Effects of Total Sleep Deprivation on Procedural Placekeeping: More Than Just Lapses of Attention

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Total sleep deprivation (TSD) impairs attention as well as higher-order cognitive processes. Because attention is a core component of many tasks, it may fully mediate the effect of sleep deprivation on higher-order processes. We examined this possibility using the Psychomotor Vigilance Task as a measure of attention and the UNRAVEL task as a measure of placekeeping, a higher-order process that involves memory operations and supports performance in a wide range of complex tasks. A large sample of participants (N = 138 contributing data) performed the Psychomotor Vigilance Task and UNRAVEL under rested or sleep-deprived conditions. TSD impaired placekeeping generally and memory maintenance processes specifically, above and beyond the effect of participants’ attentional state. The results suggest that TSD may impair a range of higher-order cognitive processes directly, not just fundamental processes such as attention, and that interventions that benefit attention may have limited scope.

Keywords: sleep deprivation, placekeeping, vigilant attention

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Total sleep deprivation (TSD) causes deficits in several domains of cognitive performance, including vigilant attention (Doran, Van Dongen, & Dingess, 2001; Graw, Kräuchi, Knoblauch, Wirz-Justice, & Cajochen, 2004) and higher-order processes such as working memory (Chee et al., 2006; Choo, Lee, Venkatraman, Sheu, & Chee, 2005) and placekeeping (Stepan, Fenn, & Altmann, 2019). Placekeeping, in particular, is the ability to perform a set of steps or subtasks in a specified order without omissions or repetitions. As such, placekeeping incorporates a variety of memory operations, including memory for the set of steps or subtasks, and memory regarding which steps have been accomplished (Altmann, Trafton, & Hambrick, 2017). In turn, placekeeping supports many complex cognitive activities, including procedural performance and problem solving. In problem solving, for example, accurate placekeeping supports exploration of all candidate solutions (i.e., without omissions) without unproductive exploration of failed ones (i.e., without repetitions). Problem solving is a basis of fluid intelligence (Gf), and placekeeping is in fact highly correlated with Gf (Hambrick & Altmann, 2015), even more so than working memory capacity (Burgoyne, Hambrick, & Altmann, in press).

Thus, placekeeping is a broadly relevant component of higher-order cognition, related to factors like Gf that predict real-world outcomes such as academic achievement and job performance.

Of interest here is whether effects of TSD on placekeeping (as a higher-order cognitive process with broad relevance) are direct or are mediated by attention. The question arises because attention is a core component of performance in many tasks (Sturm & Willmes, 2001; Sturm, Willmes, Orgass, & Hartje, 1997). Accordingly, one theoretical view is that effects of TSD on attention fully mediate effects of TSD on higher-order tasks (Balkin, Rupp, Picchioni, & Wesensten, 2008; Doran et al., 2001; Lim & Dinges, 2010). Supporting this view, effects of TSD are typically more robust for tasks that measure attention than for tasks that measure higher-order cognition (see Lim & Dinges, 2010 for a meta-analysis). Moreover, TSD can impair lower-level processes such as probe encoding and motor execution without affecting working memory (Tucker, Whitney, Belenky, Hinson, & Van Dongen, 2010), consistent with the possibility that it spares higher-order processes.

An opposing theoretical view is that TSD impairs higher-order processes directly, even if its effects are partially mediated by attention (Harrison & Horne, 2000). Supporting this view, neuroimaging studies often find that TSD affects activity in the prefrontal cortex, which mediates Gf (Duncan et al., 2000; Gray, Chabris, & Braver, 2003). The change is often a decrease in activity (Choo et al., 2005; Drummond et al., 1999; Mu et al., 2005) but can also be an increase in activity, which is typically associated with relatively spared performance and interpreted as a compensatory response (Chee & Choo, 2004; Chuah, Venkatraman, Dinges, & Chee, 2006; Drummond & Brown, 2001; Drummond, Gillin, &
Brown, 2001; Drummond, Meloy, Yanagi, Orff, & Brown, 2005). Thus, both views have support, but the question of full versus partial mediation by attention has not, to our knowledge, been directly tested.

We measured attention using the Psychomotor Vigilance Task (PVT; Dinges & Powell, 1985; Wilkinson & Houghton, 1982) because deficits in this task are the primary basis for the view that attention fully mediates effects of sleep deprivation (e.g., Lim & Dinges, 2010). We measured placekeeping using the UNRAVEL task (e.g., Altman et al., 2017), which is known to show deficits because of sleep deprivation (Stepan et al., 2019). In this task, UNRAVEL is an acronym specifying a set of steps (one per letter) and the order in which to perform them (the order of the letters). On each trial, the participant tries to perform the next step in the sequence, starting over with U upon reaching L. The task environment provides no information about which step is correct, leaving the participant to keep track of where they are in the sequence. Placekeeping is made more challenging by periodic interruptions, which require the participant to remember the step performed before an interruption in the face of decay and interference during the interruption. Interruptions allow us to isolate effects of sleep deprivation specifically on memory maintenance processes that keep the target memory active during interruptions. To isolate these processes, we measure performance on postinterruption trials, which immediately follow interruptions, while controlling for performance on noninterruption trials, which immediately follow other trials, and which involve all the same cognitive operations as postinterruption trials, except for memory maintenance. The interruptions in this task were designed to represent the influence of a dynamic, interactive environment on performance of tasks that extend in time and also to capture effects of the self-interruptions that are an integral part of problem solving. Specifically, exploring a solution path or testing a hypothesis takes time and focus, and afterward, if that path was a dead end, the solver must revisit the set of candidate solutions and ideally remember which failed and which are untested.

Participants performed the PVT and UNRAVEL twice, first in the evening and again the next morning. After the evening session, participants were randomly assigned either to sleep at home or to wake up by 9:00 AM. They also refrained from napping on the day of the study and did not consume any caffeine, alcohol, or drugs for 24 hr prior to the study. Sleep diary data, reported in Table 1, indicated that rested and sleep-deprived participants had similar amounts of sleep prior to the study. Table 2 summarizes actigraphy data from rested participants for the night between sessions. Comparison of Tables 1 and 2 suggests that rested participants slept more prior to the study than during the night between sessions, but this difference could reflect overestimation of self-reported sleep duration (Lauderdale, Knutson, Yan, Liu, & Rathouz, 2008). For rested participants, total sleep time during the night between sessions generally correlated with performance the morning after, as we discuss in the online supplemental material (som).

Of an initial sample of 154 participants, two were excluded for attrition, three for noncompliance with instructions, two for technical problems, two for missing PVT data, and seven for failing an UNRAVEL accuracy criterion described below, leaving 138 participants contributing data (18–25 years old, \( M_{\text{age}} = 19.18, SD = 1.34, 91 \) females). Our stopping rule was that we collected data through two full semesters. Participants were given course credit as compensation. Michigan State University’s Institutional Review Board approved the study and all participants gave informed consent.

### Materials

**PVT.** Participants monitored a blank computer screen for the appearance of a large red circle and were instructed to make a mouse click as quickly as possible when the circle appeared. Making a mouse click caused the circle to disappear and triggered feedback on reaction time. The circle appeared at random intervals between 1 and 10 s. The task lasted 10 min.

**UNRAVEL.** We briefly described this task in the introduction. On each step of the UNRAVEL sequence, the participant applies a different two-alternative, forced-choice decision rule to a randomly generated stimulus. Figure 1 shows sample stimuli and the seven decision rules. Any rule can apply to any stimulus, so participants must remember their place in the sequence. Participants perform the sequence in a loop, returning to U when they reach L. Performance is periodically interrupted by a typing task. Two strings of letters appear on the computer display, one string at a time, and the participant must type each string correctly into a box. Each string comprises the 14 UNRAVEL responses (see Figure 1) presented in randomized order. In our sample, participants took an average of 22.27 s (SD = 6.21) to type the two strings in the morning session. After an interruption, participants try to resume the UNRAVEL sequence where they left off prior to the interruption.

The measure of interest is placekeeping errors, meaning steps performed out of sequence. Placekeeping errors can be detected because every rule has unique response options, so from any response, we can code which step the participant selected. Placekeeping errors are coded with respect to the step performed on the

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1 Because of experimenter error, demographic information for one participant is missing.
previous trial. For example, if steps N, R, V, and E are performed in succession, V would be an error because the A step was skipped, but E would not be an error because it correctly follows V. Errors applying the decision rule can also occur (these are analyzed in the SOM). A correct trial is one on which there is neither a placekeeping error nor a decision-rule error.

We analyzed placekeeping errors separately for postinterruption trials, which immediately follow interruptions, and noninterruption trials, which immediately follow other trials. The two trial types measure the same set of cognitive operations except for memory maintenance, which is measured on postinterruption trials only.

There were four blocks of trials per session. Each block contained an average of 66 trials (SD = 11.76) and exactly 10 interruptions. Between blocks, participants received feedback and a chance to rest. If the percentage of correct trials in that block was below 70%, the participant was instructed to be more accurate. The maintenance, which is measured on postinterruption trials only.

Table 1
Sleep Characteristics From Sleep Diaries Kept Five Nights Prior to the Study

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Rested</th>
<th>Deprived</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average sleep time, 5 nights prior to study</td>
<td>7 hr 40 min (58 min)</td>
<td>7 hr 38 min (1 hr 14 min)</td>
<td>t(132) = .42, p = .67</td>
</tr>
<tr>
<td>Total sleep time, night before study</td>
<td>7 hr 39 min (1 hr 30 min)</td>
<td>7 hr 46 min (1 hr)</td>
<td>t(132) = .55, p = .58</td>
</tr>
<tr>
<td>Time going to bed, night before study</td>
<td>11:53 pm (1 hr 13 min)</td>
<td>12:10 AM (56 min)</td>
<td></td>
</tr>
<tr>
<td>Time of awakening, day of study</td>
<td>8:06 AM (55 min)</td>
<td>8:23 AM (52 min)</td>
<td></td>
</tr>
</tbody>
</table>

Note. Standard deviation is in parentheses. Four participants were missing sleep diaries and are excluded from this analysis.

Table 2
Sleep Characteristics Recorded From Actigraphy Monitors for the Night Between the Evening and Morning Sessions in the Rested Group

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Rested</th>
<th>Deprived</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total sleep time</td>
<td>5 hrs 49 min (51 min)</td>
<td></td>
</tr>
<tr>
<td>Time spent in bed</td>
<td>6 hrs 7 min (53 min)</td>
<td></td>
</tr>
<tr>
<td>Time spent awake</td>
<td>18 min (12 min)</td>
<td></td>
</tr>
<tr>
<td>Number of awakenings</td>
<td>.67 (.86)</td>
<td></td>
</tr>
<tr>
<td>Sleep efficiency</td>
<td>95% (3%)</td>
<td></td>
</tr>
</tbody>
</table>

Note. Standard deviation in parenthesis. Sleep efficiency is calculated by dividing the sleep time by the time spent in bed.

The experimental effects are plotted in Figure 2 (PVT) and Figure 3 (UNRAVEL). Analyses of variance are reported in the SOM. Here we report hierarchical regression analyses that test a subset of these effects and that test a mediation model using the approach described by Baron and Kenny (1986). The model is

Figure 1. Above: two examples of randomly generated stimuli from the UNRAVEL task. Below: the UNRAVEL rules that correspond to each step (letter) in the UNRAVEL acronym, and the correct keyboard responses for each rule based on the two stimuli above. The bolded letters represent the possible response options for each rule. Figure adapted with permission from Altmann et al. (2017). See the online article for the color version of this figure.

Deprived participants stayed awake in the laboratory with two trained (and rested) research assistants and completed sleepiness and mood assessments every 2 hr (see SOM for additional protocol and sleepiness and mood analyses). Rested participants returned to the laboratory at 8:30 AM for the morning session, which began at 9:00 AM for all participants. At this point, deprived participants were sleep-derived for approximately 24 hr. The morning session included sleepiness and mood assessments, UNRAVEL, PVT, and other cognitive tasks associated with the larger study and lasted approximately 1.5 hr. Afterward, deprived participants were given a ride home.

As part of the larger study, participants consumed capsules containing either caffeine or placebo, distributed in double-blind fashion. Deprived participants consumed a capsule every 4 hr overnight. Rested participants consumed a capsule when they returned to the laboratory at 8:30 AM. We report results from participants who received placebo.
shown in Figure 4. TSD is the independent variable, placekeeping is the dependent variable, and attention is the mediator.

We first confirmed that TSD affected attention (Path a in Figure 4). We regressed lapses in the morning session of the PVT against (a) evening lapses, to control for individual differences in attention, and (b) group (rested, deprived). Table 3 shows the results. Both predictors were significant. The effect of evening lapses indicates reliable individual differences in attention. The effect of group confirms an effect of TSD on attention, such that TSD increases lapses in attention.

We then confirmed that TSD affected placekeeping without attention as a mediator (Path c). We regressed morning placekeeping errors against (a) evening placekeeping errors, to control for individual differences in placekeeping, and (b) group, separately for postinterruption trials and noninterruption trials. Table 4 shows the results. Both predictors were significant, for both trial types. The effects of evening placekeeping errors indicate reliable individual differences in placekeeping. The effects of group indicate unmediated effects of TSD on placekeeping, such that TSD increases errors on postinterruption trials and noninterruption trials.

We then tested the mediated effects of TSD on placekeeping. We regressed morning placekeeping errors against (a) evening placekeeping errors, (b) morning lapses, and (c) group, separately for postinterruption and noninterruption trials. Table 5 shows the results. All three predictors were significant for both trial types. The effects of morning lapses indicate that morning attention predicts morning placekeeping (Path b). The effects of group indicate that TSD directly impairs placekeeping when the mediating effects of attention are removed from placekeeping ability (Path c').

Next, we compared the two models of effects of TSD on placekeeping, one with and one without attention as a mediator (Paths c vs. c'). By Sobel test, the effect of TSD was smaller with attention as a mediator (Path c') for postinterruption errors, $Z = 3.07, p < .002$, and noninterruption errors, $Z = 2.96, p < .003$. Together these analyses support partial mediation, meaning that some but not all of the effect of TSD on placekeeping is mediated by attention.

Finally, we asked whether TSD directly affected the memory maintenance component of postinterruption trials. We conducted a hierarchical regression analysis on postinterruption errors in which we removed the variance associated with noninterruption errors. The results. Both predictors were significant, for both trial types.

Table 3
Hierarchical Regression Analysis for Morning Lapses in Attention (Path a in Figure 4)

<table>
<thead>
<tr>
<th>Variables</th>
<th>$B$</th>
<th>$SE_b$</th>
<th>$\beta$</th>
<th>$t$</th>
<th>$p$</th>
<th>$R^2$</th>
<th>$\Delta R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evening lapses in attention</td>
<td>.61</td>
<td>.166</td>
<td>.291</td>
<td>3.69</td>
<td>&lt;.001</td>
<td>.064</td>
<td>.064</td>
</tr>
<tr>
<td>Step 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group (rested, deprived)</td>
<td>3.63</td>
<td>.860</td>
<td>.333</td>
<td>4.23</td>
<td>&lt;.001</td>
<td>.174</td>
<td>.109</td>
</tr>
</tbody>
</table>

Note. Statistics are from the full model. df: Step 1 (1, 136), Step 2 (2, 135).
that attention, as a core component of performance in many tasks, fully mediates the effects of TSD on higher-order processes (Balkin et al., 2008; Doran et al., 2001; Lim & Dinges, 2010). The other theory is that attention may partially mediate these effects but that TSD also has direct effects on higher-order processes (Harrison & Horne, 2000). We measured attention using the PVT as a standard measure of attention deficits caused by TSD. We tested mediation with respect to placekeeping, a higher-order process involved in procedural performance, problem solving, and other cognitive activities that depend on keeping track of location in a sequence or hierarchy of steps or subtasks.

Our results uniformly support partial mediation and direct effects. Attention accounted for about 14% of the variance in effects of TSD on placekeeping (14.1% on postinterruption trials, 13.3% on noninterruption trials), but a direct effect of TSD on placekeeping remained, accounting for an additional 5.1% of variance on postinterruption trials and 2.7% on noninterruption trials. We also found a direct effect of TSD on memory maintenance processes, which support placekeeping by maintaining target information in an active state during interruptions. After controlling for performance on noninterruption trials, which require all the same cognitive operations as postinterruption trials except for memory maintenance, a direct effect of TSD remained, accounting for an additional 5.1% of variance on postinterruption trials.

A more thorough understanding of direct effects of TSD has important implications for intervention research aimed at mitigating deficits associated with sleep loss. Specifically, different or multiple interventions may be necessary to protect against costly errors associated with sleep loss. For example, our results suggest that an intervention that benefits attention, such as caffeine (Killgore, Kahn-Greene, Grugle, Killgore, & Balkin, 2009), may not reduce costly errors in procedural performance that have been linked to TSD (e.g., Navy Office of Information, 2017).

One limitation of the present design is that the PVT may not measure all relevant aspects of attention and that additional indicators of attention could produce full mediation. However, the direct effect of TSD on memory maintenance controls for any attention process that plays a role in placekeeping generally but was not measured by the PVT, in that it removes the influence of any process active on noninterruption trials. Accordingly, to rule out full mediation would have required an indicator focused specifically on the role of attention in memory maintenance.

**Table 4**
Hierarchical Regression Analyses for Morning Placekeeping Errors, Unmediated by Attention (Path c in Figure 4)

<table>
<thead>
<tr>
<th>Variables</th>
<th>B</th>
<th>SE</th>
<th>β</th>
<th>t</th>
<th>p</th>
<th>R²</th>
<th>ΔR²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Postinterruption trials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 1 Evening placekeeping errors</td>
<td>.91</td>
<td>.139</td>
<td>.463</td>
<td>6.56</td>
<td>&lt; .001</td>
<td>.219</td>
<td>.219</td>
</tr>
<tr>
<td>Step 2 Group (rested, deprived)</td>
<td>.08</td>
<td>.016</td>
<td>.330</td>
<td>4.68</td>
<td>&lt; .001</td>
<td>.328</td>
<td>.109</td>
</tr>
<tr>
<td>Noninterruption trials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 1 Evening placekeeping errors</td>
<td>1.18</td>
<td>.280</td>
<td>.242</td>
<td>4.19</td>
<td>&lt; .001</td>
<td>.116</td>
<td>.116</td>
</tr>
<tr>
<td>Step 2 Group (rested, deprived)</td>
<td>.03</td>
<td>.010</td>
<td>.264</td>
<td>3.40</td>
<td>&lt; .001</td>
<td>.185</td>
<td>.070</td>
</tr>
</tbody>
</table>

**Note.** Statistics are from the full model. df: Step 1 (1, 136), Step 2 (2, 135).

**Table 6**
Hierarchical Regression Analyses for Morning Postinterruption Errors, Mediated by Morning Lapses in Attention, and Controlling for Noninterruption Errors (Step 3)

<table>
<thead>
<tr>
<th>Variables</th>
<th>B</th>
<th>SE</th>
<th>β</th>
<th>t</th>
<th>p</th>
<th>R²</th>
<th>ΔR²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1 Evening errors</td>
<td>.628</td>
<td>.116</td>
<td>.319</td>
<td>5.42</td>
<td>&lt; .001</td>
<td>.219</td>
<td>.219</td>
</tr>
<tr>
<td>Step 2 Morning lapses</td>
<td>.003</td>
<td>.001</td>
<td>.148</td>
<td>2.29</td>
<td>.023</td>
<td>.360</td>
<td>.141</td>
</tr>
<tr>
<td>Step 3 Morning errors, noninterruption</td>
<td>.825</td>
<td>.131</td>
<td>.270</td>
<td>7.29</td>
<td>&lt; .001</td>
<td>.558</td>
<td>.199</td>
</tr>
<tr>
<td>Group (rested, deprived)</td>
<td>.035</td>
<td>.014</td>
<td>.156</td>
<td>2.59</td>
<td>&lt; .011</td>
<td>.579</td>
<td>.021</td>
</tr>
</tbody>
</table>

**Note.** Statistics are from the full model. df: Step 1 (1, 136), Step 2 (2, 135), Step 3 (3, 134), Step 4 (4, 133).

**Discussion**

We tested two prominent theories of the role of attention in the far-reaching cognitive deficits associated with TSD. One theory is...
Another limitation is that our sample consisted of college-aged adults, who may differ from the general population in their response to sleep deprivation. For example, college-aged students may need more sleep and therefore may be more affected by sleep deprivation. Indeed, in the week leading up to the study, participants averaged approximately 7 hr 40 min of sleep per night, which is higher than the 2016 national average (Knutson et al., 2017) An important direction for sleep deprivation research generally is to make use of broader samples.

Context

This study was a collaboration between two laboratories, one with expertise in the effects of sleep and sleep deprivation on learning, memory, and cognition and the other with expertise developing tasks and cognitive models to examine goal-directed behavior. The latter laboratory developed the UNRAVEL task to study procedural error under conditions of frequent task interruption, and we have used it in a program of research sponsored by the U.S. Navy to study performance impairments because of sleep loss on a range of tasks and measures. The present study was designed to address theoretical questions raised by Stepan et al. (2019).

References


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