In press, *Journal of Experimental Psychology: General*.

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

Michelle E. Stepan
Erik M. Altmann
Kimberly M. Fenn

Department of Psychology, Michigan State University

This research was supported by grant N000141612841 from the Office of Naval Research to the second and third authors.

Correspondence concerning this article should be addressed to:

Michelle E. Stepan
Department of Psychology
316 Physics Rd
East Lansing, MI 48824
Email: stepanmi@msu.edu

Word count (pp. 2-13) = 3,226
Abstract

Total sleep deprivation 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 (PVT) 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 PVT and UNRAVEL under rested or sleep-deprived conditions. Total sleep deprivation impaired placekeeping generally and memory maintenance processes specifically, above and beyond the effect of participants’ attentional state. The results suggest that total sleep deprivation 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
Total sleep deprivation causes deficits in several domains of cognitive performance, including vigilant attention (Doran, Van Dongen, & Dinges, 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, in press). 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 is 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 total sleep deprivation (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., Altmann et al., 2017), which is known to show deficits due to sleep deprivation (Stepan et al., in press). 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 post-interruption trials, which immediately follow interruptions, while controlling for performance on non-interruption trials, which immediately follow other trials, and which involve all the same cognitive operations as post-interruption 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 afterwards, 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 remain awake in the lab. Our 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, 1975), 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 hours the night before the study and woke up by 09:00. They also refrained from napping on the day of the study and did not consume any caffeine, alcohol, or drugs for 24 hours 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 the difference could reflect over-estimation 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 Supplementary Online Material (SOM).

Of an initial sample of 154 participants, 2 were excluded for attrition, 3 for noncompliance with instructions, 2 for technical problems, 2 for missing PVT data, and 7 for failing an UNRAVEL accuracy criterion described below, leaving 138 participants contributing data (18–25 years old, $M_{age}=19.18$, $SD=1.34$, 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.

a Due to experimenter error, demographic information for one participant is missing.
Sleep Deprivation and Placekeeping

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 seconds. The task lasted 10 minutes.

**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 (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 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 post-interruption trials, which immediately follow interruptions, and non-interruption 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 post-interruption 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 evening session was coded as a failure if the percentage was below 70% on two or more blocks. Participants who failed the evening session ($n=7$) were excluded from all analyses on grounds that we could not be sure they understood the task.

**Procedure**

Participants arrived at 22:00 and completed sleepiness and mood assessments (see SOM for task descriptions and analyses). Participants then completed UNRAVEL, PVT, and other cognitive assessments associated with the larger study. The evening session took approximately 2 hours. After completing these tasks, participants were randomly assigned to a Rested ($n=61$) or Deprived ($n=77$) group. Participants and research assistants were blind to condition until all evening tasks were completed. Participants in the Rested group received a Charge 2 activity monitor (Fitbit Inc., San Francisco, CA) to track their sleep at home that night.

Deprived participants stayed awake in the laboratory with two trained (and rested) research assistants and completed sleepiness and mood assessments every 2 hours (see SOM for
additional protocol and sleepiness and mood analyses). Rested participants returned to the lab at 08:30 for the morning session, which began at 09:00 for all participants. At this point, Deprived participants were sleep-deprived for approximately 24 hours. The morning session included sleepiness and mood assessments, UNRAVEL, PVT, and other cognitive tasks associated with the larger study, and lasted approximately 1.5 hours. Afterwards, 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 hours overnight. Rested participants consumed a capsule when they returned to the lab at 08:30. We report results from participants who received only placebo.

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. Total sleep deprivation (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 (1) evening lapses, to control for individual differences in attention, and (2) 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 (1) evening placekeeping errors, to control for individual differences in placekeeping, and (2) Group, separately for post-interruption trials and non-interruption 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 post-interruption trials and non-interruption trials.

We then tested the mediated effects of TSD on placekeeping. We regressed morning placekeeping errors against (1) evening placekeeping errors, (2) morning lapses, and (3) Group, separately for post-interruption and non-interruption 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 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 post-interruption errors, Z=3.07, p=.002, and non-interruption 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 post-interruption trials. We conducted a hierarchical regression analysis on post-interruption errors in which we removed the variance associated with non-interruption errors. Non-interruption trials measure all the same cognitive operations as post-interruption trials, except
those that maintain target information active in memory during interruptions. Thus, removing variance associated with non-interruption errors removes variance associated with all processes except memory maintenance. We regressed morning post-interruption placekeeping errors against (1) evening post-interruption placekeeping errors, (2) morning lapses in attention, (3) morning non-interruption placekeeping errors (the new predictor in this analysis), and (4) 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 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 post-interruption trials, 13.3% on non-interruption trials), but a direct effect of TSD on placekeeping remained, accounting for an additional 5.1% of variance on post-interruption trials and 2.7% on non-
interruption 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 non-interruption trials, which require all the same cognitive operations as post-interruption trials except for memory maintenance, a direct effect of TSD remained, accounting for an additional 2.1% of variance on post-interruption 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 non-interruption trials. Accordingly, to rule out full mediation would have required an indicator focused specifically on the role of attention in memory maintenance.

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 7hrs 40min 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 labs, 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 lab 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 US Navy to study performance impairments due to sleep loss on a range of tasks and measures. The present study was designed to address theoretical questions raised by Stepan et al. (in press).
References


Table 1

Sleep characteristics from sleep diaries kept five nights prior to the study

<table>
<thead>
<tr>
<th></th>
<th>Rested</th>
<th>Deprived</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average sleep time,</td>
<td>7hrs 40min</td>
<td>7hrs 38min</td>
<td>$t(132)=.42, p=.67$</td>
</tr>
<tr>
<td>5 nights prior to study</td>
<td>(58min)</td>
<td>(1hr 14min)</td>
<td></td>
</tr>
<tr>
<td>Total sleep time,</td>
<td>7hrs 39min</td>
<td>7hrs 46min</td>
<td>$t(132)=.55, p=.58$</td>
</tr>
<tr>
<td>night before study</td>
<td>(1hr 30min)</td>
<td>(1hr)</td>
<td></td>
</tr>
<tr>
<td>Time going to bed,</td>
<td>23:53</td>
<td>00:10</td>
<td></td>
</tr>
<tr>
<td>night before study</td>
<td>(1hr 13min)</td>
<td>(56min)</td>
<td></td>
</tr>
<tr>
<td>Time of awakening,</td>
<td>08:06</td>
<td>08:23</td>
<td></td>
</tr>
<tr>
<td>day of study</td>
<td>(55min)</td>
<td>(52min)</td>
<td></td>
</tr>
</tbody>
</table>

Note. Standard deviation in parenthesis. 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*

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

*Note.* Standard deviation in parenthesis. Sleep efficiency is calculated by dividing the sleep time by the time spent in bed.
Table 3

Hierarchical regression analysis for morning lapses in attention (Path a in Figure 4)

<table>
<thead>
<tr>
<th>Step 1</th>
<th>B</th>
<th>SEB</th>
<th>β</th>
<th>t</th>
<th>p</th>
<th>R²</th>
<th>Δ R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evening lapses in attention</td>
<td>0.61</td>
<td>.166</td>
<td>.291</td>
<td>3.69</td>
<td>&lt; .001</td>
<td>.064</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></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).
Table 4
Hierarchical regression analyses for morning placekeeping errors, unmediated by attention
(Path c in Figure 4)

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SE_B</th>
<th>β</th>
<th>t</th>
<th>p</th>
<th>R²</th>
<th>ΔR²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Post-interruption trials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evening placekeeping errors</td>
<td>0.91</td>
<td>0.139</td>
<td>0.463</td>
<td>6.56</td>
<td>&lt; .001</td>
<td>.219</td>
<td>.219</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>0.08</td>
<td>0.016</td>
<td>0.330</td>
<td>4.68</td>
<td>&lt; .001</td>
<td>.328</td>
<td>.109</td>
</tr>
<tr>
<td><strong>Non-interruption trials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Step 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evening placekeeping errors</td>
<td>1.18</td>
<td>0.280</td>
<td>0.326</td>
<td>4.19</td>
<td>&lt; .001</td>
<td>.116</td>
<td>.116</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>0.03</td>
<td>0.010</td>
<td>0.264</td>
<td>3.40</td>
<td>.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 5

*Hierarchical regression analyses for morning placekeeping errors, mediated by morning lapses in attention (Paths b and c' in Figure 4)*

<table>
<thead>
<tr>
<th></th>
<th>B</th>
<th>SEB</th>
<th>β</th>
<th>t</th>
<th>p</th>
<th>R²</th>
<th>Δ R²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Post-interruption trials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Step 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evening placekeeping errors</td>
<td>.774</td>
<td>.134</td>
<td>.393</td>
<td>5.76</td>
<td>&lt; .001</td>
<td>.219</td>
<td>.219</td>
</tr>
<tr>
<td><strong>Step 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morning lapses in attention</td>
<td>.006</td>
<td>.001</td>
<td>.310</td>
<td>4.34</td>
<td>&lt; .001</td>
<td>.360</td>
<td>.141</td>
</tr>
<tr>
<td><strong>Step 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group (Rested, Deprived)</td>
<td>.054</td>
<td>.016</td>
<td>.238</td>
<td>3.42</td>
<td>.001</td>
<td>.411</td>
<td>.051</td>
</tr>
<tr>
<td><strong>Non-interruption trials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Step 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evening placekeeping errors</td>
<td>.919</td>
<td>.273</td>
<td>.255</td>
<td>3.37</td>
<td>.001</td>
<td>.116</td>
<td>.116</td>
</tr>
<tr>
<td><strong>Step 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morning lapses in attention</td>
<td>.004</td>
<td>.001</td>
<td>.323</td>
<td>4.08</td>
<td>&lt; .001</td>
<td>.249</td>
<td>.133</td>
</tr>
<tr>
<td><strong>Step 3</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group (Rested, Deprived)</td>
<td>.022</td>
<td>.010</td>
<td>.171</td>
<td>2.22</td>
<td>.028</td>
<td>.275</td>
<td>.027</td>
</tr>
</tbody>
</table>

*Note.* Statistics are from the full model. df: Step 1 (1, 136), Step 2 (2, 135), Step 3 (3, 134).
Table 6

Hierarchical regression analyses for morning Post-interruption errors, mediated by morning lapses in attention, and controlling for non-interruption errors (Step 3)

<table>
<thead>
<tr>
<th>Step</th>
<th>B</th>
<th>SE_B</th>
<th>β</th>
<th>t</th>
<th>p</th>
<th>R²</th>
<th>Δ R²</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 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</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>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</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morning errors, non-interruption</td>
<td>.825</td>
<td>.113</td>
<td>.470</td>
<td>7.29</td>
<td>&lt; .001</td>
<td>.558</td>
<td>.199</td>
</tr>
<tr>
<td>Step 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group (Rested, Deprived)</td>
<td>.035</td>
<td>.014</td>
<td>.156</td>
<td>2.59</td>
<td>.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).
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 from Altmann, Trafton, and Hambrick (2014).
Figure 2. Number of lapses (reaction times greater than 500 ms) in the Psychomotor Vigilance Task, separated by Group (Rested, Deprived) and Session (Evening, Morning). Errors bars are standard error of the mean.
Figure 3. Proportion of trials on which a placekeeping error occurred in the UNRAVEL task, separated by Group (Rested, Deprived), Session (Evening, Morning), and Trial Type (Post-interruption, Non-interruption). Errors bars are standard error of the mean.
Figure 4. Mediation model with sleep deprivation as the independent variable, placekeeping as the dependent variable, and attention as the mediator. Numbers are standardized regression coefficients ($\beta$). Where two are present, the first is for post-interruption placekeeping trials and the second for non-interruption placekeeping trials. **Bold**, $p < .01$. *Underline*, $p < .05$. 