the spindles were utilized in the present study. As mentioned earlier, the 2 spindle subtypes differ in scalp distribution as well as frequency. Hence, we classified the spindles not only by analyzing their frequencies but also based on spatial distribution—something that has not been done in previous studies.[32,33] Further research is required to answer questions regarding whether specific types of intelligence are reflected by specific spindle subtype parameters. Since we could not find any significant relationship between improvement in performance and the changes in spindle parameters across the nonlearning and learning nights, the relationship between sleep spindles and visuomotor learning may be complex.

The underlying mechanism by which the sleep spindles affect memory enhancement remains to be determined. Several recent studies suggest that sleep spindles contribute to synaptic plasticity in a manner that fundamentally facilitates learning and memory. Fogel and Smith[16] have suggested that sleep spindles provide an ideal mechanism for facilitation of synaptic plasticity in the neocortex (and the enhancement of motor procedural memory) because of the manner in which they intermittently and repeatedly stimulate the cortex. In fact, it has recently been demonstrated that spindle-like stimulation can generate long-term potentiation in neocortical pyramidal cells in vitro and that long-term potentiation is not consistently induced by a regular firing pattern—a mirrored spindle stimulation pattern (duration of 728 ms containing 22 spikes).[38] In the current study, augmentation of the fast-spindle activity after visuomotor learning suggests that the thalamocortical network underlying the generation of fast spindles may contribute to cortical plasticity.

In conclusion, in the present study it was demonstrated that fast spindles are associated with the learning of a new motor skill, whereas slow spindles appear to exhibit a weak relationship with procedural memory enhancement. This is the first study to clearly demonstrate a relationship between fast-spindle activity and procedural motor-learning ability. The thalamocortical network underlying the generation of fast spindles may contribute to synaptic plasticity occurring during sleep.

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