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The effects of sleep, wake activity and time-on-task on offline motor sequence learning

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A B S T R A C T

While intervening sleep promotes the consolidation of memory, it is well established that cognitive interference from competing stimuli can impede memory retention. The current study examined changes in motor skill learning across periods of wakefulness with and without competing stimuli, and periods of sleep with and without disruption from external stimuli. A napping study design was adopted where participants ($N = 44$) either had (1) a 30 min nap composed of Non-Rapid Eye Movement (NREM) sleep, (2) 30 min NREM nap fragmented by audio tone induced arousals, (3) 45 min of quiet wakefulness, or (4) 45 min of active wakefulness. Measures of subjective sleepiness (KSS), alertness (PVT) and motor skill learning (Sequential Finger Tapping Task, SFTT) were completed in the morning and evening to assess performance pre- and post-nap or wakefulness. Following a practice session, change in motor skill performance was measured over a 10 min post training rest interval, as well as following a 7 h morning to evening interval comprising one of the four study conditions. A significant offline enhancement in motor task performance (13–23%) was observed following 10 min of rest in all conditions. Following the long delay with the intervening nap/wake condition, there were no further offline gains or losses in performance in any sleep (uninterrupted/fragmented) or wake (quiet/active) condition. The current findings suggest that after controlling for offline gains in performance that occur after a brief rest and likely to due to the dissipation of fatigue, the subsequent effect of an intervening sleep or wake period on motor skill consolidation is not significant. Consistent with this null result, the impact of disrupting the sleep episode or manipulating activity during intervening wake also appears to be negligible.

1. Introduction

There is an increasing body of evidence showing that intervening sleep promotes the consolidation of memory (Diekelmann, Wilhelm, & Born, 2009; Rasch & Born, 2013). Explicit motor sequence learning tasks, have been frequently used to measure the influence of sleep on memory consolidation. These tasks have typically demonstrated that after a practice session, task performance remains stable over retention periods composed purely of wakefulness, however significant 'offline' enhancements in performance (approximately 15–20% improvements in task speed) occur following a period that contains sleep (Walker, 2005; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002). The mechanisms by which this sleep-dependent learning occurs is still debated. Sleep has been hypothesized to provide a period of reduced interference compared to wakefulness, thereby permitting consolidation to occur more efficaciously (Mednick, Cai, Shuman, Anagnostaras, & Wixted, 2011; Wixted, 2004). This does not rule out, however, the possibility that active sleep-specific processes additionally promote the consolidation of memory.

During wakefulness, retrograde interference due to similar learnt material impairs memory retention (Nairne & Pandeirada, 2008). Some contemporary interference accounts extend this concept to also include any mental activity and/or new learning that can compete for consolidative resources (Mednick et al., 2011; Wixted, 2004). Relatedly, manipulations of the amount of activity during a wake episode (e.g. allowing a participant to go about their normal daily routine, compared to having participants remain reclined while listening to music) can have a notable impact on memory consolidation outcomes. Periods of reduced activity or 'quiet' wakefulness, can therefore have a similar benefit to learning as certain periods sleep (Gottselig et al., 2004; McDevitt, Rokem, Silver, & Mednick, 2013; Mednick, Makovski, Cai, & Jiang, 2009). With this is mind, studies assessing the impact of intervening sleep on consolidation must take into account the potential interfering

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properties of the wake comparison (mental activity/potential for new learning) or risk confounding the effect of sleep with waking interference.

Interference or disruption to memory consolidation processes is not uniquely a wake phenomenon; it can also occur during sleep. Patients with substantially disrupted sleep, such as obstructive sleep apnea (OSA), demonstrate reduced offline enhancements in motor skill performance after sleep compared to healthy controls, presumably due to impaired memory consolidation processes during sleep (Djonlagic, Saboisky, Carusona, Stickgold, & Malhotra, 2012; Djonlagic et al., 2014; Landry, Anderson, Andrewartha, Sasse, & Conduit, 2014). Furthermore, as the rate of respiratory arousals (Arousal Index, AI) is negatively associated with the degree of offline improvement (Djonlagic et al., 2012), this impairment in consolidation has been attributed to sleep fragmentation. To our knowledge no study has experimentally induced sleep fragmentation in human participants to evaluate the extent to which fragmentation alone (without the associated hypoxic effects of apnea) can interfere with memory consolidation.

In addition to interference or disruption to sleep during a retention period, time on task fatigue is another factor that may affect motor learning and hence obscure offline changes in performance due to memory consolidation. Time on task fatigue has been shown to accumulate over motor task training periods (Rickard, Cai, Rieth, Jones, & Ard, 2008; Rieth, Cai, McDevitt, & Mednick, 2010). This effect on performance is greatest for trials at the end of training which are then used as a baseline to compare performance improvements that may occur over sleep/wake intervals. The change in performance measured is thus inadvertently due to both the alleviation of fatigue as well as any performance change due to consolidation. The use of spaced training regimes, (i.e. decreasing the length of task trials, while also increasing the length of rest between trials) has been shown to reduce the impact of fatigue, with the subsequent effect of eliminating the typically observed post sleep enhancement in motor performance (Rickard et al., 2008; Rieth et al., 2010). Brawn, Fenn, Nusbaum, and Margoliash (2010) using these methodological alterations, similarly found an elimination of post sleep enhancements, however demonstrated that performance would be maintained over sleep but would deteriorate over a wake period. While this finding challenges the notion that sleep imparts an offline/sleep-dependent gain in motor task performance, it does still suggest that sleep plays a beneficial role in the consolidation of learning. This benefit manifests however, as a stabilization of pre-sleep performance against losses accrued over wakefulness.

These findings discussed above suggest that there are a range of manipulable qualities of both sleep and wake intervals that can play a critical role as to whether offline-consolidation related gains in learning occur. Furthermore, typical measurements of these changes in motor learning are confounded by time on task fatigue effects, which when resolved, substantially change the way in which these consolidation related gains in performance are expressed. In order to disentangle these factors, the current study aimed to investigate the role of time on task fatigue effects as well the influence of interference applied over both wake (via activity) and disruption over sleep (via sleep fragmentation) on offline motor skill learning.

2. Methods

2.1. Design

Motor skill learning and consolidation outcomes were compared between uninterrupted and fragmented sleep periods as well as over comparable periods of wakefulness that was experimentally manipulated to be either 'quiet' or 'active' (see procedure for details). Two groups of participants completed both a sleep and a wake condition in a randomized order and separated by a wash-out period of at least one week. One group was composed of uninterrupted sleep and quiet wake conditions, while the other group was composed of a fragmented sleep and active wake conditions.

2.2. Participants

Forty-four participants (30 females, 14 males) aged 18–30 (M = 21.93, SEM = 0.46) were recruited via advertisements. Exclusion criteria included: a history of alcohol/drug dependence, a diagnosed learning, neurological, psychiatric or sleep condition; or any sedative, recreational or psychoactive drug use. To maximize the likelihood of participants falling asleep during a midday nap episode, participants were excluded if they reported either "No chance" or a "Slight chance" of dozing when "lying down to rest in the afternoon when circumstances permit" (Question #5 on the Epworth Sleepiness Scale, ESS (Johns, 1991)). Participants were also excluded if they scored higher than 10 (clinically significant sleepiness) on this scale. Ethical approval was obtained from by the Monash University Human Research Ethics Committee.

2.3. Procedure

For one week prior to participation, all subjects were required to maintain a consistent sleep schedule, sleeping at least 7 h per night and waking no later than 8am. Adherence to this schedule was verified with a sleep diary (for 7 days prior) and a portable polysomnographic (PSG) device (ZEO Sleep Manager; Zeo, Inc., Newton, MA, USA) for 3 days prior.

Participants arrived at the laboratory between 10:00 and 10:30 and were taken to a sound attenuated room where they completed a battery of tests composed of the Karolinska Sleepiness Scale (KSS), visual Psychomotor Vigilance Task (PVT) as well as the Sequential Finger Tapping Task (SFTT). An Episodic Word-pair Task was also undertaken (not reported here). From 12.00 to 13:30 participants were provided with lunch and prepared for polysomnographic (PSG) recordings. At 13:30 a 2-h nap opportunity began where, depending on the experimental condition, participants either attempted sleep or remained awake in the room. Following the 2-h nap opportunity participants were given a period of free time before being retested on the same battery of tests at 17.00–18.30. For each individual participant this retest interval was 7 h. See Fig. 1a.

2.4. Sleep protocol

During the 2-h nap opportunity (13:30–15:30), participants in the uninterrupted sleep condition were allowed to nap until 30 min of N2/N3 sleep was achieved, after which they were woken. This procedure was the same for the fragmented sleep condition, however the sleep episode was repeatedly disrupted by audio tone induced arousals, until the same total minutes of N2/N3 sleep was achieved. Participants were first allowed 5 min of stable N2 sleep. This interval was based on pilot observations that showed audio thresholds were lower and simulated arousals often resulted in sustained awakening prior to this point. After 5 min of uninterrupted sleep had elapsed, a 30 dB tone was played through a set of speakers on either side of the bed. The tone volume would be increased in 2.5 dB increments every 15 s until an EEG-derived arousal was observed. Following each arousal, a period of 60 s would elapse before the same volume tone was presented again. Arousal responses that achieved a stage change would result in a decrease in volume. If a stimulus resulted in a change to stage