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The influence of sleep on emotional and cognitive processing is primarily trait- (but not state-) dependent ☆

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ABSTRACT

Human studies of sleep and cognition have established that different sleep stages contribute to distinct aspects of cognitive and emotional processing. However, since the majority of these findings are based on single-night studies, it is difficult to determine whether such effects arise due to individual, between-subject differences in sleep patterns, or from within-subject variations in sleep over time. In the current study, we investigated the longitudinal relationship between sleep patterns and cognitive performance by monitoring both in parallel, daily, for a week. Using two cognitive tasks – one assessing emotional reactivity to facial expressions and the other evaluating learning abilities in a probabilistic categorization task – we found that between-subject differences in the average time spent in particular sleep stages predicted performance in these tasks far more than within-subject daily variations. Specifically, the typical time individuals spent in Rapid-Eye Movement (REM) sleep and Slow-Wave Sleep (SWS) was correlated to their characteristic measures of emotional reactivity, whereas the typical time spent in SWS and non-REM stages 1 and 2 was correlated to their success in category learning. These effects were maintained even when sleep properties were based on baseline measures taken prior to the experimental week. In contrast, within-subject daily variations in sleep patterns only contributed to overnight difference in one particular measure of emotional reactivity. Thus, we conclude that the effects of natural sleep on emotional cognition and category learning are more trait-dependent than state-dependent, and suggest ways to reconcile these results with previous findings in the literature.

1. Introduction

Over the last two decades, sleep has been repeatedly shown to play a central role in memory consolidation and emotional cognition. Using polysomnography (PSG) measures, human studies demonstrated that specific sleep stages tend to affect specific cognitive abilities. Generally, Rapid-Eye-Movement sleep (REM) has been linked to procedural memory, high-level linguistic processes and the processing of emotional stimuli, whereas non-REM sleep (NREM) – and Slow-Wave Sleep (SWS) in particular – have been implicated in processes such as declarative memory, context sensitivity and relational learning (e.g., Groch, Wilhelm, Diekelmann, & Born, 2013; Gujar, McDonald, Nishida, & Walker, 2010; Plihal & Born, 1997; for reviews, see Rasch & Born, 2013; Walker, 2009).

In human studies, the standard methodology for examining the effects of sleep on cognitive function involves participants learning a cognitive task, spending a night (or, in case of nap studies, an afternoon) in a sleep laboratory during which their sleep is monitored with PSG, and in some studies manipulated, and then being retested. Results from these individuals are then compared to a control group in which no sleep period is interposed between the two sessions, or no sleep manipulation is exercised. Any performance benefits in the experimental group over the control group are attributed to sleep and compared to specific sleep parameters that were measured during the night (or the afternoon nap).

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One key limitation of this single-night methodology is that it is difficult to determine whether correlations between sleep and cognitive performance are due to specific "**state-dependent**" properties of sleep that each participant happened to experience in the studied night, or, conversely, result from "**trait-dependent**" individual differences in participants' general sleep patterns. Often, single-night studies implicitly assume the former, failing to take into account individuals' baseline patterns. However, given that there is evidence suggesting that both sleep architecture (e.g., De Gennaro et al., 2008; Linkowski, 1999) and various cognitive and affective processes (e.g., Neta, Norris, & Whalen, 2009; Volk, McDermott, Roediger, & Todd, 2006) are in fact stable traits whose variability is lower within-subjects than between-subjects, it is possible that the interaction between sleep and these processes also follows a trait-like pattern.

Traditional human sleep studies suffer from several other limitations. First, due to their reliance on data from a single night, they are insufficient to address the effects of sleep on the learning of complex tasks that require multiple days to master (e.g., Shohamy, Myers, Onlaor, & Gluck, 2004). Second, the use of PSG is known to precipitate several sleep disturbances that contribute to poor sleep quality (e.g., increased awakenings and a decreased percentage of REM sleep; Agnew, Webb, & Williams, 1966). These effects have been shown to persist for up to three nights (the so called "First –night effects"), even when the PSG system is employed in participants' homes (Le Bon et al., 2001). Consequently, the ecological validity of such studies may be jeopardized, as exemplified by studies showing effects of sleep on cognition that appear only when sleep occurs without the use of PSG, but not when repeated in a laboratory (e.g., Djonlagic et al., 2009). While many of these limitations may be addressed by observing participants for extended periods of time, the nature of PSG studies typically renders long-term investigations both cost-prohibitive and logistically unfeasible. As a result, few controlled longitudinal studies that measure sleep and cognition in parallel have been performed to date (cf., Burke, Scheer, Ronda, Czeisler, & Wright, 2015).

In the present study we sought to address the limitations of traditional single-night studies by examining the longitudinal effects of sleep on behavioral performance. To that end, we utilized a combination of easy-to-use mobile devices that allowed participants to both monitor their sleep and administer cognitive tasks for multiple days, by themselves and in their own homes. We examined the effect of sleep on two behavioral tasks; one that tested emotional cognition, specifically reactivity to emotional facial expressions, and a second examining memory consolidation during category learning. Thus, our study tapped into both cognitive and affective processing, two central themes in the human sleep-cognition literature. The specific tasks were chosen for several reasons. First, both were compatible with (or could be adapted to) a long-term study that requires repeated administration over multiple days. Second, it was previously shown in single-night studies that performance in these and similar tasks is influenced by sleep (Barsky, Tucker, & Stickgold, 2015; Djonlagic et al., 2009; Gujar et al., 2010; Lara-Carrasco, Nielsen, Solomonova, Levrier, & Popova, 2009; Van Der Helm, Gujar, & Walker, 2010). Lastly, results regarding the precise role of sleep—and specific sleep stages—on performance in these previous studies have been inconsistent at best, raising the possibility that investigating these relations over a single night is insufficient.

Overall, we aimed to answer two fundamental questions: First, what are the relative contributions of daily and baseline sleep patterns on cognitive performance. If the state-like hypothesis is correct, we expected to see daily fluctuations in performance in accordance with properties of sleep during the preceding night. If, however, the nature of the relationship were more trait-like, we would expect an effect when comparing average performance and sleep levels between-subjects. Second, we sought to determine whether new relationships between sleep stages and performance emerge when taking under consideration multiple nights of sleep, and whether these can shed light on inconsistencies in previous studies.

2. General methods

2.1. Participants

Twenty-three healthy students ($n = 11$ females) from Rutgers University and the New Jersey Institute of Technology participated in this study for monetary compensation (Table 1). Exclusion criteria included personal or family history of sleep, neurological or psychiatric disorders, drug or alcohol abuse, and/or intake of medications that have any effect on sleep. Three participants were discarded from the study due to a lack of reliable use of equipment, resulting in three or more experimental days of unusable sleep and/or behavioral data (see Section 1.2.1 in the *Supplemental Materials*). Throughout the experiment participants were asked to not increase their daily caffeine intake, to maintain their regular sleep schedule, and to refrain from alcohol consumption and daytime napping. All participants provided informed consent in line with the procedures approved by the Institutional Review Board of Rutgers University.

2.2. Sleep monitoring and cognitive testing devices

2.2.1. Mobile sleep monitoring system

The mobile sleep monitoring system included an automated wireless sleep-monitoring headband (Zeo Inc., Newton, MA), an actigraphy bracelet (Micro-MotionLogger Sleep watch, Ambulatory Monitoring, Inc., Ardsley, NY), and an Android tablet (Amazon.com, Inc., Seattle, WA).

The sleep-monitoring headband is equipped with a single bi-polar fabric sensor that transmits data wirelessly to the Android tablet, which acts as a base station. The sensor is fitted with three silver-coated electrodes used to detect brain waves (EEG), eye movements (EOG), and the movement of the frontalis muscle (EMG). The signals from these electrodes are analyzed in real time to produce sleep staging in 30-s epochs. This sleep staging, the accuracy of which was validated for nocturnal sleep compared to PSG in multiple studies (e.g., Griessenberger, Heib, Kunz, Hoedlmoser, & Schabus, 2013; Shambroom, Fabregas, & Johnstone, 2012), is a reduced version of the official staging criteria by the American Association of Sleep Medicine (Iber, Ancoli-Israel, Chesson, & Quan, 2007) and differentiates between four stages rather than five – wake, N1/N2 (combined N1 and N2 stages, termed 'Light sleep'), SWS ('Deep sleep'), and REM sleep.

The actigraphy bracelet is a research-grade device that contains a built-in accelerometer used to infer sleep/wake decisions in one-minute epochs based on participants' arm movements (Ancoli-Israel et al., 2003; de Souza et al., 2003). Participants wore the actigraph on the non-dominant wrist throughout the entire study. Data was extracted from the devices at the end of the experiment, and was used to assess the sleep/wake validity of the sleep-monitoring headband (see detailed description in Section 1.2 of the *Supplemental Materials*).

2.2.2. Mobile cognitive assessment

The cognitive tasks were delivered using a separate application on the same Android tablet used to collect and transmit data from the sleep-monitoring headband. In each experimental session, participants completed an emotional reactivity task followed by a probabilistic category-learning task, described in detail below.