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Sleepless Night, Restless Mind: Effects of Sleep Deprivation on Mind Wandering

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Sleep deprivation can result in degradation of sustained attention through increased distraction by task-irrelevant exogenous stimuli. However, attentional failures in the sleep-deprived state could also be a result of task-unrelated thoughts (TUTs, or mind wandering). Here, well-rested and sleep-deprived participants performed a visual search task under high and low perceptual load conditions. Thought probes were administered at irregular intervals to gauge the frequency of TUTs and level of meta-awareness of mind wandering. Despite sleep-deprived participants reporting more TUTs, they also reported less awareness of TUTs. Although the frequency of TUTs decreased in the high load condition in well-rested participants, they were equally frequent across low and high perceptual load conditions in sleep-deprived participants. Together, these findings suggest that sleep deprivation can result in a loss of ability to allocate attentional resources according to task demands consistent with diminished executive control. This may have been exacerbated by reduced meta-awareness.

Keywords: mind wandering, sleep deprivation, meta-awareness, executive control, context-regulation

Sleep deprivation is an almost unavoidable feature of life in modern cities, and a desire to understand its impact and their remedies has stimulated numerous studies (Basner, Rao, Goel, & Dinges, 2013). Behavioral changes in sleep-deprived individuals include degraded sustained attention (Lim & Dinges, 2010), reduced perceptual processing capacity (Kong, Soon, & Chee, 2011), visual short-term memory (Chee & Chuah, 2007), and rates of rapid picture processing (Kong, Asplund, & Chee, 2014). Two additional factors that could also compromise performance are reduced distractor suppression (Kong, Soon, & Chee, 2012) and increased distractibility (Anderson & Horne, 2006).

To date, studies examining distractor suppression have largely focused on task-irrelevant exogenous stimuli (Chadick & Gazzaley, 2011; Gazzaley, Cooney, McEvoy, Knight, & D'Esposito, 2005; Kong et al., 2012). However, task-unrelated thoughts related to mind wandering can also occur in the absence of overt external distraction. Mind wandering results in disengagement of attention from the environment leading to reduced sensitivity to external inputs (Smallwood, Beach, Schooler, & Handy, 2008). This "perceptual decoupling" (Smallwood & Schooler, 2015) has been associated with poorer behavioral outcomes in a wide range of tasks ranging from simple signal detection tasks to complex tasks, such as reading comprehension (Smallwood, McSpadden, & Schooler, 2008) and driving (Cowley, 2013).

Earlier work concerning the association of mind wandering and sleep loss has yielded conflicting findings, with one study showing no increase in measures of cognitive interference following sleep deprivation (Pilcher & Walters, 1997), and another reporting a positive correlation between mind wandering and poorer sleep quality (Carciofo, Du, Song, & Zhang, 2014). As participants in these studies only retrospectively reported self-perceived level of cognitive interference at the end of the experiment (Pilcher & Walters, 1997) or their overall tendency to mind wander in daily life (Carciofo et al., 2014), it remains unclear whether sleep-deprived individuals experience greater mind wandering while they are performing a cognitively demanding task.

Resistance to mind wandering is strongly linked to deployment of executive control (McVay & Kane, 2009, 2010; Mittner et al., 2014; Smallwood, 2010). In particular, the context-regulation framework proposed by Smallwood and colleagues (2015) suggests that attentional resources are allocated to internally or externally focused cognition according to task demands. When task demands are high, executive control is engaged to suppress mind wandering in favor of task completion. Conversely, when task demands are low, executive control can be relaxed with a resultant increase in mind wandering. As sleep deprivation is accompanied by reduced executive control (Chuah, Venkatraman, Dinges, & Chee, 2006; Jennings, Monk, & van der Molen, 2003; Nilsson et al., 2005), it would seem likely that sleep-deprived persons would show increased mind wandering.

Together with loss of executive control, sleep-deprived individuals may exhibit reduced awareness of behavioral impairment (Dorrian, Roach, Fletcher, & Dawson, 2007), as well as reduced error monitoring (Hon & Poh, 2016; Raz, Deouell, & Bentin, 2001; Tsai, Young, Hsieh, & Lee, 2005). Meta-awareness provides

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insight into ongoing performance and contributes toward reducing mind wandering (Sayette, Reichle, & Schooler, 2009). As such, degraded meta-awareness could compromise remedial increases in cognitive resource allocation.

In an alternative framework relating resource allocation to task demands, Forster and Lavie (2009) posited that available perceptual processing capacity affects internally generated TUT or mind wandering in a manner similar to how it affects one's response to exogenous distractors. Specifically, load theory proposes that the processing of peripheral distractors unrelated to immediate task goals occurs when there is sufficient residual processing capacity after fulfilling task goals. As such, the theory would predict reduced mind wandering under conditions of high perceptual load. When processing capacity is diminished, for example in the sleep-deprived state, load theory would predict decreased mind wandering. This view finds some support from our prior work showing that even when sleep-deprived, participants evidenced reduced processing of task-irrelevant peripheral stimuli when central perceptual load was high (Kong et al., 2011).

Critically, context-regulation and perceptual load theories concur in predicting reduced mind wandering under high perceptual load in the well-rested state when both executive function and ample perceptual processing capacity are present. However, these theories generate divergent predictions with respect to the sleep-deprived state, when executive control and perceptual processing capacity are both diminished.

Testing how sleep deprivation affects mind wandering could thus be used to discern which theory would better explain observed behavior in the sleep-deprived state. Here, we contrasted mind wandering and meta-awareness in separate groups of sleep-deprived and well-rested participants. To ascertain the frequency of mind wandering, we employed the "probe-caught method" (Smallwood & Schooler, 2006) where participants are prompted with a thought probe while performing a task. Additionally, this technique can also quantify occurrences of mind wandering without awareness (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Sayette et al., 2009; Sayette, Schooler, & Reichle, 2010), enabling us to assay meta-awareness.

Both well-rested and sleep-deprived participants performed a visual search task under two perceptual load conditions. If the propensity to mind wander is primarily influenced by reduced processing capacity, mind wandering would be expected to decrease following sleep deprivation under conditions of high (but not low) perceptual load. Conversely, if mind wandering during task performance stems from impaired executive control (McVay & Kane, 2009, 2010; Mittner et al., 2014), mind wandering would be expected to increase following sleep deprivation regardless of perceptual load. Additionally, based on previous findings of reduced meta-awareness under altered states of consciousness, we hypothesized that meta-awareness would be reduced following sleep deprivation.

Method

Participants

Forty-eight right-handed adults were recruited and randomly assigned to either a rested-wakefulness (RW) group or a total sleep deprivation (TSD) group. Prior experiments examining effects of perceptual load on mind wandering have shown a large effect size ranging between Cohen's *d* of 1.2 to 1.6 (Forster et al., 2009). Power analysis suggests that a sample size of six to eight would provide sufficient power in detecting an effect of this magnitude. However, as the effects of sleep deprivation on mind wandering and meta-awareness have not been previously examined, we decided on a sample size of 24 per group, similar to prior research examining mind wandering and meta-awareness under altered states of cognition (Sayette et al., 2009, 2010). Data from one participant was excluded from the analysis due to below-chance performance. Due to technical error, data from another participant was also excluded. The final sample consisted of 46 participants ($N = 23$ per group) between the ages of 19 and 30 (RW: 12 males, $M = 23.87$ years; TSD: 12 males, $M = 22.43$ years).

Participants were not informed of their assignment until they entered the laboratory for their overnight experimental session. All participants had normal or corrected-to-normal vision, and none reported any symptoms of sleep apnea. They did not exhibit extreme morningness–eveningness preferences and had no history of psychiatric, neurological, and/or sleep disorders. The Institutional Review Board of the National University of Singapore approved all research procedures, and all participants provided informed consent.

Procedures

Participants visited the lab three times. Each session was scheduled approximately one week apart. The first was a briefing session, where participants were informed about the study procedure and requirements. Suitable participants were also familiarized with the experimental tasks through a practice session.

At the end of the briefing session, participants were given a wrist actigraph unit (Actiwatch, Philips Respironics, Bend, Oregon), which they were required to wear throughout the entire duration of the study. Participants in both groups were required to maintain a normal sleep–wake rhythm (6.5–9 hr a night, sleeping before 0030 hr and waking before 0900 hr) for the entire duration of the study. Each participant's sleep schedule was validated with actigraphy and a sleep diary. All participants adhered to the required sleep schedule, and total sleep time measured by actigraphy was comparable between the RW and TSD group, $t(44) = -0.26$, $p = .795$.

Participants in the RW group entered the lab at 2000 hr and were given a sleep opportunity of 9 hr (2200–0700 hr) before their experimental session (Total sleep time: $M = 7.6$ hr). Participants in the TSD group reported to the lab at 1900 hr and were kept awake under constant supervision until the end of the session next morning. During the TSD session, participants were allowed to engage in nonstrenuous activities, and were required to perform hourly psychometric tests, comprising of the psychomotor vigilance task (Dinges et al., 1997), and the Karolinska Sleepiness Scale (Åkerstedt & Gillberg, 1990). Participants in both groups were also required to abstain from caffeine, medication, and alcohol 24 hr prior to their experimental session.

Prior to the visual search task, both RW and TSD participants took part in an unrelated functional MRI scanning experiment, which lasted approximately 1 hr. They were given a break of 15 min before starting the visual search task.

Visual Search Task

Stimuli for the visual search task comprised arrays of six white letters (one target and five nontargets) arranged in a circle subtending 1.6° of visual angle (see Figure 1). The target letter in each array was either “X” or “N.” In the low perceptual load condition, the five nontarget letters were the letter ‘o’ presented in lower case. In the high perceptual load condition, nontargets were angular letters “H,” “K,” “M,” “Z,” “W,” “V,” selected at random. The position of the target was fully counterbalanced, and each target was equally likely to appear at each of the possible positions. Stimuli were generated and were presented on a 21-in. LCD display with a black background using the Psychophysics toolbox for MATLAB (Brainard, 1997). To minimize distraction from the environment participants performed the visual search task in an enclosed environment while wearing noise-cancellation headphones.

During the visual search task, participants were required to search each array for the target letter (“X” or “N”) under the high or low perceptual load conditions (see Figure 1). The experiment began with a blank screen that appeared for 2,000 ms, followed by a central fixation cross that was displayed for 500 ms. An array of letters then appeared for 100 ms, followed by a blank screen for 2,500 ms. Participants were required to indicate whether the target was the letter “X” (by pressing “1”) or the letter “N” (by pressing “0”). If the participant failed to respond, a 500-ms beep was sounded.

Stimuli were presented using a block design, with each perceptual load condition grouped into blocks of 48 trials. Participants performed a total of 16 blocks (eight low load and eight high load) in the order ABBAABBA-ABBAABBA, counterbalanced between participants (Forster & Lavie, 2009). At the end of each block, the word *break* was presented on the screen and participants waited 8 s before the start of the next block.

Thought probes were presented twice in each block, once at the end and once around the middle of the block, between the 19th to 29th trial ($M = 24$). Prior to the experiment, participants were shown an example of the thought probe. Specific examples and descriptions were provided for what constitutes “on-task” or “off-task” thought, as described in Forster and Lavie (2009). The thought probe consisted of the question, “Where was your attention focused on just before the probe?” Participants were instructed to press ‘Z’ if their thoughts were on-task, or “/” if their thoughts were off-task. This was followed by a second question, “Were you aware of where your attention was focused?” Participants pressed “Z” if they were aware, or “/” if they were unaware. Participants were informed that response to the probe was not timed, that there were no “right” or “wrong” answers, and that they should respond honestly to the questions.

To ensure familiarity with the task during the experimental session, participants practiced the task by performing eight blocks of 60 trials with feedback and 16 blocks of 48 trials without feedback during the briefing session. Thought probes were not presented during this practice. The RW and TSD groups did not differ in accuracy or response times (RT) during the practice for both the low, accuracy: $t(44) = 1.87$, $p = .068$; RT: $t(44) = -0.40$, $p = .690$, and high, accuracy: $t(44) = 1.18$, $p = .246$; RT: $t(44) = 0.49$, $p = .626$, load conditions.

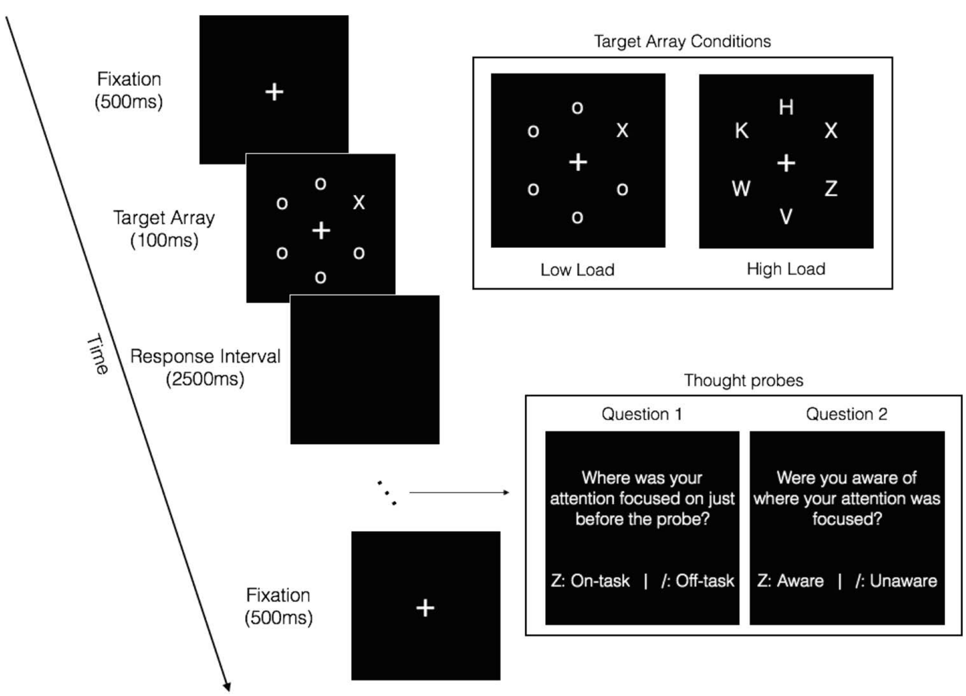

Figure 1. Stimuli from the visual search task. Participants were presented with a target array and were required to identify the target letter (X or N) among other distractors. Thought probes were presented in the middle and at the end of each block.

Results

Visual Search Task

To assess performance on the visual search task, we performed a 2 × 2 mixed analysis of variance (ANOVA) on accuracy and RTs with State (RW, TSD) as a between-subjects factor and Load (high, low) as a within-subject factor. All RT analyses reported here were conducted only on trials where a correct response was made.

There was a main effect of load on accuracy: The high load condition resulted in lower target detection accuracy than the low load condition, $F(1, 44) = 156.79$, $p < .001$, $\eta_p^2 = .78$; Figure 2a, indicating that increased perceptual load made the task more difficult for both RW, $t(22) = 8.44$, $p < .001$, mean difference = 14%, 95% confidence interval (CI) [10.5, 17.3], $d = 4.42$ and TSD groups, $t(22) = 9.28$, $p < .001$, mean difference = 19%, 95% CI [14.9, 23.4], $d = 1.95$.

There was also a main effect of group on accuracy: the RW group ($M = 90\%$, $SE = 1.4\%$) performed significantly better than the TSD group ($M = 76\%$, $SE = 1.4\%$), with higher task accuracy, $F(1, 44) = 48.59$, $p < .001$, $\eta_p^2 = .78$. A marginal interaction was observed for accuracy, $F(1, 44) = 3.91$, $p = .054$.

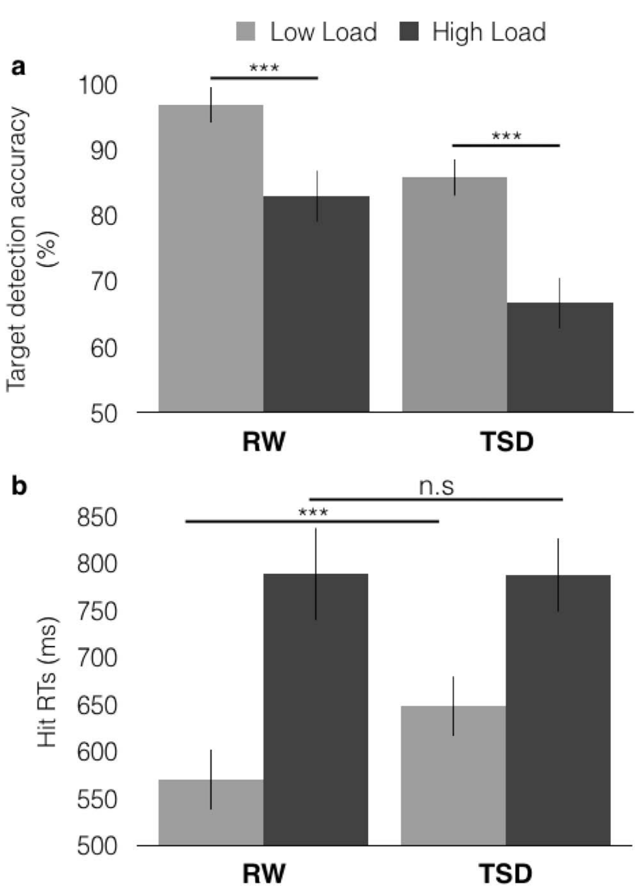

Figure 2. Target detection rate (a) and mean response times (b) under the different load conditions for rested-wakefulness (RW) and total sleep deprivation (TSD). Error bars indicate 95% confidence interval. *** $p < .001$.

For RT, we observed a significant State × Load interaction, $F(1, 44) = 7.15$, $p = .010$, $\eta_p^2 = .14$. Follow-up comparisons showed that RTs were significantly lower in the RW group compared to the TSD group in the low load condition, $t(44) = 3.47$, $p = .001$, mean difference = 0.08, 95% CI [0.03, 0.12], $d = 1.05$, but not in the high load condition, $t(44) = -0.03$, $p = .980$ (Figure 2b).

Self-Reported Task-Unrelated Thoughts (TUTs)

A 2 (State: RW, TSD) × 2 (Load: high, low) mixed ANOVA was used to examine TUT reports. We observed a significant State × Load interaction, $F(1, 44) = 229.36$, $p = .009$, $\eta_p^2 = .15$. Post hoc paired comparisons indicated that in the RW group, percentage of TUT was significantly greater in the low load condition compared to the high load condition, $t(22) = 2.63$, $p = .015$, mean difference = 13%, 95% CI [2.77, 23.32], $d = 0.58$, confirming previous findings on the effect of perceptual load on TUT (see Figure 3). This effect of perceptual load on TUT was absent in the TSD group, $t(22) = -1.11$, $p = .279$.

Examining the difference across states, we observed that the TSD group was significantly more likely than the RW group to report having TUT in the high load condition, $t(44) = 3.25$, $p = .002$, mean difference = 26%, 95% CI [9.75, 41.88], $d = 0.98$, but not in the low load condition, $t(44) = 0.89$, $p = .377$.

TUT and Task Performance

To examine the relationship between mind wandering and task performance, we examined task performance on five trials prior to each thought probe, expecting task performance to be poorer during off-task segments compared to on-task segments. A window of five trials was chosen because previous work suggests that attentional state fluctuates with a periodicity of around 10–15 s (Sonuga-Barke & Castellanos, 2007). This timing has been widely used to capture on-task and off-task differences (Kam & Handy, 2014; Seli et al., 2014; Smallwood, Beach, et al., 2008). Only participants with at least one on-task and one off-task report were included in this analysis. Based on this criterion, we excluded five RW participants (three did not have off-task reports under high load, and two did not have off-task reports in both conditions) and one TSD participant, who did not have any on-task reports (RW: $N = 18$, TSD: $N = 22$).

We performed a 2 (State: RW, TSD) × 2 (Load: high, low) mixed ANOVA on the difference in task performance during on-task and off-task segments (i.e., $\text{Accuracy}_{\text{On-task}} - \text{Accuracy}_{\text{Off-task}}$). A significant main effect of state was observed, $F(1, 38) = 24.62$, $p < .001$, $\eta_p^2 = .39$, indicating that periods recognized by the participants themselves as “mind wandering” were associated with lower performance in the TSD group (see Figure 4). There was no significant main effect of load, $F(1, 38) = 1.09$, $p = .303$, or interaction, $F(1, 38) = 0.06$, $p > .811$.

Post hoc-testing showed that for the RW group, the difference between on-task and off-task performance was not significantly above zero, low: $t(17) = 0.38$, $p > .250$; high: $t(17) = 1.51$ $p = .150$.

Meta-Awareness of TUT

Beyond reports of on-task or off-task, we considered a second measure that indexed meta-awareness of TUT. Five subjects from

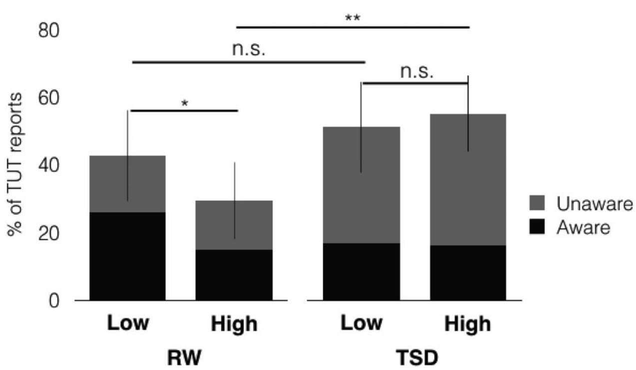

Figure 3. Frequency of task-unrelated thoughts (TUT) at each load condition for rested-wakefulness (RW) and total sleep deprivation (TSD). Each bar was partitioned based on reported awareness of TUT (meta-awareness). Participants were probed a total of 32 times (16 for each load condition) across the entire task. The RW group showed a greater proportion of TUT in the low load condition than the high load condition. This difference was not observed in the TSD group. Error bars indicate 95% confidence interval for total TUT. * $p < .05$. ** $p < .01$.

the RW group did not report any TUT in the high load condition, and were excluded from this analysis (inclusion of these five subjects did not affect our conclusions).

A 2 (State: RW, TSD) × 2 (Load: high, low) mixed ANOVA was performed on the reports of meta-awareness. A significant main effect of load was found $F(1, 39) = 5.44$, $p = .025$, $\eta_p^2 = .12$, indicating that meta-awareness of TUT was greater in the low load condition ($M = 51\%$, $SE = 5.4\%$) than in the high load condition ($M = 39\%$, $SE = 4.6\%$).

Critically, despite being more likely to report TUT, the TSD group exhibited significantly lower meta-awareness compared to the RW group, $F(1, 39) = 10.80$, $p = .002$, $\eta_p^2 = .21$. This was evident in both high, $t(39) = 2.62$, $p = .013$, mean difference = 24.25, 95% CI [5.52, 42.98], $d = 0.84$ and low load conditions, $t(39) = 2.81$, $p = .008$, mean difference = 27.76, 95% CI [7.75, 47.77], $d = 0.90$ (Figure 3). No significant interaction was observed.

Discussion

Using self-reported TUTs as an indicator of mind wandering, we found that a night of TSD increased mind wandering and reduced meta-awareness of mind wandering. Critically, in the rested state, the frequency of mind wandering was reduced by task demands as predicted by load theory. However, following TSD, mind wandering became insensitive to higher perceptual load, suggesting deficient executive control.

The present findings are consistent with predictions arising from context-regulation theory, where attentional resources are allocated to internally or externally focused cognition according to task demands. In the well-rested state, reduced TUT with increasing perceptual load reflects one's ability to allocate attentional resources to meet increasing task demands. In contrast, the absence of such modulation in the sleep-deprived state likely reflects weakened ability to sustain task goals, resulting in their displacement by TUTs. Indeed, control of mind wandering when perceptual processing capacity is attenuated in the sleep-deprived state appears to be contingent on intact executive function, meta-awareness or both.

Meta-awareness of thought content is crucial for maintaining task goals, particularly when one's attention is shifted off-task. Mind wandering results in perceptual decoupling whereby responding to the external environment is hijacked by internal thoughts (Smallwood & Schooler, 2015). In the absence of exogenous capture, redirection of attention toward task goals is dependent on the awareness that one is off-task. Without such meta-awareness, one would be less able to recover from off-task episodes, resulting in poorer task performance. Reduced meta-awareness of cognitive operations in daily life can have other consequences (Smallwood, McSpadden, & Schooler, 2007). For example, individuals with reduced meta-awareness of mind wandering exhibit poorer reading comprehension (Smallwood, McSpadden, & Schooler, 2008), perceive greater disruption to everyday task performance (McVay, Kane, & Kwapil, 2009), and are at increased risk of motor vehicle accidents (Cowley, 2013).

While neuroimaging studies have yet to directly examine mind wandering in sleep-deprived individuals, alterations in task-related activation and intrinsic functional connectivity in sleep-deprived individuals appear consistent with present observations. For example, mind wandering can result in coactivation of parts of the default mode network and executive control network (Christoff et al., 2009). Coactivation of the default mode and sensorimotor as well as cognitive control networks has independently been observed as a result of sleep deprivation (Ong et al., 2015). Reduced anticorrelation of Blood Oxygenation Level Dependent (BOLD) signal fluctuation between the default mode network and networks typically involved in externally oriented cognition in the sleep-deprived state (De Havas, Parimal, Soon, & Chee, 2012; Ong et al., 2015; Sämann et al., 2010) represents reduced segregation between brain networks that could facilitate or signify increased mind wandering.

In conclusion, sleep deprivation can reduce executive control and meta-awareness, impairing one's ability to allocate attentional resources to meet task demands and to suppress task-unrelated thoughts. Sleep-deprived individuals are less aware of off-task episodes, which could lead to delayed reorientation of attention

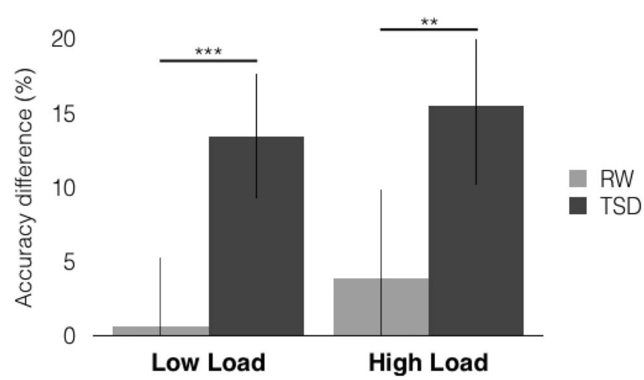

Figure 4. Magnitude of difference in task accuracy ($\text{Accuracy}_{\text{On-task}} - \text{Accuracy}_{\text{Off-task}}$) was significantly greater in the total sleep deprivation (TSD) group than in the rested-wakefulness (RW) group for both high and low load condition. Error bars indicate 95% confidence interval. ** $p < .01$. *** $p < .001$.

back to the task. Through simultaneously increasing tendency for mind wandering, and decreasing meta-awareness, sleep deprivation could therefore induce a state of prolonged perceptual decoupling, where individuals lose track of the task at hand and concurrently fail to notice this.

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