Increased Automaticity and Altered Temporal Preparation Following Sleep Deprivation

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Study Objectives: Temporal expectation enables us to focus limited processing resources, thereby optimizing perceptual and motor processing for critical upcoming events. We investigated the effects of total sleep deprivation (TSD) on temporal expectation by evaluating the foreperiod and sequential effects during a psychomotor vigilance task (PVT). We also examined how these two measures were modulated by vulnerability to TSD.

Design: Three 10-min visual PVT sessions using uniformly distributed foreperiods were conducted in the wake-maintenance zone the evening before sleep deprivation (ESD) and three more in the morning following approximately 22 h of TSD. TSD vulnerable and nonvulnerable groups were determined by a tertile split of participants based on the change in the number of behavioral lapses recorded during ESD and TSD. A subset of participants performed six additional 10-min modified auditory PVTs with exponentially distributed foreperiods during rested wakefulness (RW) and TSD to test the effect of temporal distribution on foreperiod and sequential effects.

Setting: Sleep laboratory.

Participants: There were 172 young healthy participants (90 males) with regular sleep patterns. Nineteen of these participants performed the modified auditory PVT.

Measurements and Results: Despite behavioral lapses and slower response times, sleep deprived participants could still perceive the conditional probability of temporal events and modify their level of preparation accordingly. Both foreperiod and sequential effects were magnified following sleep deprivation in vulnerable individuals. Only the foreperiod effect increased in nonvulnerable individuals.

Conclusions: The preservation of foreperiod and sequential effects suggests that implicit time perception and temporal preparedness are intact during total sleep deprivation. Individuals appear to reallocate their depleted preparatory resources to more probable event timings in ongoing trials, whereas vulnerable participants also rely more on automatic processes.

Keywords: foreperiod, implicit timing, sequential effect, sleep deprivation, temporal expectation, vulnerability

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INTRODUCTION

Whether we are waiting for a traffic light to turn green or for a starter's horn to sound, expectations about when a critical event will occur can affect response time. Temporal expectation enables us to focus attention so as to optimize perceptual and motor processing for a forthcoming event.[1–3] The perceptual boost that arises from engaging attention is brief,[4] and sustaining attention to detect and respond to temporally unpredictable stimuli is cognitively demanding.[5,6] The latter is evidenced by the decline in performance with time-on-task[7–11] as well as poorer performance when target stimuli are temporally irregular.[12]

Sleep deprivation can degrade performance simply by increasing the likelihood of microsleeps.[13,14] However, even when responding is possible, the reduced visual processing rate[15] and diminished capacity to process task-unrelated peripheral information[16] point to a decreased availability of perceptual and cognitive resources. Retaining the ability to use temporal information to focus processing at the most propitious time could thus benefit performance in sleep deprived persons. The manner in which such temporal preparation is affected by sleep deprivation remains relatively unexplored.

Elapsed time prior to an imperative event has consistently been shown to modulate behavior.[17] For example, when waiting for a traffic light to turn green, one's readiness to hit the accelerator pedal increases with elapsed time because the probability that the light will turn green increases with time given that it has not already done so (known as the hazard function). Research on implicit time perception and the engagement of "nonspecific preparation" dates back over a century[18,19] but has recently attracted renewed interest.[20–22]

Implicit temporal expectation has been studied using the foreperiod (FP) effect, in which the interval between a preceding warning signal and an imperative signal (the foreperiod) strongly modulates response speed. When FP durations are randomly and uniformly distributed, as in "variable FP" experiments, responses become faster with longer FP durations. Traditionally, the FP effect has been explained by proposing that a strategic preparatory process is invoked. A key feature of this strategic process is that the conditional probability of stimulus occurrence is continuously monitored to optimize behavior.[18,23]

A more automatic process has been posited to account for an additional phenomenon observed in variable FP experiments. This "sequential effect" is characterized by longer response times for trials in which the FP is shorter than the preceding one, in comparison to trials in which FP are equal or longer.[19,24]

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This effect is thought to be driven by an automatic process whereby preparedness is temporarily increased following a short FP and temporarily decreased following a long FP.[25] The sequential effect is also typically asymmetrical, affecting current short FP trials more than long FP ones.[17] The asymmetry of the sequential effect also contributes to the shape of the FP effect itself.[23]

Although the sequential and FP effects are related, they are also at least partially dissociable. Patients with prefrontal damage,[26,27] young children with incompletely developed frontal areas,[23] adults undergoing transcranial magnetic stimulation (TMS) of the frontal cortex,[20] and those engaged in cognitively demanding tasks[17] show evidence of impaired FP but preserved sequential effects. Such dissociations have supported the view that the sequential effect reflects an automatic, low-level process, whereas higher cognitive functions supported by the prefrontal cortex contribute to the FP effect.

Consistent with the notion that implicit timing may be intact despite sleep deprivation, the FP effect (Also referred to as the "variable response-stimulus interval" [RSI] effect) was found to be spared by sleep deprivation.[28] Here, we extended prior research by reexamining this finding with a much larger sample size and by studying the effect of sleep deprivation on the sequential effect. We also examined how interindividual differences in vulnerability to sleep deprivation[29,30] affect FP and sequential effects.

We hypothesized that the sleep deprived brain would conserve depleted processing capacity by relying on more automatic processes and by deploying attention selectively when targets are most likely to occur in an ongoing trial (i.e., as conditional probability increases). Such changes would yield larger FP and sequential effects compared to the rested state, especially in persons more vulnerable to sleep deprivation. In addition, as FP and sequential effects utilize implicit timing, their full expression may be dependent on the distribution of interstimulus intervals. We thus examined how using an exponential instead of a uniform distribution would affect the FP effect in sleep deprived persons.

MATERIALS AND METHODS

Participants

One hundred seventy-two healthy, right-handed participants (mean age 21.9 ± 1.9 y; 90 males) contributed data to this study. Each participant provided informed consent in accordance with study protocols approved by the National University of Singapore Institutional Review Board (IRB). Participants were derived from six different functional imaging studies[32–37] and one behavioral study[38] conducted in the same research laboratory, under similar experimental conditions.

In each of the contributing studies, participants were selected from respondents to a web-based questionnaire who: (1) were right-handed, (2) had regular sleeping habits, (3) slept no less than 6.5 h/night, (3) were not on any long-term medications, (4) had neither symptoms nor history of sleep disorders, (5) had no history of psychiatric or neurologic disorders, (6) drank fewer than three caffeinated drinks per day, and (7) were not of an extreme chronotype as assessed by the Horne-Östberg Morningness-Eveningness questionnaire,[39] i.e., participants must have had a score between 35 and 65.

The sleep pattern of each participant was monitored throughout the study and only those whose actigraphy (Actiwatch, Philips Respironics, Pittsburgh, PA, USA) data indicated habitual good sleep (i.e., sleeping no later than 12:30 and waking no later than 09:00) were recruited. All participants indicated that they did not smoke or consume any medication, stimulants, caffeine, or alcohol for at least 24 h prior to the test session.

Study Procedure

In the sleep deprivation sessions from which data were analyzed, participants arrived at the laboratory at 19:30 and were kept awake continuously overnight under the supervision of a research assistant. A 10-min visual Psychomotor Vigilance Task (PVT) was administered on a handheld device every hour from 20:00 to 05:00 (10 test periods). A single additional PVT was administered at approximately 08:00 after a good night of sleep (rested wakefulness; RW), at least one week before or after the sleep deprivation testing (counterbalanced order). This RW session was used as a control for practice effects. Participants were seated upright during testing and were exposed to ordinary room light throughout the sessions.

Nineteen of the 172 participants also completed two additional experimental sessions while lying supine in a magnetic resonance scanner. During each session, they performed six repetitions of a 10-min auditory vigilance task, with each separated by a 1-min break. The modified auditory "PVT" (part of a previously published experiment[38]) is included here to determine whether sleep deprived persons would remain sensitive to a change in the temporal distribution of stimuli. Although this experiment employed auditory stimuli, previous work has demonstrated a similar pattern of response slowing, lapses, anticipations, time-on-task declines, and state instability across auditory and visual PVTs used during sleep deprivation,[18] as well as comparable results for FP effects across these sensory modalities. The experiment was administrated once at 06:00 following sleep deprivation after the 10 sessions of visual PVT and once at around 08:10 after a good night of sleep (RW), at least one week before or after the sleep deprivation testing (counterbalanced order).

The rationale for the selected test times has been described in prior publications[15] and is intended to evaluate participants at times that are maximally unfavorable to the sleep deprived session.[7,40] Thus, our effects represent a combination of circadian and homeostatic effects.

Psychomotor Vigilance Tasks

During the visual PVT, participants were instructed to press a button as quickly as possible in response to a simple visual stimulus. Hourly 10-min PVT tests were delivered using a PVT-192 device (Ambulatory Monitoring, Inc., Ardsley, NY, USA).[41] The times from a response until the next target (FPs) were uniformly distributed from 2 to 10 sec. A false alarm warning signal ("FS") was displayed on the screen for 1 sec if participants made a button press before the onset of a stimulus.

In the modified auditory vigilance task, auditory tones (a simple low-frequency beep) were presented, to which participants were instructed to respond as quickly as possible by squeezing a response trigger (Nordic Neurolab, Bergen, Norway) with their right index finger. Stimulus onset asynchrony (SOA) values ranged from 4–12 sec (mean = 6 sec) and were randomly sampled from an exponential distribution (decay constant, tau = 2.03) so that trials with shorter FPs would occur more frequently than those with longer ones. A total of 600 tones were presented across six 10-min runs, each separated by a ~1-min break.[38]

Data Analysis

To investigate the effect of sleep deprivation on implicit time processing, visual PVT test bouts 2 to 4 (21:00–23:00) in the wake maintenance zone on the sleep deprivation night were aggregated for each participant to reflect the rested state (evening before sleep deprivation, ESD). Test bouts 7 to 9 (03:00– 05:00 the next day) were aggregated in each participant to reflect the sleep deprived state (total sleep deprivation, TSD, Figure 1A). Trials with response times (RT) less than 150 ms, or those for which participants responded before stimulus onset, were recorded as false alarms (FAs). The two trials following each FA were not included in subsequent analyses.

The foreperiod (FP_n) refers to the interval between the response to the previous (n–1) trial and stimulus onset, marked by the appearance of running digits on the PVT's timer display, of the current (n) trial (Figure 1B). Each FP_n was classified into one of three uniformly divided bins – short (2–4.67 sec), medium (4.67–7.33 sec), or long (7.33–10 sec). In the auditory task, which had a slightly different timing regimen to accommodate an exponential distribution with the same stimulus presentation density, FP_n were classified into short (4–6.67 sec), medium (6.67–9.33 sec), or long (9.33–12 sec) bins. Within each bin, median RTs were calculated for individual participants and then averaged across participants. FP and sequential effects were explored using analyses of variance (ANOVAs) and, for clarity, specific planned contrasts. For example, the FP effect was defined as the difference between response times associated with short FP_n and those with long FP_n[18,28] as follows:

$$\textit{Foreperiod effect} = \textit{RT short } FP_n - \textit{RT long } FP_n$$

To further explore the sequential effect in *post hoc* contrasts, we considered the conditions in which it would be expected to be largest (because of its asymmetry), specifically when the current FP was short. This contrast was defined as follows:

$$\textit{Sequential effect} = (\textit{RT short } FP_n \mid \textit{long } FP_{n-1}) - (\textit{RT short } FP_n \mid \textit{short } FP_{n-1})$$

Participants were classified as nonvulnerable or vulnerable to TSD on the basis of the *change* in that person's number of recorded lapses between TSD and ESD ($\delta l = l_{TSD} - l_{ESD}$). A lapse was defined as a trial with RT ≥ 500 ms.[7,13] These trials were used for vulnerability classification and included in the FP and sequential effect analyses. Persons belonging to the upper third were classified as vulnerable, whereas nonvulnerable persons were in the lower third.

As PVT testing in ESD always preceded TSD sessions, we evaluated the effect of order by comparing the three PVT test bouts conducted between 21:00–23:00 (ESD) with a single rested wakefulness PVT test bout (RW, 08:00) conducted one week *after* the ESD session (92 participants).

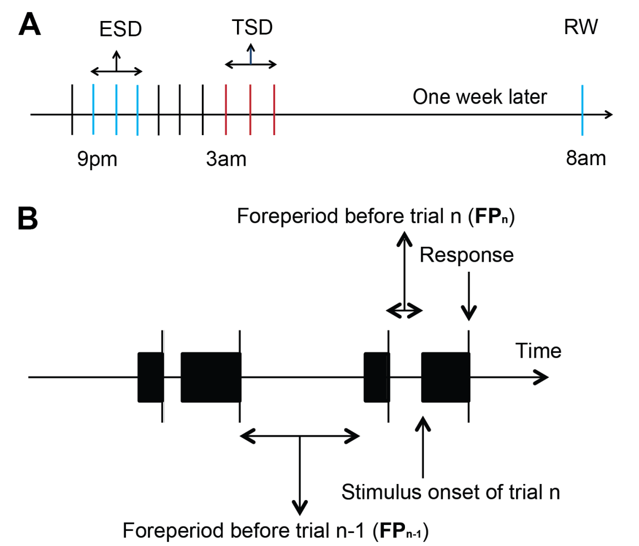

Figure 1—(A) During the sleep deprivation session, the PVT was administered every hour from 20:00 until 05:00 the next morning (10 test periods). PVT data collected from 21:00 to 23:00 constituted the evening before sleep deprivation (ESD) state, whereas the last three test epochs (03:00 to 05:00) constituted the total sleep deprivation (TSD) state. **(B)** Schematic showing how foreperiod, stimulus onset, and response are inter-related.

All statistical analyses were conducted using SPSS 21 (IBM, Chicago, IL, USA), R (R Foundation for Statistical Computing, Vienna, Austria), and Matlab 2012a (The MathWorks, Inc., Natick, MA, USA).

RESULTS

Effects of Sleep Deprivation on Psychomotor Vigilance

During TSD, responses were slower (mean response time ± standard error of the mean [SEM] for ESD: 267 ± 3 ms; for TSD: 357 ± 11 ms; t_{171} = 8.79, P < 0.0001), more variable (standard deviation of response time ± SEM for ESD: 79 ± 5 ms; for TSD: 262 ± 31 ms; t_{171} = 5.90, P < 0.0001) and associated with a significant increase in lapses (ESD: 1.37 ± 0.15 lapses per PVT session; TSD: 6.11 ± 0.48 lapses per PVT session; t_{171} = 10.86, P < 0.001). For completeness, the means of the median RTs at each hourly PVT test bout throughout the TSD night are shown (Figure S1, supplemental material). Nonvulnerable participants (n = 57) had a smaller average state-related change in lapse count per 10-min PVT Δcount ≤ 4) relative to vulnerable participants (n = 57; Δcount ≥ 16). A summary of the differences in PVT responses between the vulnerable and nonvulnerable groups can be found in Table 1.

Foreperiod (FP_n) durations were grouped into three bins—short, medium, and long—for our principal analyses. For completeness, RT data in 1-sec resolution bins were also plotted (Figure S2, supplemental material). There were significant main effects of state ($F_{1,171}$ = 285.24, P < 0.001) and FP duration on response time ($F_{2,342}$ = 1,483.70, P < 0.001). Participants responded faster when FPs were longer (Figure 2A). There was also a significant interaction between FP duration and state ($F_{2,342}$ = 71.21, P < 0.0001), whereby the difference between the response time for short and long FPs was larger during TSD. A two-way repeated-measures ANOVA on the FP effect with state and vulnerability as factors revealed significant main effects of state ($F_{1,56}$ = 63.64; P < 0.001) and vulnerability ($F_{1,56}$ = 9.81; P < 0.01). There was also a significant state by vulnerability interaction ($F_{1,56}$ = 8.42, P < 0.01), indicating that the FP effects in the nonvulnerable and vulnerable groups were differentially modulated by state (Figure 4A), with the vulnerable group showing a greater increase in the magnitude of the FP effect.

In order to test for asymmetric sequential effects, we examined the effect of FP_n and FP_{n-1} combinations on response time. Two-way repeated-measures ANOVAs were performed in both ESD and TSD separately. Significant FP_n by FP_{n-1} duration interactions were found in both states (ESD: $F_{4,684}$ = 122.60, P < 0.001; TSD: $F_{4,684}$ = 55.02, P < 0.001; Figures 3A and 3B) in addition to a main effect of FP_{n-1} on response time, indicative of a sequential effect ($F_{2,342}$ = 260.86, P < 0.001). Consistent with an asymmetric sequential effect, when FP_n was short, a short FP_{n-1} resulted in faster response times compared to a long FP_{n-1}. A planned *post hoc* paired *t* test showed that the sequential effect was larger following TSD than ESD (t_{171} = 3.29, P < 0.05).

There was a significant state by vulnerability interaction on the sequential effect ($F_{1,56}$ = 5.18, P < 0.05; Figures 3C and 3D), in addition to significant main effects of state ($F_{1,56}$ = 5.59; P < 0.05) and vulnerability ($F_{1,56}$ = 10.64; P < 0.005). *Post hoc* tests revealed that vulnerable participants showed a significant increase in the sequential effect from ESD to TSD (t_{56} = 2.63, P = 0.01; Figure 4B), whereas there was no significant change in the magnitude of the sequential effect across state for the nonvulnerable group (t_{56} = 0.38, not significant).

Effect of Sleep Deprivation on FA Rates

FAs are "errors of commission" that indicate continued effort on the part of participants.[7] There was a main effect of state on the total number of FAs ($F_{1,56}$ = 18.21; P < 0.001) as well as a significant state by vulnerability interaction ($F_{1,56}$ = 6.53, P < 0.02). The latter indicates that the number of FAs was differentially modulated by TSD in nonvulnerable and vulnerable groups (Figure 5). *Post hoc* paired *t* tests showed that TSD increased the number of FAs in the vulnerable group (t_{56} = 4.02, P < 0.001). In contrast, no significant change in FA rate was observed in the nonvulnerable group (t_{56} = 1.26, not significant).

Effect of Temporal Distribution on FP Effect

Based on the data from the modified auditory PVT, the FP effect was markedly attenuated when FPs followed an exponential distribution ($F_{2,36}$ = 2.31; not significant; Figure 6). Only a significant main effect of state was observed ($F_{1,18}$ = 20.19; P < 0.001).

Controlling for "Practice"

When comparing ESD and RW sessions for the visual PVT, there were significant main effects of session ($F_{1,91}$ = 7.19, P < 0.01; Figure 7A) and FP on response time ($F_{2,182}$ = 272.08, P < 0.001;

Table 1—Summary statistics of number of lapses, mean response time, standard deviation and number of false alarms in nonvulnerable and vulnerable participants in each state.

	Nonvulnerable		Vulnerable	
	ESD	TSD	ESD	TSD
Number of lapses	3.9 ± 0.9	4.6 ± 0.9	5.5 ± 0.7	39.2 ± 2.4
Mean RT (ms)	262 ± 6	279 ± 6	278 ± 4	480 ± 24
Std Deviation of RT (ms)	70 ± 7	81 ± 7	95 ± 11	569 ± 79
Number of false alarms	4.2 ± 0.9	5.0 ± 0.7	4.1 ± 0.6	8.3 ± 1.3

Values are for 30 min of PVT performance (three aggregated sessions per state). Errors are standard error of the mean. ESD, evening before sleep deprivation; RT, response time; TSD, total sleep deprivation.

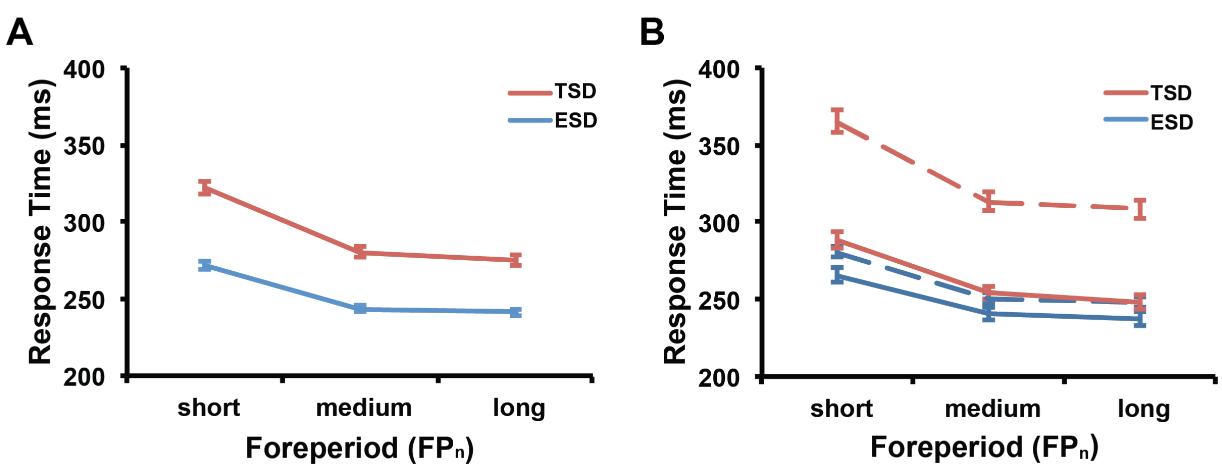

Figure 2—**(A)** Mean of median response times as a function of the current foreperiod (FP_n: short, medium and long) and state (ESD versus TSD). **(B)** There was a significant effect of vulnerability on response times at all foreperiod durations ($F_{1,56}$ = 32.68; P < 0.01). Solid lines and dashed lines denote data pertaining to nonvulnerable and vulnerable participants, respectively. Error bars represent standard error of the mean. ESD, evening before sleep deprivation; TSD, total sleep deprivation.

Figure 7A). However, the absence of any significant foreperiod by session interaction ($F_{2,182}$ = 1.72, not significant), suggests that repeated performance of the PVT did not have an appreciable effect on FP. A paired t test on the FP effect itself also found no significant difference between the two sessions (t_{91} < 1; not significant).

DISCUSSION

We investigated the effect of sleep deprivation on temporal preparation by using the PVT, a speeded response time task that provides feedback and whose trials have FPs that follow a simple uniform distribution. Remarkably, in spite of behavioral lapses and increased response times, participants could

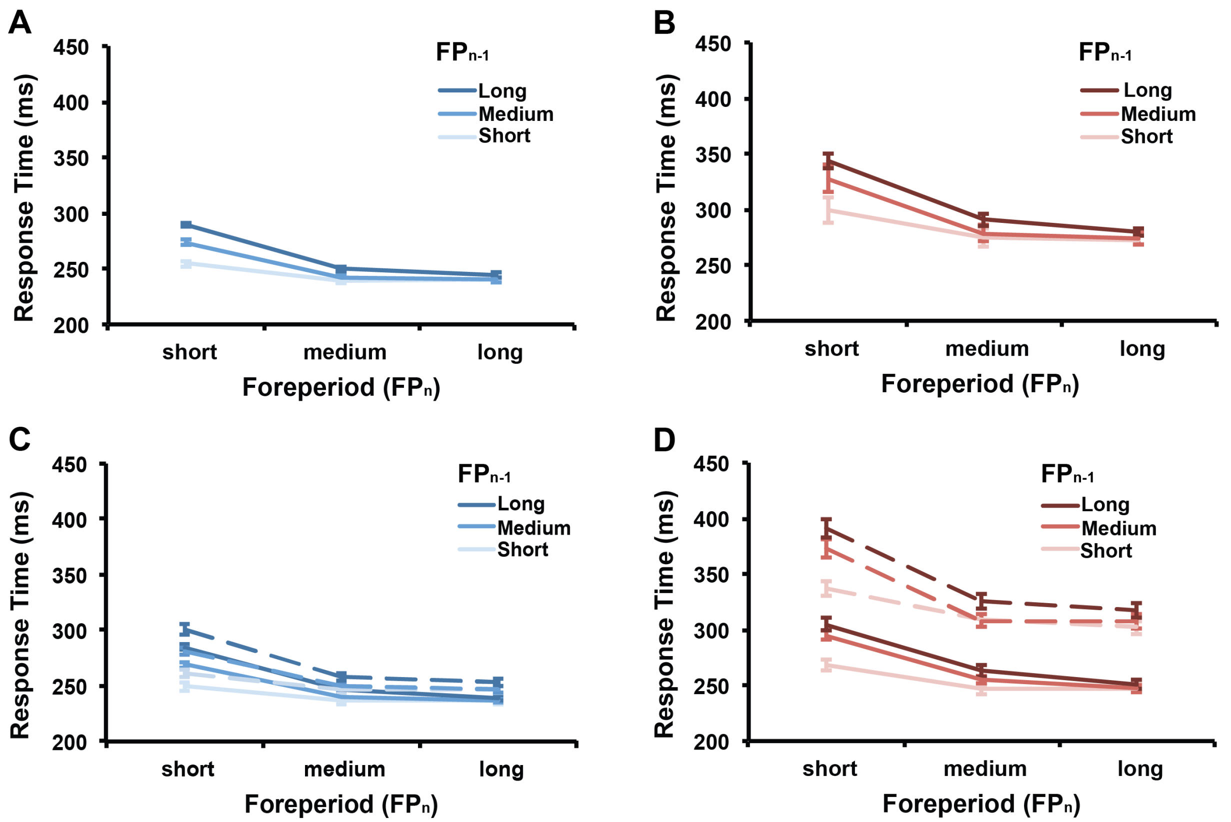

Figure 3—Mean of median response times as a function of the current foreperiod (FP_n) and the immediately prior foreperiod (FP_{n-1}) displayed separately for **(A)** ESD and **(B)** TSD. Response times separated by vulnerability to sleep deprivation during **(C)** ESD and **(D)** TSD are shown. Solid lines and dashed lines denote data pertaining to nonvulnerable and vulnerable participants respectively. Error bars represent standard error of the mean. ESD, evening before sleep deprivation; TSD, total sleep deprivation.

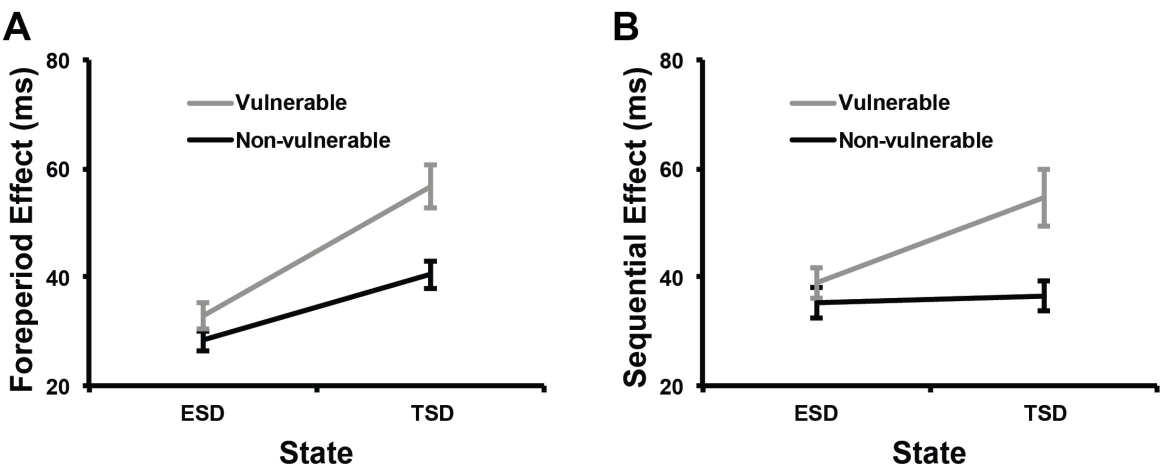

Figure 4—**(A)** Foreperiod effect and **(B)** sequential effect for short current foreperiods as a function of state (ESD versus TSD) and vulnerability to sleep deprivation. Sleep deprivation increased the magnitude of the foreperiod effect in both vulnerable and nonvulnerable groups, but the increase was larger in vulnerable individuals. A significant increase in the sequential effect was observed in vulnerable but not nonvulnerable participants following TSD. Error bars represent standard error of the mean. ESD, evening before sleep deprivation; TSD, total sleep deprivation.

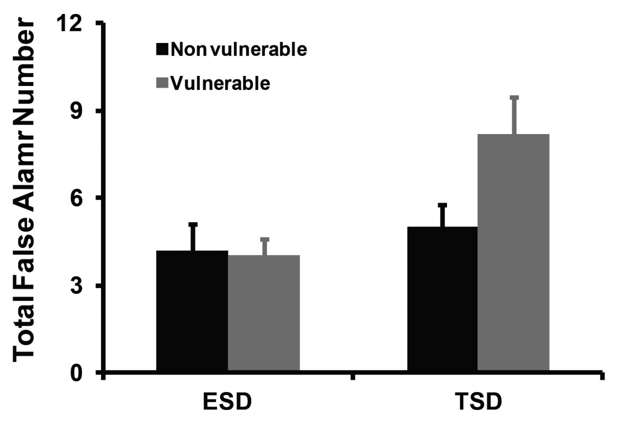

Figure 5—Average number of false alarms per subject in ESD and TSD. The number of false alarms increased significantly following sleep deprivation in the vulnerable group. Error bars represent standard error of the mean. ESD, evening before sleep deprivation; TSD, total sleep deprivation.

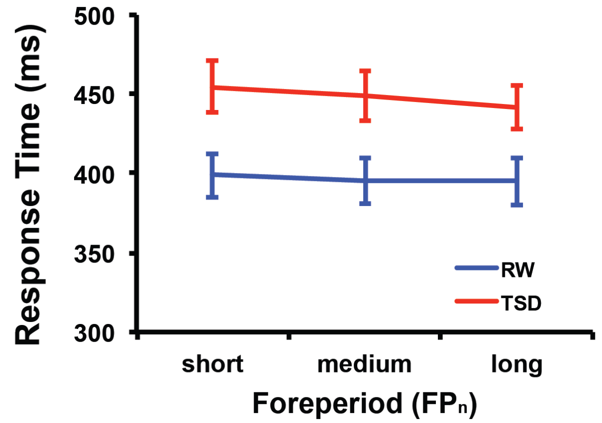

Figure 6—Response time as a function of current foreperiod (FP_n) and state when foreperiod durations were drawn from an exponential distribution in the modified auditory PVT. Foreperiod effects were eliminated in both RW and TSD states. Error bars represent standard error of the mean. RW, rested wakefulness; TSD, total sleep deprivation.

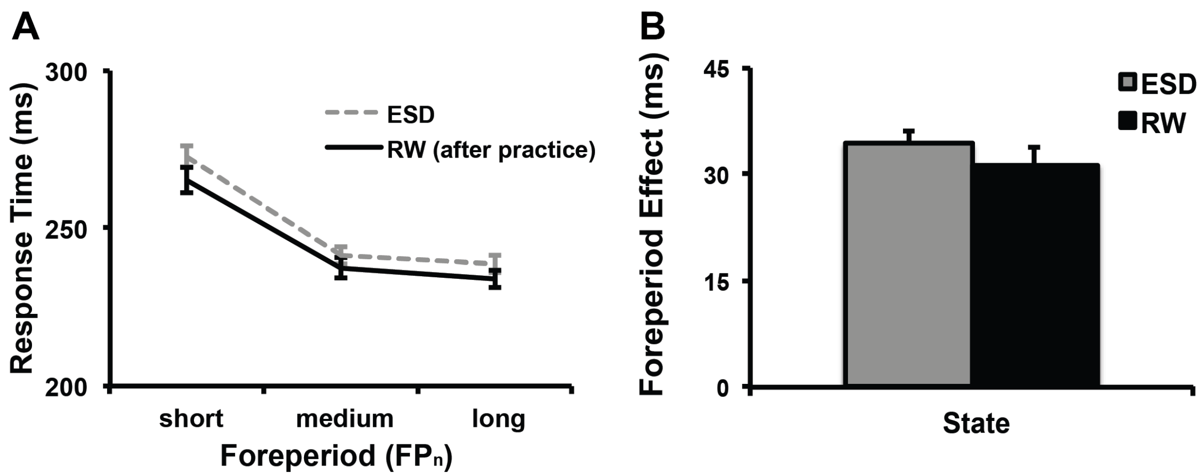

Figure 7—**(A)** Mean of median response times as a function of the current foreperiod and state (ESD versus RW) for 92 participants who had their RW session approximately one week after ESD. **(B)** Foreperiod effect as a function of session. Error bars represent standard error of the mean. ESD, evening before sleep deprivation; RW, rested wakefulness.

still perceive the conditional probability of temporal events and modify their level of preparation accordingly. Both FP and sequential effects were magnified following sleep deprivation in vulnerable individuals. Only the FP effect increased in nonvulnerable individuals. Taken together, these findings reflect (1) a greater reliance on automatic processing and (2) systematically delayed allocation of processing resources toward more likely imperative events, whose conditional probability increases during each ongoing trial.

Preserved Perception of Conditional Probability following Sleep Deprivation

The FP effect has been attributed to a strategic process,[18,23] which modulates preparedness according to this perceived conditional probability.[17] Expectations concerning the probability of stimulus occurrence over time can minimize effort.[42] In support of a "strategic" aspect to the FP effect are findings that it is impaired in patients with prefrontal damage,[26,27] in adults undergoing transcranial magnetic stimulation (TMS) to the frontal lobe,[20] in children,[23] and in adults with an increased cognitive load.[17]

Orthogonal to these findings but relevant to work on sleep deprivation is a popular hypothesis that sleep deprivation alters behavior largely through its effects on prefrontal function.[43] However, the significant increase in the FP effect in sleep deprived persons is surprising in light of generally decreased FP effects following challenges to the frontal lobe. One potential explanation is that sleep deprivation most strongly affects sustained attention,[44] whose degradation is also observed during time-on-task effects. Resource models attribute these declines to the exhaustion of cognitive[5,6] or neural[7] resources, which can be hastened by temporal unpredictability as to when a critical stimulus will appear.[45,46] In support of this notion, faster target detection can be achieved by reducing temporal variability and uncertainty about stimulus onset.[18] To account for our findings, we suggest that during sleep deprivation, the impaired frontal lobe allocates the limited neurocognitive attentional resources toward periods of time in each unfolding trial when the stimulus is most likely to appear.

The results from our manipulation of temporal expectations by using an exponential distribution of FPs are consistent with this interpretation. By employing this FP distribution, the conditional probability of stimulus occurrence is equal for all critical moments, which generally yields a flat RT-FP function.[47,48] We observed these same results in our auditory vigilance task, with only a main effect of slower RTs overall during TSD. The contrast between enhancement of the FP effect during TSD when stimuli were uniformly distributed and the abolition of the effect when stimuli were exponentially distributed under the same conditions provides clear evidence that sensitivity to conditional probability is preserved following sleep deprivation.

Critically, we posit that the combination of intact tracking of conditional probability, intact sense of the passage of time, and allocation of limited attention to later timepoints of imperative events, leads to the observed increase in the FP effect during TSD. Note that none of these processes need to be conscious or deliberately strategic, but they do integrate information across multiple trials. As such, they may represent a passive combination of inbuilt processes that serve to optimize speeded responsiveness in the context of impoverished processing resources. In short, it is remarkable that despite the expectation that we "tune out" during lapses, sleep deprived participants somehow retain the ability to keep track of the temporal features of a task.

Temporal Preparedness in Vulnerable and Nonvulnerable Individuals

Although both vulnerable and nonvulnerable subjects evidenced increased FPs during sleep deprivation, the effect was magnified in the former. In addition, the more automatic sequential effect and FA rates were only increased in vulnerable individuals. These findings argue for a resource-conserving adaptation during sleep deprivation that appears "strategic" in the sense that it makes use of the flow of time and conditional probability information. Because individuals who are most affected by sleep deprivation show the largest effects of such resource allocation, this adaptation is "passive" from the viewpoint that it does not engage controlled processing and is instead a combination of several automatic processes.

In the most vulnerable individuals, the additional behavioral changes suggest that more cognitive processes are affected. For example, FAs increase markedly across states, suggesting a high degree of motor response instability in addition to potential perceptual difficulties. The increase in the sequential effect suggests that sleep deprivation may have also intermittently exhausted strategic control of preparation, allowing automatic processes to dominate behavior. These automatic processes would have also contributed to the FP effect,[20–22] potentially accounting for its further increase in the most vulnerable individuals.

Recently, there has been great interest in characterizing individual differences in the neurocognitive effects of sleep deprivation. These differences are both substantial and trait-like.[29,30] Our results suggest that individuals who are vulnerable to sleep deprivation may show increased automaticity in their behaviors, though fundamental timing processes still appear to be intact. Such results are pertinent to various occupations in the medical, military, and traffic control fields, in which cognitive timing is crucial.

Reliance on Automatic Processing Increases following Sleep Deprivation

A critical feature of the sequential effect is that RTs are longer if the current FP is shorter than the preceding one. The effect has been proposed to originate from an automatic preparation component.[21,49] In support of a separate automatic process underlying the sequential effect, disruption of executive function, top-down control of attention, or the brain regions that support these functions (i.e., dorsolateral prefrontal cortex) reduces the FP effect while leaving the sequential effect intact. For example, the sequential effect is undiminished by cognitive load,[17] prefrontal lesions,[26] or transcranial magnetic stimulation (TMS) pulses[20] that are significant enough to disrupt executive function. The sequential effect is also present in children who have not yet developed a strong FP effect.[23] It is notable that the asymmetrically faster RTs in the more automatic short-short sequences makes it unlikely that RTs in long-short sequences is due to an increased response refractory period during TSD.

In the current results, faster responses were clearly evident when contrasting short-short with long-short FP sequences for those most vulnerable to sleep deprivation's effects, and FAs were likewise elevated during sleep deprivation. These results accord with greater automaticity in task performance in TSD, as evidenced by a reduced stop rate,[50,51] elevated FA rate in Go/No-Go experiments,[52] as well as increased errors of commission in the Sustained Attention to Response Test (SART).[53] More automatic behavior following sleep deprivation is a likely consequence of having reduced processing resources[15,54] and impaired attention.[55–57] As such, the increase in the sequential effect is likely due to a passive process by which sleep deprived individuals respond more *automatically* to a stimulus that arrives at the same time or later than it did on the previous trial, but they are slow at responding if a stimulus arrives unexpectedly early.

CONCLUSIONS

Responses to uniformly distributed random events become more automatic and reflect a different allocation of limited attentional resources in sleep deprived persons. Remarkably, sleep deprived persons retain sensitivity to the passage of time and to the temporal conditional probability of imperative events in spite of response slowing and increased lapses. The larger increase in FP and sequential effects in persons vulnerable to sleep deprivation reflects lowered ability to respond to imperative stimuli that occur unexpectedly soon. These findings extend previous work concerning diminished processing resources in the sleep deprived state and adaptations to accommodate this resource-impoverished state. On a practical level, they indicate that manipulating something as seemingly trivial as interstimulus intervals can have beneficial effects on behavior in fatigued persons. Perhaps in the future, boring but critical tasks such as baggage screening or quality control could be temporally gated by machine to avoid unfavorable exposure timings. Finally, the current work also demonstrates that deeper analysis of a stream of reaction time data can provide higher order information regarding behavior not evident from summary statistics of aggregated trials.

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DISCLOSURE STATEMENT

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REFERENCES

1. Bausenhart KM, Rolke B, Hackley SA, Ulrich R. The locus of temporal preparation effects: evidence from the psychological refractory period paradigm. Psychon Bull Rev 2006;13:536–42.
2. Coull JT, Nobre AC. Dissociating explicit timing from temporal expectation with fMRI. Curr Opin Neurobiol 2008;15:137.
3. Vallesi A, Lozano VN, Correa A. Dissociating temporal preparation processes as a function of the inter-trial interval duration. Cognition 2013;127:22–30.
4. Ling S, Carrasco M. When sustained attention impairs perception. Nat Neurosci 2006;9:1243–5.
5. Warm JS, Parasuraman R, Matthews G. Vigilance requires hard mental work and is stressful. Hum Factors 2008;50:433–41.
6. Shaw TH, Warm JS, Finomore V, Tripp L, Matthews G, Weiler E, Parasuraman R. Effects of sensory modality on cerebral blood flow velocity during vigilance. Neurosci Lett 2009:207–11.
7. Doran SM, Van Dongen HPA, Dinges DF. Sustained attention performance during sleep deprivation: evidence of state instability. Arch Ital Biol 2001;139:253–67.
8. Langner R, Steinborn MB, Chatterjee A, Sturm W, Willmes K. Mental fatigue and temporal preparation in simple reaction-time performance. Acta Psychol (Amst) 2010;133:64–72.
9. Lim J, Wu WC, Wang J, Detre JA, Dinges DF, Rao H. Imaging brain fatigue from sustained mental workload: an ASL perfusion study of the time-on-task effect. Neuroimage 2010;49:3426–35.
10. Smit AS, Eling PATM, Coenen AML. Mental effort causes vigilance decrease due to resource depletion. Acta Psychol (Amst) 2004;115:35–42.
11. Bills AG. Blocking: a new principle of mental fatigue. Am J Psychol 1931;43:230–45.
12. Lisper HO, Tornros J. Effects of intersignal interval regularity on increase in reaction time in a one hour auditory monitoring task. Acta Psychol 1974;38:455–60.
13. Anderson C, Wales AW, Horne JA. PVT lapses differ according to eyes open, closed, or looking away. Sleep 2010;33:197–204.
14. Van Dongen HP, Belenky G, Krueger JM. Investigating the temporal dynamics and underlying mechanisms of cognitive fatigue. In: Ackerman, PL, eds. Cognitive fatigue: multidisciplinary perspectives on current research and future applications. Washington, DC: American Psychological Association, 2011.
15. Kong D, Asplund CL, Chee MWL. Sleep deprivation reduces the rate of rapid picture processing. Neuroimage 2014;91:169–76.
16. Kong D, Soon CS, Chee MWL. Functional imaging correlates of impaired distractor suppression following sleep deprivation. Neuroimage 2012;61:50–5.
17. Vallesi A, Arbula S, Bernardis P. Functional dissociations in temporal preparation: evidence from dual-task performance. Cognition 2014;130:141–51.
18. Niemi P, Näätänen R. Foreperiod and simple reaction time. Psychol Bull 1981;89:133–62.
19. Woodrow H. The measurement of attention. Psychol Monogr 1914;17:1–158.
20. Vallesi A, Shallice T, Walsh V. Role of the prefrontal cortex in the foreperiod effect: TMS evidence for dual mechanisms in temporal preparation. Cereb Cortex 2007;17:466–74.
21. Los SA, Knol DL, Boers RM. The foreperiod effect revisited: conditioning as a basis for nonspecific preparation. Acta Psychol 2001;106:121–45.
22. Los SA. Foreperiod and sequential effects: theory and data. In: Nobre AC, Coull JT, eds. Attention and time. Oxford, UK: Oxford University Press, 2010.
23. Vallesi A, Shallice T. Developmental dissociations of preparation over time: deconstructing the variable foreperiod phenomena. J Exp Psychol Hum Percept Perform 2007;33:1377–88.
24. Karlin L. Reaction time as a function of foreperiod duration and variability. J Exp Psychol 1959;58:185–91.
25. Soetens E, Boer LC, Hueting JE. Expectancy or automatic facilitation? Separating sequential effects in two-choice reaction time. J Exp Psychol Hum Percept Perform 1985;11:598–616.
26. Triviño M, Correa A, Arnedo M, Lupiañez J. Temporal orienting deficit after prefrontal damage. Brain 2010;133:1173–85.
27. Vallesi A, Mussoni A, Mondani M, Budai R, Skrap M, Shallice T. The neural basis of temporal preparation: insights from brain tumor patients. Neuropsychologia 2007;45:2755–63.
28. Tucker AM, Basner R, Stern Y, Rakitin B. The variable response-stimulus interval effect and sleep deprivation: an unexplored aspect of psychomotor vigilance task performance. Sleep 2009;32:1393–5.
29. Rupp TL, Wesensten NJ, Balkin TJ. Trait-like vulnerability to total and partial sleep loss. Sleep 2012;35:1163–72.
30. Van Dongen HP. Connecting the dots: from trait vulnerability during total sleep deprivation to individual differences in cumulative impairment during sustained sleep restriction. Sleep 2012;35:1031–3.
31. Cousineau D, Chartier S. Outliers detection and treatment: a review. Int J Psychol Res 2010;3:58–67.
32. Asplund CL, Chee MWL. Time-on-task and sleep deprivation effects are evidenced in overlapping brain areas. Neuroimage 2013;82:326–35.
33. Chee MWL, Chuah LYM. Functional neuroimaging and behavioral correlates of capacity decline in visual short-term memory after sleep deprivation. Proc Natl Acad Sci USA 2007;104:9487–92.
34. Chee MWL, Tan JC, Parimal S, Zagorodnov V. Sleep deprivation and its effects on object-selective attention. Neuroimage 2010;49:1903–10.
35. Chuah LY, Chee MWL. Cholinergic augmentation modulates visual task performance in sleep-deprived young adults. J Neurosci 2008;28:11369–77.
36. Chuah LY, Dolcos F, Chen AK, Zheng H, Parimal S, Chee MWL. Sleep deprivation and interference by emotional distracters. Sleep 2010;33:1305–13.
37. Venkatraman V, Chuah YM, Huettel SA, Chee MWL. Sleep deprivation elevates expectation of gains and attenuates response to losses following risky decisions. Sleep 2007;30:603–9.
38. Ong JL, Asplund CL, Chia TT, Chee MWL. Now you hear me, now you don't: eyelid closures as an indicator of auditory task disengagement. Sleep 2013;36:1867–74.
39. Horne JA, Östberg O. A self-assessment questionnaire to determine morningness-eveningness in human circadian phase and time awake on visual selective attention and vigilance. Int J Chronobiol 1976;4:97–110.
40. Graw P, Krauchi K, Knoblauch V, Wirz-Justice A, Cajochen C. Circadian and wake-dependent modulation of fastest and slowest reaction times during the psychomotor vigilance task. Physiol Behav 2004;80:695–701.
41. Dinges DF, Powell JW. Microcomputer analyses of performance on a portable, simple visual rt task during sustained operations. Behav Res Meth 1985;17:652–5.
42. Jones MR, Moynihan H, MacKenzie N, Puente J. Temporal aspects of stimulus-driven attending in dynamic arrays. Psychol Sci 2002;13:313–9.
43. Harrison Y, Horne JA, Rothwell A. Prefrontal neuropsychological effects of sleep deprivation in young adults: a model for healthy aging? Sleep 2000;23:1067–73.
44. Lim J, Dinges DF. A meta-analysis of the impact of short-term sleep deprivation on cognitive variables. Psychol Bull 2010;136:375–89.
45. Sarter M, Givens B, Bruno JP. The cognitive neuroscience of sustained attention: where top-down meets bottom-up. Brain Res Brain Res Rev 2001;35:146–60.

46. Parasuraman R. Vigilance, monitoring, and search. In: Boff KR, Kaufman L, Thomas JP, eds. Handbook of human perception and performance. Vol. 2. Cognitive processes and performance. New York: Wiley, 1986.
47. Cravo AM, Rohenkohl G, Wyart V, Nobre AC. Endogenous modulation of low frequency oscillations by temporal expectations. J Neurophysiol 2011;106:2964–72.
48. Cui X, Stetson C, Montague PR, Eagleman DM. Ready…go: amplitude of the fMRI signal encodes expectation of cue arrival time. PLoS Biol 2009;7:e1000167.
49. Los SA, van den Heuvel CE. Intentional and unintentional contributions to nonspecific preparation during reaction time foreperiods. J Exp Psychol Hum Percept 2001;27:370–86.
50. Chuah YM, Venkatraman V, Dinges DF, Chee MW. The neural basis of interindividual variability in inhibitory efficiency after sleep deprivation. J Neurosci 2006;26:7156–62.
51. Sagaspe P, Taillard J, Amiéva H, et al. Influence of age, circadian and homeostatic processes on inhibitory motor control: a Go/Nogo task study. PLoS One 2012;7:e39410.
52. Drummond SP, Paulus MP, Tapert SF. Effects of two nights sleep deprivation and two nights recovery sleep on response inhibition. J Sleep Res 2006;15:261–5.
53. Lo JC, Groeger JA, Santi N, et al. Effects of partial and acute total sleep deprivation on performance across cognitive domains, individuals and circadian phase. PLoS One 2012;7:e45987.
54. Kong D, Soon CS, Chee MWL. Reduced visual processing capacity in sleep deprived persons. Neuroimage 2011;55:629–34.
55. Chee MW, Tan JC, Zheng H, et al. Lapsing during sleep deprivation is associated with distributed changes in brain activation. J Neurosci 2008;28:5519–28.
56. Chee MWL, Tan JC. Lapsing when sleep deprived: neural activation characteristics of resistant and vulnerable individuals. Neuroimage 2010;51:835–43.
57. Tomasi D, Wang RL, Telang F, et al. Impairment of attentional networks after 1 night of sleep deprivation. Cereb Cortex 2009;19:233–40.

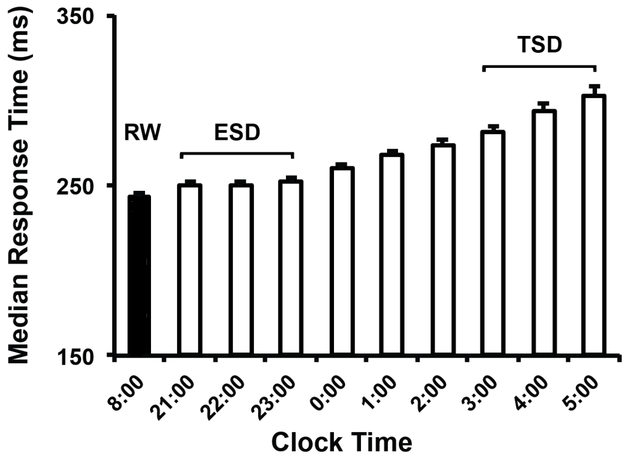

Figure S1—Mean of median response times at each testing period. Error bars represent standard error of the mean. ESD, evening before sleep deprivation; RW, rested wakefulness; TSD, total sleep deprivation.

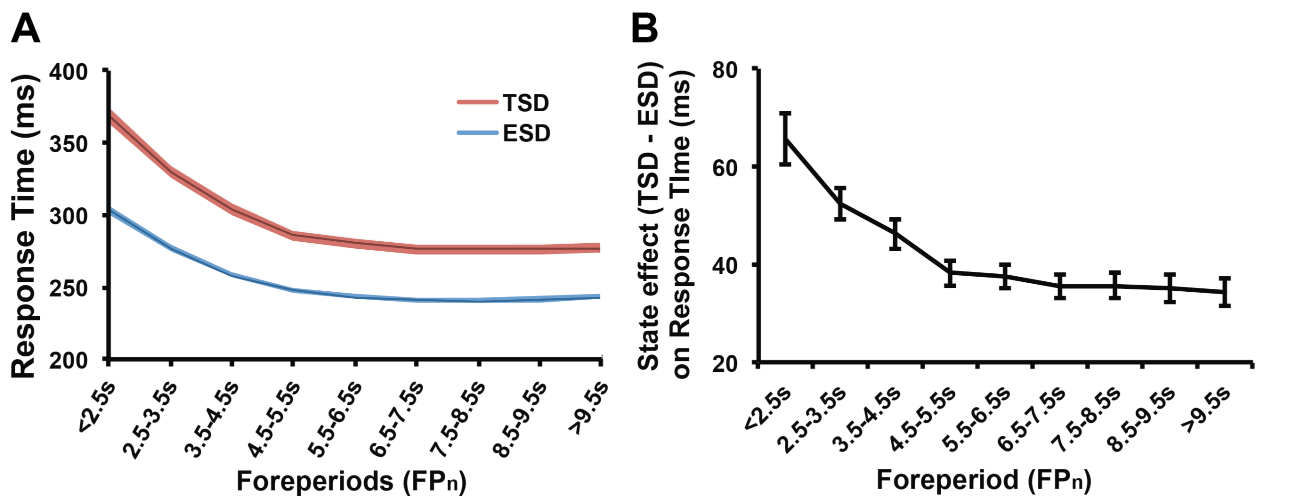

Figure S2—**(A)** Foreperiod effect was present in both ESD and TSD conditions. **(B)** The foreperiod effect was significantly larger during TSD. Error bars represent standard error of the mean. ESD, evening before sleep deprivation; TSD, total sleep deprivation.