TESTING THE ROLE OF VIGILANT ATTENTION AS A MEDIATING PROCESS FOR COGNITIVE DEFICITS DUE TO SLEEP DEPRIVATION

By

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SUPPLEMENTAL MATERIAL

Experiment 1

Additional Methods

Materials

Stanford Sleepiness Scale (SSS). The SSS assesses subjective sleepiness (Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973). Participants indicated their current level of tiredness or alertness on a 7-point Likert scale ranging from 1 (feeling active, vital, alert, or wide awake) to 7 (no longer fighting sleep, sleep onset soon, having dream-like thoughts).

International Positive and Negative Affect Schedule Short Form (I-PANAS-SF). The I-PANAS-SF (Thompson, 2007) measures mood and is a 10-item scale devised from the 20-item Positive and Negative Affect Schedule (Watson, Clark, & Tellegen, 1988). Participants rated 10 adjectives on how well each described their current mood, ranging from "very slightly or not at all" to "extremely." Five of the ten adjectives were used to calculate the positive affect score (alert, inspired, determined, attention, active) and the other five were used to compute the negative affect score (upset, hostile, ashamed, nervous, afraid).

Additional Results

UNRAVEL. We also analyzed decision-rule errors, which occurred when the participant selected the correct step, and therefore did not make a placekeeping error, but chose the wrong response from the two alternatives. Decision-rule errors tend be very rare. We performed an ANOVA with Group (Rested, Sleep-Deprived) as a between-subjects factor and Session (Evening, Morning) as a within-subjects factor. See Table S1 for means and standard errors. There was a main effect of Group, $F(1, 136) = 4.74$, $p = .031$, $\eta_p^2 = .034$, with more errors in the

Sleep-deprived group than the Rested group. There was no effect of Session, $F < 1$, and no Group X Session interaction, $F < 1$.

Table S1

UNRAVEL decision-rule errors for Experiment 1

	Evening	**Morning**
Rested	.01 (.003)	.01 (.003)
Sleep-deprived	.02 (.003)	.02 (.003)

Note. Standard error in parentheses.

We also performed a regression analyses on decision-rule errors as we did with post-interruption and non-interruption errors. We regressed morning decision-rule errors against evening decision-rule errors and Group, and the effect of Group was not significant, $t(135) = 1.40$, $p = .164$. This result was not due to suppression by attention, as the effect remained null when we included morning lapses, $t < 1$. Thus, TSD had no effect on the representations and processes involved in mapping a stimulus to a response using a decision-rule. These results suggest that not all processes required to perform the UNRAVEL task were directly impaired by TSD. One measure that was not affected was decision-rule accuracy; although, these errors occurred very infrequently and there may be floor effects.

Sleepiness and Mood. First, we examined at how sleepiness and mood changed from the evening session to the morning session for rested and sleep-deprived participants. Means and standard error are reported in Table S2[1]. We performed ANOVAs with Group (Rested, Sleep-

[1] Participants who were missing data ($n = 1$) were excluded from analyses.

deprived) as a between-subjects factor and Session (Evening, Morning) as a within-subjects factor for sleepiness, positive affect, and negative affect.

Table S2

Sleepiness and Mood for Experiment 1

	22:00	**01:00**	**03:00**	**05:00**	**07:00**	**09:00**
			Sleepiness			
Sleep-deprived	2.55 (.09)	3.18 (.12)	3.82 (.16)	4.48 (.17)	5.25 (.18)	5.25 (.19)
Rested	2.57 (.10)	--	--	--	--	2.77 (.19)
			Positive Affect			
Sleep-deprived	14.29 (.38)	12.14 (.43)	10.36 (.42)	8.80 (.42)	7.69 (.39)	7.89 (.41)
Rested	13.90 (.43)	--	--	--	--	13.77 (.50)
			Negative Affect			
Sleep-deprived	6.26 (.18)	5.69 (.16)	5.73 (.17)	5.78 (.17)	6.22 (.21)	6.55 (.24)
Rested	5.93 (.18)	--	--	--	--	5.80 (.23)

Note. Standard error in parentheses.

For sleepiness, there was a main effect of Group, $F(1, 135) = 63.23$, $p < .001$, $\eta_p^2 = .319$, such that the Sleep-deprived group ($M = 3.87$, $SE = .10$) rated themselves as sleepier than the Rested group ($M = 2.67$, $SE = .11$). There was also a main effect of Session, $F(1, 135) = 120.91$, $p < .001$, $\eta_p^2 = .472$, which indicated that participants rated themselves as sleepier in the morning ($M = 4.15$, $SE = .12$) than in the evening ($M = 2.55$, $SE = .07$). Importantly, there was also a Group X Session interaction, $F(1, 135) = 89.74$, $p < .001$, $\eta_p^2 = .399$, which qualified the main effects. Paired t-tests showed that the Sleep-deprived group reported an increase in sleepiness between the evening and morning session, $t(76) = -14.17$, $p < .001$; whereas, the Rested group did not, $t(59) = -1.17$, $p = .25$.

Next, we examined how mood changed from the evening to the morning session. For positive affect, there was a main effect of Group, $F(1, 135) = 27.91$, $p < .001$, $\eta_p^2 = .171$, such that sleep-deprived participants were less positive ($M = 11.17$, $SE = .33$) than rested participants ($M = 13.83$, $SE = .38$). There was also a main effect of Session, $F(1, 135) = 86.92$, $p < .001$, $\eta_p^2 = .392$, which indicated that participants rated themselves as less positive in the morning ($M = 10.84$, $SE = .33$) than in the evening ($M = 14.16$, $SE = .29$). Finally, there was also a significant interaction, $F(1, 135) = 80.06$, $p < .001$, $\eta_p^2 = .372$, and paired t-tests showed that the Sleep-deprived group became significantly less positive from the evening to the morning session, $t(76) = 13.99$, $p < .001$; whereas, rested participants did not, $t(59) = .25$, $p = .81$.

For negative affect, there was also a main effect Group, $F(1, 135) = 5.99$, $p = .02$, $\eta_p^2 = .042$, indicating that sleep-deprived participants rated themselves as overall more negative ($M = 6.38$, $SE = .14$) than rested participants ($M = 5.87$, $SE = .16$). There was no main effect of Session, $F(1, 135) = .11$, $p = .74$, $\eta_p^2 = .001$, and no interaction, $F(1, 135) = 1.22$, $p = .27$, $\eta_p^2 = .009$.

For the next set of analyses, we looked at how sleepiness and mood changed across the night for sleep-deprived participants[2]. See Table S2 for means and standard error. We performed a repeated measures ANOVA with Time (22:00, 01:00, 03:00, 05:00, 07:00, 09:00) as a within-subjects factor. There was a main effect of Time for sleepiness, $F(5, 360) = 103.42$, $p < .001$, η_p^2

[2] Participants missing data at any of the timepoints ($n = 4$) were excluded from analyses.

= .590, positive affect, $F(5, 360) = 94.59$, $p < .001$, $\eta_p^2 = .568$, and negative affect, $F(5, 360) = 7.02$, $p < .001$, $\eta_p^2 = .089$. We performed post-hoc comparisons between each timepoint and the following timepoint to see how sleepiness and mood progressed over the night (22:00 vs. 01:00, 01:00 vs. 03:00, 03:00 vs. 05:00, 05:00 vs. 07:00, 07:00 vs. 09:00). Sleepiness generally increased over the night and then stabilized in the morning – specifically, sleepiness increased between 22:00 and 01:00, $t(72) = -5.58$, $p < .001$, between 01:00 and 03:00, $t(72) = -4.70$, $p < .001$, between 03:00 and 05:00, $t(72) = -5.32$, $p < .001$, and between 05:00 and 07:00, $t(72) = -5.83$, $p < .001$. Sleepiness remained stable between 07:00 and 09:00, $t(72) = .00$, $p = 1.00$.

There was a very similar trend for positive affect in that positive affect decreased over the night but then stabilized in the morning. Positive affect decreased between 22:00 and 01:00, $t(72) = 5.21$, $p < .001$, between 01:00 and 03:00, $t(72) = 5.78$, $p < .001$, between 03:00 and 05:00, $t(72) = 5.56$, $p < .001$, and between 05:00 and 07:00, $t(72) = 4.42$, $p < .001$. Positive affect did not change between 07:00 and 09:00, $t(72) = -.65$, $p = .52$.

Lastly, negative affect increased between 22:00 and 01:00, $t(72) = 3.69$, $p < .001$, and between 05:00 and 07:00, $t(72) = -3.24$, $p = .002$. There was a marginal increase in negative affect between 07:00 and 09:00, $t(72) = -1.99$, $p = .051$. Negative affect did not change between 01:00 vs. 03:00, $t(72) = -.29$, $p = .77$, or 03:00 vs. 05:00, $t(72) = -.42$, $p = .68$.

Sleep Duration and Performance for Rested Participants. We examined the relationship between total sleep time (TST) during the night between sessions and performance the morning after for rested participants[3]. TST was correlated with morning lapses, $r = -.387$, $p = .01$, and morning post-interruption errors, $r = -.425$, $p < .01$, such that participants who slept

[3] Thirteen participants were missing actigraphy data due to technical problems and were excluded from this analysis.

more had fewer lapses in attention and fewer post-interruption errors. TST was not correlated with morning non-interruption errors, r = -.201, p = .170, although the trend was in the expected direction.

Experiment 2

Additional Methods

The additional methods are the same as Experiment 1.

Additional Results

UNRAVEL. We examined decision-rule errors which occurred when the participant performed the correct step but chose the wrong response from the two alternative forced choice decision-rule. We performed an ANOVA with Group (Rested, Sleep-deprived) as a between-subjects factor and Session (Evening, Morning) as a within-subjects factor. See Table S3 for means and standard errors. There was no main effect of Group, $F(1, 252) = .55$, $p = .46$, $\eta_p^2 = .002$, and no main effect of Session, $F(1, 252) = .21$, $p = .64$, $\eta_p^2 = .001$. There was, however, a Group X Session interaction, $F(1, 252) = 9.18$, $p = .003$, $\eta_p^2 = .035$. To understand this interaction, we compared evening and morning performance, separately for rested and sleep-deprived participants. Paired t-tests showed that rested participants made fewer errors in the morning than in the evening, $t(93) = -3.79$, $p < .001$, while sleep-deprived participants had a similar error rate in both sessions, $t(159) = 1.79$, $p = .08$.

Table S3

UNRAVEL decision-rule errors for Experiment 2

	Evening	**Morning**
Rested	.02 (.002)	.01 (.004)
Sleep-deprived	.01 (.002)	.02 (.003)

Note. Standard error in parentheses.

We also performed hierarchical regressions on decision-rule errors as we did with post-interruption and non-interruption errors. We regressed morning decision-rule errors against (1) evening decision-rule errors and (2) Group and the effect of Group was significant, $t(253) = 2.51$, $p = .01$. We then added PVT lapses as a mediator: (1) evening decision-rule errors, (2) morning lapses, and (3) Group. Group was no longer significantly related to decision-rule errors, $t(253) = 1.11$, $p = .27$, but morning lapses were, $t(253) = 5.32$, $p < .001$. We then tested mediating effects of resistance to proactive interference: (1) evening decision-rule errors, (2) resistance to proactive interference, and (3) Group. Group was significantly related to decision-rule errors, $t(253) = 2.51$, $p = .01$, but resistance to proactive interference was not, $t(253) = -.12$, $p = .90$. Finally, we performed a regression with both mediators: (1) evening decision-rule errors, (2) morning lapses, (3) resistance to proactive interference, and (4) Group. Morning lapses was significant, $t(253) = 5.32$, $p < .001$, but resistance to proactive interference, $t(253) = -.28$, $p = .78$, and Group, $t(253) = 1.12$, $p = .27$, were not. These results suggest that vigilant attention underlies deficits in decision-rule errors after TSD. Interestingly, in Experiment 1, TSD did not significantly affect decision-rule errors. Taken together, the results from Experiments 1 and 2 suggest that TSD does not directly impair decision-rule errors but when deficits are present that they are mediated by vigilant attention deficits.

Sleepiness and Mood. For the first set of analyses, we examined how sleepiness and mood changed from the evening to the morning session. We performed mixed ANOVAs with Group (Rested, Sleep-deprived) as a between-subjects factor and Session (Evening, Morning) as a within-subjects factor[4]. Summary data is reported in Table S4.

Table S4

Sleepiness and mood for Experiment 2

	22:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00
						Sleepiness				
Sleep-deprived	2.68 (.09)	3.41 (.10)	3.80 (.10)	4.22 (.12)	4.59 (.12)	4.64 (.13)	4.80 (.12)	4.96 (.12)	4.87 (.14)	4.73 (.12)
Rested	2.73 (.11)	--	--	--	--	--	--	--	--	2.36 (.14)
						Positive Affect				
Sleep-deprived	13.84 (.28)	10.95 (.30)	9.73 (.27)	8.92 (.28)	8.27 (.29)	8.13 (.26)	7.87 (.27)	7.66 (.26)	7.96 (.28)	8.30 (.27)
Rested	13.57 (.36)	--	--	--	--	--	--	--	--	13.75 (.36)
						Negative Affect				
Sleep-deprived	6.72 (.15)	5.97 (.15)	5.86 (.14)	5.90 (.14)	5.77 (.15)	5.96 (.17)	5.99 (.16)	5.93 (.16)	6.08 (.16)	6.36 (.17)
Rested	6.48 (.17)	--	--	--	--	--	--	--	--	5.68 (.20)

Note. Standard errors in parentheses.

For sleepiness, there was a main effect of Group, $F(1, 248) = 92.85$, $p < .001$, $\eta_p^2 = .272$, which indicated that sleep-deprived participants rated themselves as sleepier than rested participants and a main effect of Session, $F(1, 248) = 69.55$, $p < .001$, $\eta_p^2 = .219$, which

[4] Four participants were missing data and are not included in analyses.

indicated that participants rated themselves as sleepier in the morning than the evening. Importantly, there was also a Group X Session interaction, $F(1, 248) = 144.93$, $p < .001$, $\eta_p^2 = .369$. To understand this interaction, we used paired t-tests to examine how performance changed across sessions, separately for rested and sleep-deprived participants. Rested participants rated themselves as less sleepy in the morning than the evening, $t(93) = -2.61$, $p = .01$; whereas, Sleep-deprived participants showed the opposite pattern and rated themselves as more sleepy in the morning than the evening, $t(155) = 15.72$, $p < .001$.

Next, we examined positive affect. There was a main effect of Group, $F(1, 248) = 43.89$, $p < .001$, $\eta_p^2 = .150$, and a main effect of Session, $F(1, 248) = 136.54$, $p < .001$, $\eta_p^2 = .355$, which together indicated that sleep-deprived participants rated themselves as less positive than rested participants and participants in the morning rated themselves as less positive than in the evening. There was also a Group X Session interaction, $F(1, 248) = 154.48$, $p < .001$, $\eta_p^2 = .384$. Paired t-tests showed that rested participants rated themselves similarly in both sessions, $t(93) = .47$, $p = .64$, but sleep-deprived participants rated themselves as less positive in the morning than in the evening, $t(155) = -19.77$, $p < .001$.

Finally, we investigated negative affect. There was a main effect of Group, $F(1, 248) = 5.55$, $p = .02$, $\eta_p^2 = .022$, which showed that sleep-deprived participants rated themselves as having more negative affect that rested participants. There was also a main effect of Session, $F(1, 248) = 18.80$, $p < .001$, $\eta_p^2 = .070$, such that participants rated themselves as more negative in the evening than in the morning. The Group X Session interaction was marginal, $F(1, 248) = 2.93$, $p = .09$, $\eta_p^2 = .012$.

For the second set of analyses, we examined how sleepiness and mood changed across the night within the Sleep-deprived group. We performed a linear mixed effects model with Time (22:00, 01:00, 02:00, 03:00, 04:00, 05:00, 06:00, 07:00, 08:00, 09:00) as a within-subjects fixed effect. Summary data is reported in Table S4.

There was a significant effect of Time for sleepiness, $F(9, 133) = 44.86$, $p < .001$, positive affect, $F(9, 127) = 62.17$, $p < .001$, and negative affect, $F(9, 121) = 5.62$, $p < .001$. We compared each timepoint with the following timepoint using post-hoc pairwise comparisons to examine how sleepiness and mood progressed across the night (22:00 vs. 01:00, 01:00 vs. 02:00, 02:00 vs. 03:00, 03:00 vs. 04:00, 04:00 vs. 05:00, 05:00 vs. 06:00, 06:00 vs. 07:00, 07:00 vs. 08:00, and 08:00 vs. 09:00). Sleepiness increased, *ps* < .001, and positive affect decreased, *ps* < .001, between all timepoints up until 04:00. After 04:00, sleepiness, *p*s > .10, and positive affect, *p*s > .06, plateaued and remained consistent between all remaining timepoints. Negative affect initially decreased between 22:00 and 01:00, $p < .001$, but then remained stable between all timepoints until 08:00, *p*s > .20. Negative affect then showed an increase between 08:00 and 09:00, $p = .01$.

Sleep Duration and Performance for Rested Participants. We correlated TST from the night between sessions for rested participants with morning performance on UNRAVEL and PVT[5]. TST was not correlated with morning post-interruption errors, $r = -.057$, $p = .64$, or non-interruption errors, $r = -.056$, $p = .64$. TST was marginally correlated with morning PVT lapses, $r = -.231$, $p = .05$, in the direction that more TST was related to fewer lapses in the morning.

[5] Twenty-three participants were missing actigraphy data due to technical problems and are excluded from the analyses.

Experiment 3

Additional Methods

The additional methods are the same as Experiment 1.

Additional Results

UNRAVEL. We analyzed decision-rule errors, which occurred when the participant selected the correct step in the UNRAVEL sequence but chose the wrong response from the two alternatives. Summary data on effects of TSD and caffeine on decision-rule errors are reported in Table S5. We analyzed the data using a mixed ANOVA with Group (Rested, Sleep-deprived) and Pill (Caffeine, Placebo) as between-subjects factors and Session (Evening, Morning) as a within-subjects factor.

Table S5

UNRAVEL decision-rule errors, separated by Pill condition, for Experiment 3

	Evening	**Morning**
Rested: Placebo	.01 (.002)	.01 (.002)
Rested: Caffeine	.01 (.002)	.01 (.002)
Sleep-deprived: Placebo	.02 (.002)	.01 (.002)
Sleep-deprived: Caffeine	.02 (.002)	.01 (.001)

Note. Standard error in parentheses.

There was no main effect of Group, $F(1, 318) = 1.24$, $p = .27$, $\eta_p^2 = .004$. However, there was a main effect of Session which indicated that participants made more decision-rule errors in the evening than in the morning, $F(1, 318) = 19.17$, $p < .001$, $\eta_p^2 = .057$. There was no Group X

Session interaction, $F(1, 318) = 1.89$, $p = .17$, $\eta_p^2 = .006$. Turning to the effects of caffeine, there was no main effect of Pill, $F(1, 318) = .001$, $p = .97$, $\eta_p^2 < .001$. There were also no interactions involving Pill: $F(1, 318) = .57$, $p = .45$, $\eta_p^2 = .002$ for the Group X Pill interaction, $F(1, 318) = .34$, $p = .56$, $\eta_p^2 = .001$ for the Session X Pill interaction, and $F(1, 318) = 1.74$, $p = .19$, $\eta_p^2 = .005$ for the Group X Pill X Session interaction.

For the next set of analyses, we specifically assessed the Sleep-deprived group and examined whether pattern of caffeine administration had any effect on decision-rule errors. Summary data on effects of caffeine administration schedule for sleep-deprived participants are reported in Table S6. We performed a mixed ANOVA with Session and Administration (Sustained, Acute, Placebo) as factors. There was no main effect of Administration, $F(2, 190) = .18$, $p = .84$, $\eta_p^2 = .002$, and no Administration X Session interaction, $F(2, 190) = 1.03$, $p = .36$, $\eta_p^2 = .011$.

Table S6

UNRAVEL decision-rule errors in the Sleep-deprived group, separated by caffeine administration schedule, for Experiment 3

	Evening	**Morning**
Sustained	.02 (.003)	.01 (.002)
Acute	.01 (.003)	.01 (.002)
Placebo	.02 (.003)	.01 (.002)

Note. Standard error in parentheses.

Sleepiness and Mood. First, we assessed the effects of TSD and caffeine on sleepiness and mood from the evening (baseline) session to the morning session (collapsing across the Sustained and Acute Sleep-deprived subgroups). Means and standard error are reported in Table

S7. We performed mixed ANOVAs for sleepiness[6], positive affect, and negative affect[7], each with Group (Rested, Sleep-deprived) and Pill (Caffeine, Placebo) as between-subjects factors and Session (Morning, Evening) as a within-subjects factor.

[6] Two participants were missing sleepiness data from either the evening or morning session and were not included in any sleepiness analyses.
[7] Participants who were missing positive (*n* = 3) or negative affect (*n* = 2) data from either the evening or morning session were not included in their respective analyses.

Table S7

Sleepiness and mood, separated by Pill condition, for Experiment 3

	22:00	01:00	03:00	05:00	07:00	09:00
Sleepiness						
Sleep-deprived: Caffeine	2.65 (.08)	2.99 (.09)	3.61 (.11)	4.29 (.13)	4.79 (.14)	4.84 (.14)
Sleep-deprived: Placebo	2.55 (.11)	3.24 (.13)	3.83 (.16)	4.47 (.20)	5.21 (.21)	5.12 (.21)
Rested: Caffeine	2.78 (.10)	--	--	--	--	2.69 (.17)
Rested: Placebo	2.57 (.11)	--	--	--	--	2.77 (.18)
Positive Affect						
Sleep-deprived: Caffeine	13.97 (.29)	12.60 (.34)	10.76 (.34)	9.65 (.35)	8.30 (.32)	8.63 (.31)
Sleep-deprived: Placebo	14.26 (.43)	12.17 (.49)	10.47 (.49)	8.85 (.52)	7.67 (.47)	7.97 (.46)
Rested: Caffeine	13.09 (.41)	--	--	--	--	13.49 (.46)
Rested: Placebo	13.90 (.43)	--	--	--	--	13.77 (.49)
Negative Affect						
Sleep-deprived: Caffeine	6.39 (.13)	5.71 (.11)	5.70 (.12)	5.83 (.14)	5.92 (.14)	6.02 (.16)
Sleep-deprived: Placebo	6.33 (.20)	5.60 (.16)	5.55 (.17)	5.76 (.20)	6.16 (.21)	6.41 (.23)
Rested: Caffeine	6.37 (.17)	--	--	--	--	5.44 (.20)
Rested: Placebo	5.93 (.19)	--	--	--	--	5.80 (.21)

Note: Standard error in parentheses.

For sleepiness, there was a main effect of Group showing that sleep-deprived participants rated themselves as overall more sleepy, $F(1, 316) = 113.47$, $p < .001$, $\eta_p^2 = .264$. There was also a main effect of Session indicating that participants rated themselves as more sleepy during the morning session, $F(1, 316) = 182.76$, $p < .001$, $\eta_p^2 = .366$. Importantly, there was a Session X Group interaction, $F(1, 316) = 166.74$, $p < .001$, $\eta_p^2 = .345$. Sleep-deprived participants only rated themselves as more sleepy than the rested group during the morning session, $t(318) = 13.82$, $p < .001$, but not the evening session, $t(318) = -.77$, $p = .44$. Turning to the effects of caffeine, there was no main effect of Pill, $F(1, 316) < .001$, $p = .999$, $\eta_p^2 < .001$, and no interactions between Pill and Session, $F(1, 316) = 3.20$, $p = .08$, $\eta_p^2 = .010$, or Pill and Group, $F(1, 316) = .44$, $p = .51$, $\eta_p^2 = .001$. Finally, there was no a three way interaction between Pill, Session, and Group, $F(1, 316) = .05$, $p = .82$, $\eta_p^2 < .001$.

Next, we looked at positive affect. There was a main effect of Group indicating that sleep-deprived participants rated themselves as less positive than rested participants, $F(1, 315) = 45.96$, $p < .001$, $\eta_p^2 = .127$. There was also a main effect of Session which indicated that participants rated themselves as more positive in the evening than in the morning, $F(1, 315) = 156.46$, $p < .001$, $\eta_p^2 = .332$. However, there was also an interaction between Group and Session that qualified the main effects, $F(1, 315) = 171.03$, $p < .001$, $\eta_p^2 = .352$. Sleep-deprived and rested participants showed similar positive affect in the evening, $t(317) = 1.60$, $p = .11$, but sleep-deprived participants were less positive than rested participants in the morning, $t(317) = -12.26$, $p < .001$. As with sleepiness, there was no main effect of Pill, $F(1, 315) = .37$, $p = .54$, $\eta_p^2 = .001$, no interaction between Pill and Session, $F(1, 315) = 2.63$, $p = .11$, $\eta_p^2 = .008$, and no interaction between Pill and Group, $F(1, 315) = .90$, $p = .34$, $\eta_p^2 = .003$. There was also not a three-way interaction between Pill, Session, and Group, $F(1, 315) = .23$, $p = .63$, $\eta_p^2 = .001$.

Lastly, we analyzed negative affect. There was a significant main effect of Group such that sleep-deprived participants rated themselves as overall more negative than rested participants, $F(1, 316) = 7.07$, $p = .01$, $\eta_p^2 = .022$. There was a main effect of Session which indicated that participants were overall more negative in the evening than the morning, $F(1, 316) = 8.65$, $p = .004$, $\eta_p^2 = .027$. Finally, there was a marginal interaction between Group and Session, $F(1, 316) = 3.68$, $p = .06$, $\eta_p^2 = .011$. There was no main effect of Pill, $F(1, 316) = .14$, $p = .71$, $\eta_p^2 < .001$, and no Pill by Group interaction, $F(1, 316) = .41$, $p = .52$, $\eta_p^2 = .001$. However, there was an interaction between Pill and Session, $F(1, 316) = 7.32$, $p = .01$, $\eta_p^2 = .023$. Paired t-tests showed that participants who received caffeine had a significant decrease in negative affect from the evening to morning session, $t(198) = -4.08$, $p < .001$, whereas participants who received placebo did not, $t(120) = -.14$, $p = .89$. Finally, there was not a three way interaction between Pill, Session, and Group, $F(1, 316) = .87$, $p = .35$, $\eta_p^2 = .003$.

For the next set of analyses, we examined the Sleep-deprived group specifically and how sleepiness[8] and mood[9] changed across the night. Means and standard error are reported in Table S7. We performed mixed ANOVAs with Time (22:00, 01:00, 03:00, 05:00, 07:00, 09:00) as a within-subjects factor and Pill (Caffeine, Placebo) as a between-subjects factor.

There was a main effect of Time for sleepiness, $F(5, 910) = 153.89$, $p < .001$, $\eta_p^2 = .458$, positive affect, $F(5, 905) = 154.26$, $p < .001$, $\eta_p^2 = .460$, and negative affect, $F(5, 910) = 11.04$, $p < .001$, $\eta_p^2 = .057$. We compared each timepoint with the following timepoint using post-hoc

[8] Participants who were missing sleepiness data from any of the time points ($n = 9$) were removed from sleepiness analyses.
[9] Participants who were missing positive ($n = 10$) or negative affect ($n = 9$) data from any of the time points were removed from their respective analyses.

pairwise comparisons to examine how sleepiness and mood progressed across the night. Polynomial trend analyses indicated that sleepiness linearly increased across the night, $F(1, 182) = 421.33$, $p < .001$, $\eta_p^2 = .698$, while positive affect linearly decreased across the night, $F(1, 181) = 435.68$, $p < .001$, $\eta_p^2 = .706$. Negative affect showed a quadratic trend indicative of an initial decrease in negative affect early in the night followed by a steady increase, $F(1, 182) = 34.20$, $p < .001$, $\eta_p^2 = .158$. There was no main effect of Pill for sleepiness, $F(1, 182) = 1.78$, $p = .18$, $\eta_p^2 = .010$, positive affect, $F(1, 181) = .86$, $p = .36$, $\eta_p^2 = .005$, or negative affect, $F(1, 182) = .06$, $p = .81$, $\eta_p^2 < .001$. There was also no Pill x Time interaction for sleepiness, $F(5, 910) = 1.16$, $p = .33$, $\eta_p^2 = .006$, positive affect, $F(5, 905) = 1.01$, $p = .41$, $\eta_p^2 = .006$, or negative affect, $F(5, 910) = 1.47$, $p = .20$, $\eta_p^2 = .008$.

Our second aim was to investigate two patterns of caffeine administration within the Sleep-deprived group. Means and standard error reported in Table S8. For sleepiness, positive, and negative affect we ran a mixed ANOVA with Time as a within-subjects factor and Administration (Sustained, Acute, Placebo) as a between-subjects factor. There was no main effect of Administration for sleepiness, $F(2, 181) = .89$, $p = .41$, $\eta_p^2 = .010$, positive, $F(2, 180) = 1.28$, $p = .28$, $\eta_p^2 = .014$, or negative affect, $F(2, 181) = .23$, $p = .80$, $\eta_p^2 = .002$. There was also no interaction between Administration and Time for negative affect, $F(10, 905) = 1.19$, $p = .30$, $\eta_p^2 = .013$. However, there was an interaction between Administration and Time for sleepiness, $F(10, 905) = 1.97$, $p = .03$, $\eta_p^2 = .021$, and positive affect, $F(10, 900) = 2.81$, $p = .002$, $\eta_p^2 = .030$. To understand these interactions, we compared the three administration subgroups at each timepoint. There was an effect of Administration only at 01:00 for sleepiness, $F(2, 181) = 3.64$, $p = .03$, $\eta_p^2 = .039$, and positive affect, $F(2, 180) = 5.75$, $p = .004$, $\eta_p^2 = .060$. Post-hoc comparisons with a Bonferroni corrected p-value (.017) showed that the Acute subgroup rated themselves as sleepier than the Placebo subgroup at 01:00, $p = .016$, but not sleepier than the Sustained subgroup, $p = .03$. The Sustained and Placebo subgroups did not differ from each other, $p = .78$. At 01:00, the Acute subgroup showed higher positive affect than the Sustained subgroup, $p = .001$, and marginally higher positive affect than the Placebo subgroup, $p = .02$. The Sustained and Placebo subgroups did not differ from each other, $p = .33$. There was no effect of Administration at any other timepoints for sleepiness or positive affect, $Fs < 2.50$, $ps > .09$.

Table S8

Sleepiness and mood in the Sleep-deprived group, separated by caffeine administration schedule, for Experiment 3

	22:00	**01:00**	**03:00**	**05:00**	**07:00**	**09:00**
			Sleepiness			
Sustained	2.76 (.11)	3.19 (.13)	3.64 (.16)	4.19 (.19)	4.57 (.20)	4.89 (.20)
Acute	2.54 (.11)	2.79 (.13)	3.59 (.16)	4.40 (.19)	5.00 (.20)	4.79 (.20)
Placebo	2.55 (.11)	3.24 (.13)	3.83 (.16)	4.47 (.20)	5.21 (.21)	5.12 (.21)
			Positive Affect			
Sustained	13.70 (.41)	11.52 (.46)	10.37 (.47)	9.75 (.50)	8.49 (.45)	8.10 (.43)
Acute	14.24 (.42)	13.69 (.47)	11.16 (.48)	9.55 (.50)	8.10 (.46)	9.18 (.44)
Placebo	14.26 (.43)	12.17 (.48)	10.47 (.49)	8.85 (.52)	7.67 (.47)	7.97 (.45)
			Negative Affect			
Sustained	6.18 (.19)	5.60 (.15)	5.65 (.17)	5.91 (.19)	5.89 (.20)	5.98 (.23)
Acute	6.60 (.19)	5.83 (.15)	5.75 (.17)	5.75 (.19)	5.95 (.20)	6.05 (.23)
Placebo	6.33 (.20)	5.60 (.16)	5.55 (.17)	5.76 (.20)	6.16 (.21)	6.41 (.24)

Note. Standard error in parentheses.

Sleep Duration and Performance for Rested Participants. TST the night between sessions for rested participants[10] was correlated with post-interruption errors, r = -.274, p = .003, non-interruption errors, r = -.201, p = .03, and lapses, r = -.306, p = .001, in the morning. Thus, more TST was related to better performance – fewer placekeeping errors and fewer lapses in the morning.

[10] Fourteen participants were missing actigraphy data and are not included in analyses.

Experiment 4

Additional Methods

The additional methods are the same as Experiment 1.

Additional Results

UNRAVEL. We examined decision-rule errors. We performed a mixed ANOVA with Group (Rested, Sleep-deprived) as a between-subjects factor and Session (Evening, Morning) as a within-subjects factor. Means and standard error are reported in Table S9. There was no main effect of Group, $F(1, 261) = 1.14$, $p = .29$, $\eta_p^2 = .004$. There was a main effect of Session, $F(1, 261) = 15.56$, $p < .001$, $\eta_p^2 = .056$, indicating that participants made fewer decision-rule errors in the morning. There was also a Group X Session interaction, $F(1, 261) = 7.55$, $p = .01$, $\eta_p^2 = .028$. To understand this interaction, we examined how performance changed from the evening to the morning, separately for rested and sleep-deprived participants. Rested participants made fewer errors in the morning than in the evening, $t(101) = -3.84$, $p < .001$; whereas, sleep-deprived participants made a similar number of errors in both sessions, $t(160) = -1.04$, $p = .30$.

Table S9

UNRAVEL decision-rule errors for Experiment 4

	Evening	**Morning**
Rested	.02 (.002)	.01 (.002)
Sleep-deprived	.01 (.001)	.01 (.001)

Note. Standard error in parentheses.

Next, we examined decision-rule errors within the Sleep-deprived group based on nap opportunity. We performed a mixed ANOVA with Nap Opportunity (0, 30, 60 min) as a between-subjects factor and Session as a within-subjects factor. Means and standard error are reported in Table S10. There was no main effect of Nap Opportunity, $F(2, 158) = .45$, $p = .64$, $\eta_p^2 = .006$, or Session, $F(1, 158) = 1.63$, $p = .20$, $\eta_p^2 = .010$. There was also no interaction, $F(2, 158) = 2.12$, $p = .12$, $\eta_p^2 = .026$.

Table S10

UNRAVEL decision-rule errors in the Sleep-deprived group, separated by nap opportunity, for Experiment 4

	Evening	**Morning**
60 min	.01 (.002)	.01 (.002)
30 min	.01 (.002)	.01 (.003)
0 min	.01 (.002)	.01 (.003)

Note. Standard error in parentheses.

Sleepiness and Mood. For the first set of analyses, we examined how sleepiness and mood changed from the evening to the morning session for rested and sleep-deprived participants. We performed mixed ANOVAs with Group (Rested, Sleep-deprived) as a between-subjects factor and Session (Evening, Morning) as a within-subjects factor[11]. Summary data is reported in Table S11.

[11] Six participants were missing sleepiness and mood data and are not included in analyses.

Table S11

Sleepiness and mood for Experiment 4

	Evening	**Morning**
	Sleepiness	
Sleep-deprived	2.67 (.08)	4.74 (.10)
Rested	2.75 (.10)	2.41 (.13)
	Positive Affect	
Sleep-deprived	13.85 (.26)	8.43 (.27)
Rested	13.57 (.34)	13.62 (.34)
	Negative Affect	
Sleep-deprived	6.66 (.12)	6.38 (.15)
Rested	6.46 (.16)	5.69 (.19)

Note. Standard errors in parentheses.

First, we investigated sleepiness. There was a main effect of Group, $F(1, 276) = 92.53$, $p < .001$, $\eta_p^2 = .251$, which indicated that sleep-deprived participants rated themselves as sleepier than rested participants. There was also a main effect of Session, $F(1, 276) = 80.24$, $p < .001$, $\eta_p^2 = .225$, such that participants rated themselves as sleepier in the morning than in the evening. Finally, there was a Group X Session interaction, $F(1, 276) = 154.99$, $p < .001$, $\eta_p^2 = .360$. To understand the interaction, we examined how sleepiness changed from the evening to the morning session, separately for rested and sleep-deprived participants. Paired t-tests showed that rested participants were less sleepy in the morning compared to the evening, $t(103) = -2.43$, $p = .02$; whereas, sleep-deprived participants were more sleepy in the morning, $t(173) = 16.65$, $p < .001$.

Next, we examined positive affect. There was a main effect of Group, $F(1, 276) = 43.11$, $p < .001$, $\eta_p^2 = .135$, which indicated that sleep-deprived participants rated themselves as less positive than rested participants. There was also a main effect of Session, $F(1, 276) = 153.49$, $p < .001$, $\eta_p^2 = .357$, such that participants rated themselves as less positive in the morning. Finally, there was a Group X Session interaction, $F(1, 276) = 159.04$, $p < .001$, $\eta_p^2 = .366$. Paired t-tests indicated that rested participants had similar amounts of positive affect in both sessions, $t(103) = .14$, $p = .89$, but sleep-deprived participants were less positive in the morning compared to the evening, $t(173) = -20.71$, $p < .001$.

Finally, we examined negative affect. There was a main effect of Group, $F(1, 276) = 5.78$, $p = .02$, $\eta_p^2 = .021$, which showed that sleep-deprived participants rated themselves as more negative than rested participants. There was also a main effect of Session, $F(1, 276) = 18.04$, $p < .001$, $\eta_p^2 = .061$, such that participants rated themselves as more negative in the evening. Finally, there was a Group X Session interaction, $F(1, 276) = 3.89$, $p = .049$, $\eta_p^2 = .014$. Paired t-tests indicated that sleep-deprived participants had similar amounts of negative affect in both sessions, $t(173) = 1.70$, $p = .09$, but sleep-deprived participants had higher negative affect in the evening compared to the morning, $t(103) = 4.79$, $p < .001$.

For the second set of analyses, we examined how sleepiness and mood changed across the night based on nap opportunity within the Sleep-deprived group. We performed a linear mixed effects model with Nap Opportunity (0, 30, 60 min) as a between-subjects fixed effect and Time (22:00, 01:00, 02:00, 03:00, 04:00, 05:00, 06:00, 07:00, 08:00, 09:00) as a within-subjects fixed effect. Summary data is reported in Table S12.

Table S12

Sleepiness and mood for sleep-deprived participants, separated by nap opportunity, for Experiment 4

	22:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00
					Sleepiness					
60 min	2.71 (.13)	3.20 (.15)	3.58 (.15)	3.99 (.18)	4.29 (.22)	4.63 (.23)	4.40 (.20)	4.81 (.20)	4.48 (.21)	4.45 (.19)
30 min	2.64 (.14)	3.49 (.16)	3.87 (.16)	4.19 (.19)	4.61 (.21)	4.58 (.20)	4.86 (.21)	4.85 (.20)	5.11 (.23)	4.73 (.20)
0 min	2.58 (.15)	3.33 (.17)	3.87 (.17)	4.31 (.20)	4.65 (.20)	4.83 (.19)	5.11 (.19)	5.21 (.21)	5.17 (.23)	5.04 (.21)
					Positive Affect					
60 min	14.07 (.43)	11.18 (.47)	10.16 (.43)	9.36 (.44)	8.55 (.49)	8.04 (.47)	8.38 (.45)	7.89 (.42)	8.63 (.43)	8.92 (.42)
30 min	13.63 (.45)	11.13 (.49)	9.53 (.45)	8.90 (.46)	8.30 (.48)	8.33 (.43)	7.79 (.47)	7.46 (.42)	7.35 (.46)	7.99 (.46)
0 min	14.02 (.48)	10.79 (.59)	9.72 (.53)	8.68 (.54)	8.29 (.54)	7.98 (.48)	7.68 (.50)	7.88 (.46)	8.08 (.50)	8.36 (.46)
					Negative Affect					
60 min	6.60 (.22)	5.72 (.23)	5.81 (.22)	5.83 (.22)	5.91 (.25)	5.92 (.32)	5.76 (.26)	5.90 (.25)	5.93 (.25)	6.14 (.27)
30 min	6.73 (.23)	6.26 (.24)	5.82 (.23)	5.79 (.23)	5.57 (.25)	5.56 (.28)	5.85 (.27)	5.58 (.25)	5.75 (.26)	6.04 (.28)
0 min	6.61 (.25)	5.78 (.30)	5.90 (.28)	6.03 (.27)	5.89 (.27)	6.48 (.30)	6.62 (.28)	6.46 (.28)	6.69 (.29)	7.06 (.30)

Note. Standard error in parentheses.

For sleepiness, there was an effect of Time, $F(9, 167) = 54.04$, $p < .001$, but no effect of Nap Opportunity, $F(2, 174) = 1.84$, $p = .16$, and no interaction, $F(18, 182) = 1.24$, $p = .23$. We compared each timepoint with the following timepoint using post-hoc pairwise comparisons to examine how sleepiness changed across the night. Sleepiness increased between each timepoint and the following timepoint up until 04:00, *ps* < .001, and then plateaued from 04:00 to 08:00, *ps* > .12. Sleepiness then decreased between 08:00 and 09:00, *p* = .046.

For positive affect, there was also an effect of Time, $F(9, 140) = 66.47$, $p < .001$, but no effect of Nap Opportunity, $F(2, 172) = .48$, $p = .62$, and no interaction, $F(18, 145) = .89$, $p = .59$. As we did with sleepiness, we compared each timepoint with the following timepoint using post-hoc pairwise comparisons to examine how positive affect progressed across the night. Positive affect decreased between each timepoint until 04:00, *ps* < .001. Positive affect then plateaued between 04:00 and 08:00, *ps* > .16, but increased again between 08:00 and 09:00, *p* = .03.

Lastly, we examined negative affect. Again, there was an effect of Time, $F(9, 135) = 5.32$, $p < .001$, but no effect of Nap Opportunity, $F(2, 159) = 1.40$, $p = .23$, and no interaction, $F(18, 143) = 1.40$, $p = .14$. Post-hoc pairwise comparisons showed that negative affect decreased between 22:00 and 01:00, *p* < .001, and increased between 08:00 and 09:00, *p* = .01. Negative affect was stable between all timepoints between 01:00 and 08:00, *ps* > .18.

Sleep Duration and Performance for Rested Participants. For the Rested group[12], TST the night between sessions was correlated with lapses, r = -.283, *p* = .01, such that participants who slept more made fewer lapses in the morning. TST was not correlated with post-interruption errors, r = -.058, *p* = .60, or non-interruption errors in the morning, r = -.063, *p* = .58.

[12] Twenty-four participants were missing actigraphy data and are not included in analyses.

References

Buysse, D.J., Reynolds, C.F., Monk, T.H., Berman, S.R., non& Kupfer, D.J. (1989). The Pittsburgh Sleep Quality Index (PSQI): A new instrument for psychiatric research and practice. *Psychiatry Research, 28*, 193-213.

Hoddes, E., Zarcone, V., Smythe, H., Phillips, R., & Dement, W. C. (1973). Quantification of sleepiness: a new approach. *Psychophysiology*, *10*(4), 431-436.

Horne, J.A., & Ostberg, O. (1975). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International Journal of Chronobiology*, *4*, 97-110.

Thompson, E. R. (2007). Development and validation of an internationally reliable short-form of the positive and negative affect schedule (PANAS). *Journal of cross-cultural psychology*, *38*(2), 227-242.

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: the PANAS scales. *Journal of personality and social psychology*, *54*(6), 1063.