

Brief Communication

Consolidation of sensorimotor learning during sleep

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Consolidation of nondeclarative memory is widely believed to benefit from sleep. However, evidence is mainly limited to tasks involving rote learning of the same stimulus or behavior, and recent findings have questioned the extent of sleep-dependent consolidation. We demonstrate consolidation during sleep for a multimodal sensorimotor skill that was trained and tested in different visual-spatial virtual environments. Participants performed a task requiring the production of novel motor responses in coordination with continuously changing audio-visual stimuli. Performance improved with training, decreased following waking retention, but recovered and stabilized following sleep. These results extend the domain of sleep-dependent consolidation to more complex, adaptive behaviors.

Learning new skills initiates a process of memory formation that begins to consolidate in the absence of further practice, and this consolidation can result in improved and more stable skill performance (Walker 2005). Previous research has shown that sleep may play an important role in the consolidation of rote learning of motor sequences (Karni et al. 1998; Fischer et al. 2002; Walker et al. 2002) and retinotopically specific texture discrimination (Karni et al. 1994; Gais et al. 2000; Stickgold et al. 2000). In these tasks, participants train repeatedly on the same fixed motor sequence or visual stimulus, resulting in learning that is limited to the exact training stimulus; performance improvements do not generalize beyond the specific patterns or spatial locations encountered during training (Karni and Sagi 1991; Gais et al. 2000; Karni et al. 1998; Fischer et al. 2002). Moreover, learning a similar task shortly after training on an initial task can disrupt the consolidation of the first task, resulting in reduced post-sleep performance gains (Walker et al. 2003).

The utility of such specific learning would seem limited to repetitive tasks and the development of highly automatized behaviors. Yet, many natural behaviors such as courtship, territorial defense, foraging, and predator/prey interactions require the ability to perform skills under varying circumstances. Because the tasks previously used to study sleep-dependent consolidation have been limited to very specific training stimuli or simple sensorimotor responses, it remains unresolved whether sleep consolidates more adaptive skills. Consolidation during sleep has been reported in a perceptual learning speech task that required generalization of phonological categories across different acoustic patterns (Fenn et al. 2003), but this could be an exceptional case since special mechanisms have been attributed to speech perception (Liberman and Mattingly 1989) involving a relatively specialized cortical network (e.g., Hickok and Poeppel 2007).

Furthermore, recent work has questioned the breadth of sleep-dependent consolidation. Rickard et al. (2008) demonstrated that sleep may not enhance performance in rote-trained motor sequence learning, contrary to previous results (e.g., Fischer et al. 2002; Walker et al. 2002). Additionally, sleep does not appear to consolidate probabilistic motor sequence learning (Keisler et al. 2007; Song et al. 2007), a sensorimotor task in

which a random item is inserted between each sequence item. Consequently, participants do not produce fixed sequences as in rote-trained motor sequence learning. Therefore, a myriad of previous work suggesting sleep plays a role in the consolidation of explicit, rote-trained motor skills has recently been questioned, and there is concurring evidence that sleep does not provide performance benefits when learning is implicit or probabilistic (Robertson et al. 2004; Spencer et al. 2006; Keisler et al. 2007; Song et al. 2007) or entails more than one specific behavior (Walker et al. 2003).

The aim of the current study was to investigate whether sleep consolidates sensorimotor skill learning in a task that cannot depend solely on rote learning. We examined learning to play first-person shooter (FPS) video games, where players encounter a rich, multisensory virtual environment in which they must produce novel bimanual motor responses in coordination with continuously changing visual and auditory stimuli. The goal of an FPS video game is to kill enemy bots (software avatars that play against the participant) as many times as possible and to avoid being killed. Players must learn to manipulate the keyboard controls and mouse in order to execute suitable motor responses, which could include any combination of left-hand arrow key presses (navigation) overlapping with right-hand mouse movements (aiming) and left clicks (shooting) that successfully allow the players to kill enemy bots and to avoid being killed. Rather than simply performing fixed response sequences, the movements that constitute suitable motor responses change each moment depending on the artificially intelligent movement of the enemy bots, requiring participants to constantly adapt their motor responses to the current situation. None of the response patterns is fixed in either sequence or bimanual coordination. Accordingly, FPS video games provide a task for investigating the role of sleep in adaptive sensorimotor skill learning with varying stimulus input and motor responses.

Right-handed University of Chicago students ($n = 207$; 163 female; mean age = 19.9) with no more than 10 prior experiences playing FPS games were participants. A preponderance of video game experience among males resulted in the sex bias in our sample. Participants provided written informed consent and were compensated \$15(US). Three participants did not complete the experiment, and data from 26 participants were not analyzed because the participants either did not follow task instructions ($n = 5$), did not sleep on the night before the study ($n = 1$),

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Table 1. FPS video game training and testing protocol

A. Condition	Pretest and training time		Retention interval	Post-test time	
A.M.-Control	9:00 a.m.–9:45 a.m.		X	9:45 a.m.	
P.M.-Control	9:00 p.m.–9:45 p.m.		X	9:45 p.m.	
12-h Wake	9:00 a.m.–9:45 a.m.		12 h	9:00 p.m.	
12-h Sleep	9:00 p.m.–9:45 p.m.		12 h	9:00 a.m. (day 2)	
24-h A.M.	9:00 a.m.–9:45 a.m.		24 h	9:00 a.m. (day 2)	
24-h P.M.	9:00 p.m.–9:45 p.m.		24 h	9:00 p.m. (day 2)	
B. Session procedure	Game	Environment	Skill level	No. of enemy bots	Time
Familiarization	<i>Unreal Tournament 2003</i>	DM-Antalus	Novice	0	2 min
Pretest	<i>Unreal Tournament 2003</i>	DM-Gael or DM-Training Day	Novice	5 4	7 min
Training 1	<i>Quake 3</i>	Q3DM-3	I Can Win	5	7 min
Training 2	<i>Quake 3</i>	Q3DM-1	I Can Win	1	7 min
Training 3	<i>Quake 3</i>	Q3DM-19	I Can Win	6	7 min
Training 4	<i>Quake 3</i>	Q3DM-8	I Can Win	11	7 min
Post-test	<i>Unreal Tournament 2003</i>	DM-Training Day or DM-Gael	Novice	4 5	7 min

(A) Experiment design. (B) Session procedure. Two distinct *Unreal Tournament*® 2003 environments were used for testing before and after training. An extra enemy bot was added to one of the environments to compensate for the environment's larger area. The order of test environments was counterbalanced across participants. Four distinct *Quake 3* environments were used for training. The order of training was the same for each participant. The enemy bots that the participants competed against were different for each of the four training rounds, but the bots within each respective training round were the same for all participants. Prior to pretest, participants completed a 2-min practice round in a novel *Unreal Tournament*® 2003 environment without any enemy bots to familiarize themselves with the video game controls. The difficulty level of both games was set at the lowest level because the participants had minimal prior experience with FPS video games.

napped during the 12-h waking period ($n = 8$), experienced motion sickness during training ($n = 2$), or exceeded the predetermined limit for FPS video game experience ($n = 10$).

To establish whether training would generate immediate, practice-dependent improvements, two groups received a pretest, training, and post-test within a single 1-h session, at either 9 a.m. (A.M.-Control; $n = 29$) or 9 p.m. (P.M.-Control; $n = 29$) to control for time-of-day effects. Next, we examined whether this learning undergoes time-dependent or sleep-dependent consolidation (Walker et al. 2002). Two groups were given a pretest and training in one session and returned for a post-test after a 12-h retention interval. For one group (12-h Wake; $n = 29$), pretest and training began at 9 a.m., and the post-test was given following 12 h of wakefulness, at 9 p.m. For the second group (12-h Sleep; $n = 29$), pretest and training began at 9 p.m., and the post-test was given at 9 a.m. on the following morning, after a 12-h interval that included a regular sleep period. Two additional groups were given a pretest and training at 9 a.m. (24-h A.M.; $n = 30$) or 9 p.m. (24-h P.M.; $n = 32$) and returned for a post-test 24 h later (Table 1A).

Participants recorded their sleep patterns during the week before their session. On the night before the study, the average amount of sleep per group ranged between 6.93 ± 0.30 (mean \pm SEM) and 7.55 ± 0.25 h, and there were no significant differences between the groups ($F_{(5,172)} = 0.67$, $P = 0.65$). Sleep during the study for the three groups that included a sleep interval ranged between 6.66 ± 0.23 and 6.98 ± 0.24 h, and no significant group differences were found ($F_{(2,88)} = 0.49$, $P = 0.62$).

Playing four unique rounds of one FPS video game produced significant learning (for scoring measures, see Fig. 1) when tested on a different FPS video game in a single session ($t_{(56)} = 8.09$, $P < 0.0001$). Combined control-group performance improved by an average of 8.17 ± 1.29 (mean \pm SEM) percentage points from pretest (3.24 ± 1.26) to post-test (11.41 ± 1.32). Data from the six groups (Table 1A) were analyzed using a six-factor ANOVA with planned comparison t -tests. Video game performance improved after training for all groups (Fig. 1), but the amount of improvement differed among groups ($F_{(5,172)} = 2.32$, $P < 0.05$).

Video game performance in the A.M.-Control group im-

proved by an average of 8.63 ± 1.62 percentage points (1.87 ± 1.85 to 10.50 ± 1.90). By comparison, after a 12-h waking retention period, performance improvement was only 4.28 ± 1.08 percentage points (4.89 ± 1.83 to 9.17 ± 1.81), which represents a significant reduction in learning compared with A.M.-Control performance ($t_{(56)} = 2.06$, $P < 0.05$). In contrast, after a 24-h retention period consisting of a full day of wakefulness followed by a regular night of sleep, performance improved by 9.81 ± 1.29 percentage points (3.59 ± 1.75 to 13.40 ± 1.93), which was significantly greater than the 12-h Wake group ($t_{(57)} = 2.64$, $P < 0.05$) and not statistically different from A.M.-Control performance ($t_{(57)} = 1.18$, $P = 0.58$). This indicates that sleep either enhanced learning after video game performance had significantly degraded during the waking hours of the previous day or restored learning that had been lost. It remains unresolved which aspects of learning degrade during wakefulness and whether sleep restores the same aspects that are lost or improves performance on different aspects of the task.

Video game performance in the P.M.-Control group improved by an average of 7.71 ± 1.23 percentage points (4.61 ± 1.67 to 12.32 ± 1.85). After a 12-h retention period that included a regular night of sleep, performance improved by 10.34 ± 1.55 percentage points (1.79 ± 1.85 to 12.13 ± 1.72), which is not significantly different from P.M.-Control performance ($t_{(56)} = 1.02$, $P = 0.22$). Likewise, after a 24-h retention interval that consisted of a night of sleep followed by a full day of wakefulness, performance improved by 9.95 ± 1.86 percentage points (2.51 ± 2.15 to 12.46 ± 1.79). This was not significantly different from P.M.-Control ($t_{(59)} = 1.09$, $P = 0.28$) or 12-h Sleep group improvement ($t_{(59)} = 0.19$, $P = 0.85$). Thus, whereas 12 h of wakefulness after training resulted in significant performance deterioration, 12 h of wakefulness after training and a night of sleep resulted in no such loss, indicating that sleep stabilized learning so that subsequent waking did not adversely affect performance. Finally, although P.M.-Control improvement only approached being significantly greater than 12-h Wake performance ($t_{(56)} = 1.63$, $P = 0.11$), improvement scores for the 12-h Sleep and 24-h P.M. groups were significantly greater than those of the 12-h Wake group ($t_{(56)} = 2.87$ and $t_{(59)} = 2.75$, $P < 0.01$ for both),

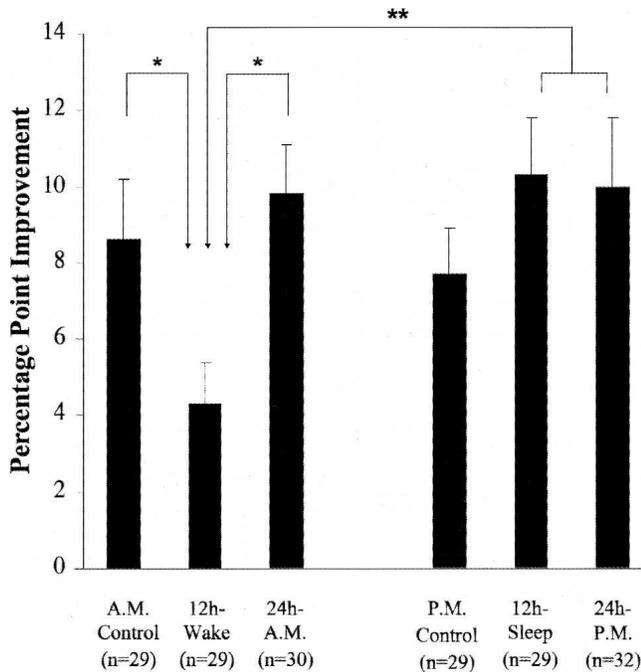


Figure 1. Mean percentage point improvement scores by condition. Performance improvement was measured as the difference between the player's post-test and pretest scores. Video game performance in a round was measured as the difference between the player's "kills percentage" and "killed percentage." The kills percentage was the percentage of total bot death for which the player was responsible in a round. For example, if the player had 10 kills and the bots were collectively killed 80 times (by the player and each other), the player's kills percentage for the round would be 12.5%. The killed percentage was the percentage of the bots' total kills for which the player was the victim. For instance, if the player was killed five times and the bots' collectively had 75 kills, the player's killed percentage would be 6.7%. Together, the player's percentage point score for the round would be +5.8. This normalization of the raw scores takes into account the inherent variation of each FPS video game round (e.g., enemy bots may be more efficient at killing in one round but less competent in the next), thus making comparisons between rounds more reliable. Error bars, SEM. * $P < 0.05$, ** $P < 0.01$.

confirming that performance was significantly greater when training was followed by a 12 or 24-h retention interval that included sleep than when the interval consisted only of wakefulness.

The results reported here cannot be explained by different abilities between groups at pretest ($F_{(5,172)} = 0.52$, $P = 0.76$) or to different performance during training ($F_{(5,172)} = 0.25$, $P = 0.94$). Moreover, significant differences were not found when comparing morning and evening pretest scores for all groups ($t_{(176)} = 0.33$, $P = 0.74$) or when comparing A.M.- and P.M.-Control improvement ($t_{(56)} = 0.43$, $P = 0.67$), indicating no circadian effects on performance.

We have demonstrated consolidation during sleep for a multimodal sensorimotor skill in a task requiring adaptive behavior. Video game performance was shown to display an immediate, practice-dependent improvement in a single session. Performance deteriorated significantly after a full day of wakefulness but recovered and stabilized follow-

ing a night of sleep. The performance improvement acquired during training demonstrates generalization, the ability to apply learning from limited experiences to novel situations (Poggio and Bizzi 2004), which is not surprising because playing FPS games produces cognitive benefits that generalize to very different perceptual tasks (Green and Bavelier 2003, 2006). Not only do players encounter within-round variation that requires producing novel motor patterns in response to autonomously moving bots, but the visual and spatial attributes of the environments used in the pretest, post-test, and each training round were all unique (Fig. 2). Accordingly, post-test performance was achieved by applying skills acquired during training to the novel visual-spatial environment of the post-test round, and improvements could not be attributed to prior knowledge of important features of the post-test environment such as the spatial layout or location of weapons. These results provide the first evidence in humans of sleep-dependent consolidation for a generalized sensorimotor skill.

Although sleep-dependent consolidation of procedural skills seems widely accepted (Stickgold 2005), the evidence is more nuanced. In the motor domain, sleep-dependent learning has been consistently replicated using a rote-trained motor sequence task (Karni et al. 1998; Fischer et al. 2002; Walker et al. 2002, 2003), but Rickard et al. (2008) have recently shown the sleep-enhancement effect disappears when the experimental design and analyses are modified to account for several confounding factors. Though the results of Rickard et al. (2008) do not preclude the possibility of sleep-dependent stabilization, the role of sleep in the enhancement of learning fixed motor sequences is less certain. Explicit sequence learning on a serial response time task (SRTT) does benefit from sleep while implicit sequence learning does not (Robertson et al. 2004), unless a contextual component is included (Spencer et al. 2006). Song et al. (2007) demonstrated that sleep does not benefit general-skill or sequence-specific learning when using a probabilistic SRTT. Using the same task, Keisler et al. (2007) found an overnight benefit but claimed that time of day, not sleep, was responsible for the effect. This interpretation, however, is questionable because the analysis relied on comparisons of groups with vastly different retention intervals. For instance, when comparing session-3 performance, only 2 h had transpired since the previous session for the early and mid groups whereas 11 h had passed for the late group. In the sensory domain, sleep has been shown to consolidate visual texture discrimination learning (Karni et al. 1994; Gais et al. 2000; Stickgold et al. 2000), speech perception learning (Fenn et al. 2003), and pitch memory (Gaab et al. 2004), but sleep-

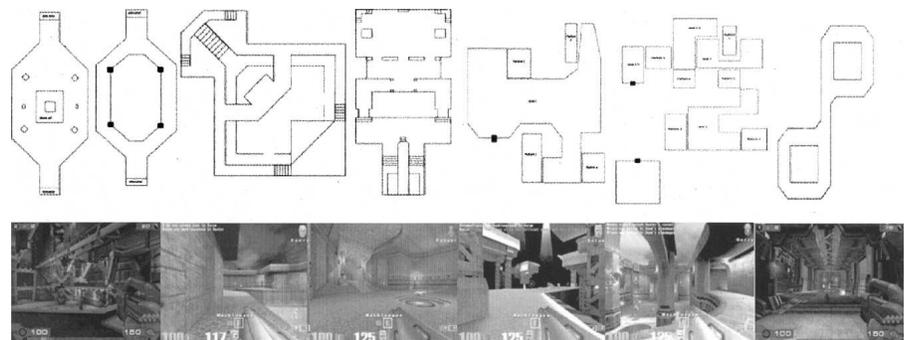


Figure 2. Environment maps and screenshots from the FPS testing rounds (Unreal Tournament® 2003 ©2002 Epic Games, Inc. All rights reserved. Used with permission.) and training rounds (Quake 3 ©2002 Id Software, Inc. All rights reserved. Used with permission.). In order from left to right, the maps depict the following environments: Gael first floor, Gael second floor, Q3DM-3, Q3DM-1, Q3DM-19 second floor, Q3DM-19 second floor, and Training Day. The spatial layout of the training round Q3DM-8 was too complicated to map out in this manner. The screenshots depict the following environments from left to right: Gael, Q3DM-3, Q3DM-1, Q3DM-19, Q3DM-8, and Training Day.

dependent performance benefits were not found in either an auditory tone sequence (Atienza et al. 2004) or verbal identification (Roth et al. 2005) task. Overall, evidence suggests that sleep contributes to the consolidation of many procedural tasks, but the extent of sleep-dependent consolidation remains unknown. It will be important for future behavioral studies to clarify the conditions that produce sleep-dependent consolidation.

Evidence of consolidation during sleep for a sensorimotor task like FPS game playing provides support that sleep-dependent consolidation extends to more complex, naturalistic behaviors. FPS game playing is a complicated task that entails learning a diverse set of interacting skills, integrating visual and auditory information, and coordinating distinct bimanual hand and finger movements. These component skills are likely subserved by a broad range of cortical and subcortical systems, including visual, auditory, and motor cortices as well as the hippocampal formation, which has been suggested to mediate sleep-dependent consolidation (Spencer et al. 2006). Eichenbaum and Cohen (2001) have hypothesized that the hippocampus is recruited whenever learning requires intersensory or sensorimotor integration, and the hippocampus is activated during spatial navigation in virtual environments (Peigneux et al. 2004) similar to navigation in FPS games. The complexity of FPS games implicates several brain regions that could plausibly benefit from processes of sleep-dependent consolidation. However, the specific task components that benefit from sleep are unknown. This leaves open for future study the question of whether consolidation of complex behaviors primarily results from the independent consolidation of multiple low-level skills or the integration of various component skills into a coordinated behavior.

A neurophysiologic perspective may help explain the pattern of wake-state performance degradation and sleep-state recovery and stabilization demonstrated in the present study. One hypothesis for memory consolidation is trace reactivation (Buzsaki 1989), whereby memory traces are modified via coordinated “offline” replay of stimulus driven activity (Hoffman and McNaughton 2002). Replay has been observed during sleep in animals (Wilson and McNaughton 1994; Dave and Margoliash 2000; Poe et al. 2000), and performance-related sleep activation of specific regions is associated with task learning in humans (Huber et al. 2004; Peigneux et al. 2004). We hypothesize that sleep replay recruits more extensive neural networks as behaviors become more complex, which could involve additional modalities, increasingly elaborate rote behaviors, or progressing from fixed to adaptive responses. Coordinated replay across multiple networks could carry additional (mutual) information in the distributed representation. Learning a simple skill may establish a pattern of coordinated recruitment across a specific set of cortical and subcortical structures (Doyon and Benali 2005; Walker et al. 2005), but learning complex behaviors that engage the coordination of various sensory and motor systems likely involves changes within the systems as well as in the functional connectivity of networks.

It is commonly believed that a new skill trace remains labile when first learned (Walker 2005). The recruitment of different networks in service of regular waking activity could reduce the stability of the newly acquired trace, leaving more complex behaviors susceptible to deterioration during wakefulness. For example, FPS game playing and generalized speech learning (Fenn et al. 2003) undergo wake-state performance degradation whereas learning rote finger-tapping sequences does not (Fischer et al. 2002; Walker et al. 2002), though there is evidence for a transient performance boost that disappears within 4 h post-training (Hotermans et al. 2006). Although texture discrimination performance can decrease throughout the day, this deterioration likely results from repeated testing rather than from time

spent awake (Mednick et al. 2002, 2003). Conversely, the extensive networks underlying complex behaviors would provide more opportunities for the newly acquired trace to be consolidated via a replay mechanism during sleep. Indeed, Kuriyama et al. (2004) varied motor sequence complexity and found the most complex configuration showed greater post-sleep performance improvements than the simpler task configurations. This model would predict the patterns of interactions among sleep, waking, and skill learning and could potentially be tested in both animals and humans. This suggests the importance of future comparative studies of sleep-dependent consolidation, especially in species where this learning can be studied in behaviors whose ecological significance is well defined.

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