BRIEF REPORT

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 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; Chua, 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., Altmann 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. Intermittent feedback on reaction time. The circle appeared at random intervals following 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.

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 sleep at the lab overnight and again the next morning. After the evening session, participants were randomly assigned to either sleep at home or to stay awake in the laboratory. The analyses focused on the morning session, with evening performance used to control for stable individual differences in ability to perform the tasks.

Method

Participants

Participants were native English-speaking undergraduates at Michigan State University. Individuals were eligible for participation if they had never been diagnosed with any memory or sleep disorder, were not color blind, did not have a strong time-of-day preference (scores of 42–58 on the Morningness-Eveningness Questionnaire; Horne & Ostberg, 1976), and did not have any major sleep disturbances (scores of 0–10 on the sleep disturbance section of the Pittsburgh Sleep Quality Index; Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). Additionally, as part of the requirements of a larger study, participants reported no heart conditions and moderate caffeine use (up to 400 mg daily).

Participants slept a minimum of 6 hr the night before the study and woke 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 indicates 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, tage = 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

1 Because of experimenter error, demographic information for one participant is missing.
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.

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.

Results
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
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.

### 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>$SE_m$</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).
placekeeping generally.

directly affected memory maintenance specifically as well as

Note.

Step 3

Step 2

Step 1

Errors, Mediated by Morning Lapses in Attention (Paths b and
c' in Figure 4)

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

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

Noninterruption trials measure all the same cognitive operations as
postinterruption trials, except those operations that maintain target
information active in memory during interruptions. Thus, removing
variance associated with noninterruption errors removes vari-
ance associated with all processes except memory maintenance.
We regressed morning postinterruption placekeeping errors against
(a) evening postinterruption placekeeping errors, (b) morning
lapses in attention, (c) morning noninterruption placekeeping er-
ors (the new predictor in this analysis), and (d) group (rested,
deprived). Table 6 shows the results. The effect of morning non-
interruption placekeeping errors was significant, indicating that the
two trial types correlated. With this effect removed, the effect of
group was still significant (p = .011), which is evidence that TSD
directly affected memory maintenance specifically as well as
placekeeping generally.

Discussion

We tested two prominent theories of the role of attention in the
far-reaching cognitive deficits associated with TSD. One theory is

Table 5
Hierarchical Regression Analyses for Morning Placekeeping
Errors, Mediated by Morning Lapses in Attention (Paths b and
c’ in Figure 4)

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 pro-
cess 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 ef-
fects. 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 placekeep-
ing 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 perfor-
ance on noninterruption trials, which require all the same cog-
nitive operations as postinterruption trials except for memory
maintenance, a direct effect of TSD remained, accounting for an
additional 2.1% of variance on postinterruption trials.

A more thorough understanding of direct effects of TSD has
important implications for intervention research aimed at mitigat-
ing deficits associated with sleep loss. Specifically, different or
multiple interventions may be necessary to protect against costly
effects 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 indi-
cators 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 spe-
cifically on the role of attention in memory maintenance.

Variables B SE\textsubscript{\textit{B}} \textit{t} \textit{p} \textit{R}^2 \Delta \textit{R}^2
Postinterruption trials
Step 1 Evening placekeeping errors .91 .139 .646 6.56 <.001 .219 .219
Step 2 Group (rested, deprived) .08 .016 .330 4.68 <.001 .328 .109
Noninterruption trials
Step 1 Evening placekeeping errors 1.18 .280 .326 4.19 <.001 .116 .116
Step 2 Group (rested, deprived) .03 .010 .264 3.40 <.001 .185 .070

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

Variables B SE\textsubscript{\textit{B}} \textit{t} \textit{p} \textit{R}^2 \Delta \textit{R}^2
Step 1 Evening placekeeping errors .628 .116 .319 5.42 <.001 .219 .219
Step 2 Morning lapses .003 .010 .148 2.29 <.023 .360 .141
Step 3 Morning errors, noninterruption .825 .113 .470 7.29 <.001 .558 .199
Step 4 Group (rested, deprived) .035 .014 .156 2.59 <.011 .579 .021

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