The Variable Response-Stimulus Interval Effect and Sleep Deprivation: An Unexplored Aspect of Psychomotor Vigilance Task Performance

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Study Objectives: The Psychomotor Vigilance Task (PVT) contains variable response-stimulus intervals (RSI). Our goal is to investigate the effect of RSI on performance to determine whether sleep deprivation affects the ability to attend to events across seconds and whether this effect is independent of impairment in sustaining attention across minutes, as measured by time on task.

Design: A control group following their normal sleep routines and 3 groups exposed to 54 hours of total sleep deprivation performed a 10-minute PVT every 6 hours for 9 total test runs.

Setting: Sleep deprivation occurred in a sleep laboratory with continuous behavioral monitoring; the control group took the PVT at home.

Subjects: Eighty-four healthy sleepers (68 sleep deprivation, 16 controls; 22 women; aged 18-35 years).

Measurements and Results: Across groups, as the RSI increased from 2 to 10 seconds, mean RT was reduced by 69 milliseconds (main effect of RSI, P < 0.001). There was no interaction between the sleep deprivation and RSI effects. As expected, there was a significant interaction of sleep deprivation and time on task for mean RT (P = 0.002). Time on task and RSI effects were independent. Parallel analyses of percentage of lapses and percentage of false starts produced similar results.

Conclusions: We demonstrate that the cognitive mechanism of attention responsible for response preparation across seconds is distinct from that for maintaining attention to task performance across minutes. Of these, only vigilance across minutes is degraded by sleep deprivation. Theories of sleep deprivation should consider how this pattern of spared and impaired aspects of attention may affect real-world performance.

Keywords: Sleep deprivation, attention, reaction time, Psychomotor Vigilance Task, response-stimulus interval, time on task, vigilance, response preparation

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THE PSYCHOMOTOR VIGILANCE TASK (PVT)[1] HAS EMERGED AS THE GOLD-STANDARD METHOD OF ASSESSING CHANGES TO VIGILANT ATTENTION STEMMING from sleep deprivation in both applied and basic research. The standard PVT consists of a 10-minute speeded detection task with stimuli presented randomly 2 to 10 seconds after each response. During sleep deprivation, there is a time on task (ToT) effect for PVT performance as, for example, mean reaction time (RT) increases across minutes of the task.[2]

The variable (2 -10 s) response-stimulus interval (RSI) of the PVT is a manipulation that can directly address the relationship between sleep deprivation and the ability to sustain attention and readiness to respond across the seconds before the stimulus is presented. On experimenter-paced choice RT tests using RSIs in the range of milliseconds, longer RSI values have been documented to give rise to shorter RTs and an increased rate of errors.[3,4] That is, subjects respond faster and less accurately on those trials with longer intervals before stimulus presentation.

Two previous studies found that the RSI effect was unchanged after a single night of sleep deprivation.[4,5] The current study is the first to test whether the RSI effect is present within the PVT, an instrument known to be highly sensitive to sleep loss.[2]

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Specifically, we hypothesize that mean RT will decrease at the relatively longer RSIs, and we explore whether the percentage of either false starts or lapses changes with RSI. Next, we want to see if the RSI effect is altered when performance is tested after a second night of sleep deprivation, allowing more homeostatic pressure for sleep to accrue than was present in previous studies. Third, our main goal is to replicate the ToT effect on mean RT and to compare this with the RSI effect during sleep deprivation. Dissociation between the two effects during sleep deprivation would imply both that the cognitive mechanism of attention responsible for response preparation across seconds is distinct from that maintaining task performance across minutes and that not all forms of attention are degraded with sleep deprivation.

METHODS

PVT data were collected in three studies of total sleep deprivation as well as from one study conducted to obtain PVT control data from subjects maintaining their normal sleep patterns.

Subjects

Subjects were young healthy regular sleepers, aged 18 to 35 years (25 ± 3.7 years). All participants were carefully screened to ensure that they had no history of medical, psychiatric, neurologic, or sleep disorders. Subjects were screened for substance abuse and were instructed to refrain from drinking caffeine for the 24-hour period before and for the duration of the study. The three sleep deprivation studies included 25, 24, and 19 subjects, respectively, for a total of 68 subjects (16 women), whereas the control group included 16 subjects (6 women).

Procedures

The sleep-deprivation protocol lasted 54 hours and involved multiple experimental tasks. Here we report the results for the 10-minute PVT. In this task, subjects responded with a space-bar press to the appearance of a red "X," which was followed by RT feedback. The RSI varied randomly from 2 to 10 seconds. Although changes were made to other experimental tasks, the PVT was administered using the same protocol in each sleep-deprivation study.

The initial PVT session was administered before 0930 of the first day after a normal night of sleep at home. This first session was considered a practice run, and the data were not included in analyses. Eight additional sessions were administered every 6 hours beginning at noon of the first day and extending until 0600 of the third and final day. Data from these 8 sessions were included in the data analyses. The final session was after 48 hours of sleep deprivation for the three sleep-deprivation groups.

For the sleep-deprivation groups, subjects were constantly monitored by video camera and periodic visits by sleep laboratory staff, who also initiated and monitored cognitive testing. When not performing cognitive tests, participants had access to the Internet, music, TV, movies, and video games.

For the control group, the first administration of the PVT was conducted under experimenter supervision, whereas the subsequent runs were conducted by the subjects in their home and work environments. Program logs and data file-time stamps were used to confirm that runs occurred at the appointed times. Subjects were afforded a half-hour leeway in the execution times of the midnight and early morning runs to ensure that they could maintain their normal sleep patterns. All control subjects reported sleeping a minimum of 6 hours a night for the 2 weeks before the experiment and that participation was not disruptive to their sleep patterns.

Statistical Analyses

For the main "4-group model" analysis, a mixed-effects model using variance components with a random effect on the intercept for each participant was used, with $\alpha = 0.05$. There were four independent variables: (1) *Group*, with 4 levels: one for each of the three sleep-deprivation groups and 1 for the control group; (2) *ToT*, with 2 levels consisting of two successive 5-minute bins of PVT trials within each PVT testing session; (3) *RSI*, with three levels that grouped the short (2-, 3-, and 4-s), medium (5-, 6-, and 7-s), and long (8-, 9-, and 10-s) RSI values, respectively; and (4) Day, with 2 levels: runs 2 through 5 (first 24 hours of the study) and runs 6 through 9 (hours 24-48 of the study). Independent variables 2 through 4 are within subjects.

The dependent variable was mean *RT* by subject, *ToT*, *RSI*, and *Day*. (Analyses of median RT produced equivalent results.) Trials in which no response was made in the 30 seconds allotted (< 2% of all trials) and responses that were made before the stimulus was presented combined with responses with RTs less than 100 milliseconds (i.e., false starts, which were < 6% of all trials), were discarded from the RT analyses. Parallel analyses were also performed with the DVs of percentage of false starts (%FS) and the percentage of lapses (%Lapses)—as defined as all RTs longer than 500 milliseconds.

A possible effect of sleep deprivation in this design is indicated by the interaction of Group, Day, and either RSI or ToT, in conjunction with a planned contrast that ensures the group effect is between the control group and the average of the sleep-deprivation groups. First, a model was run for RSI and RSI-by-Day effects in the control group alone, the "control-group model," to ascertain whether an RSI effect is present in the PVT and, if so, to determine whether there are any practice effects.

RESULTS

In the control-group model, there was a main effect of RSI on RT ($F_{2,165} = 85.48$, P < 0.001), %Lapses ($F_{2,165} = 31.35$, P < 0.001), and %FS ($F_{2,165} = 21.84$, P < 0.001). Specifically, as the RSI increased from 2 to 10 seconds, RT and %Lapses decreased, whereas %FS increased. Thus, the RSI phenomenon is indeed present in the PVT. There was no main effect of Day in the control group on any of the 3 variables (P = 0.24; P = 0.59; P = 0.34), indicating a lack of sleep pressure sufficient to affect performance and an absence of practice effects. The absence of sleep pressure is also indicated by the absence of ToT (P = 0.47; P = 0.63; P = 0.66) and Day-by-ToT effects (P = 0.24; P = 0.34; P = 0.84) for all variables.

In the 4-group model, the RSI effect was significant for RT ($F_{2,868} = 21.22$, P < 0.001), %Lapses ($F_{2,868} = 136.49$, P < 0.001), and %FS ($F_{2,868} = 129.51$, P < 0.001). Specifically, as the RSI increased from 2 to 10 seconds, mean RT was reduced by 69.31 ± 10.70 milliseconds, %Lapses decreased by 6.65%, and %FS increased by 5.71%. There was no significant Group-by-Day-by-RSI interaction for RT (P = 0.89), for %Lapses (P = 0.72), or for %FS (P = 0.17). A planned comparison between the control and sleep-deprivation groups within the Day-by-RSI interaction was also not significant for any of the three variables (P = 0.57; P = 0.21; P = 0.07). Thus, the RSI effect was preserved across 48 hours of total sleep deprivation. (See Figure 1.) In the 4-group model, there was a significant Group-by-Day-by-ToT interaction for RT ($F_{3,868} = 4.99$, P = 0.002), as had been hypothesized. A planned comparison confirmed that the Day-by-ToT interaction differed significantly between the sleep-deprivation groups and the control group (P < 0.001). We thus replicated the sleep deprivation–related ToT effect on RT.[2] There was no significant Group-by-Day-by-ToT-by-RSI interaction on RT (P = 0.99). A planned comparison between the control and the sleep-deprivation groups was also not significant (P = 0.73). There were no Group-by-Day-by-ToT or Group-by-Day-by-ToT-by-RSI interactions for either %Lapses (P = 0.14; P = 1.0) or %FS (P = 0.34; P = 0.92).

DISCUSSION

To our knowledge, this is the first demonstration that the variable RSI affects performance on the PVT—a simple RT task with intervals in the seconds range. Previous studies that have reported the presence and magnitude of RSI effects used choice RT tasks with intervals in the milliseconds range.[3,4] Controls showed RSI effects—at shorter intervals, responses are slower and there are a greater percentage of lapses, whereas, at longer intervals, responses are faster and there are a greater percentage of false starts. The RSI effects were not changed by

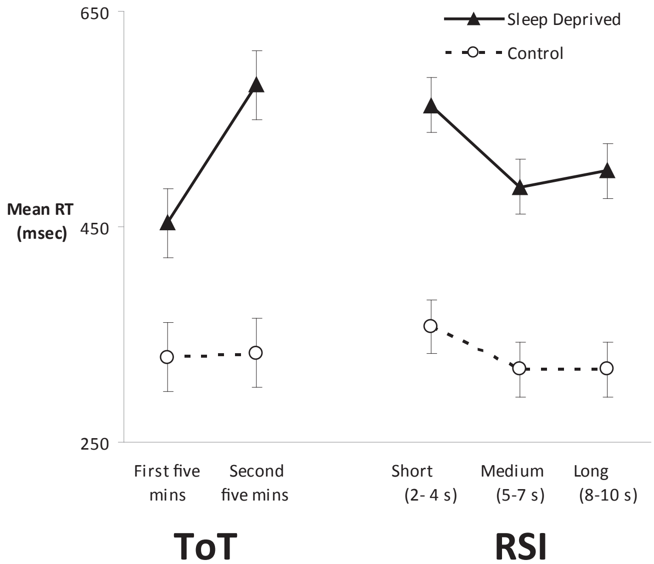

Figure 1—Sleep deprivation and the readiness to perform across minutes and seconds. Mean reaction time (RT) is shown during runs 6-9 (Day 2) for control and sleep-deprived subjects. On the left, the data are broken up into the first 5 minutes and the second 5 minutes to display readiness to respond across minutes, or the time on task (ToT) effect. There is a significant ToT effect in the sleep-deprived subjects across the sleep-deprived runs and no significant ToT effect in control subjects across these same time points in the experiment. On the right, the data are broken up into short, medium, and long response-stimulus intervals (RSI) to display readiness to respond across seconds, or the variable RSI effect. Both the control and sleep-deprived subjects show a significant RSI effect. Symbols indicate the model estimated mean ± standard error.

practice, as they did not vary from the first 4 to the last 4 testing runs. Second, sleep-deprived subjects also showed RSI effects that were preserved for all three variables across two nights of sleep loss. That is, sleep deprivation did not alter the RSI effect in terms of either speed or accuracy. This finding effectively replicates previous studies of the effect of sleep deprivation on the RSI effect within the tightly constrained context of a simple RT task like the PVT. Third, we replicated the ToT effect on RT during sleep deprivation and demonstrated that this vigilance effect was independent of the RSI effect.[2]

The dissociation between the vigilance decrement and the RSI effect demonstrates the specificity with which sleep deprivation affects aspects of attention. That is, even when vigilance is impaired by sleep deprivation, individuals retain response preparation across seconds. We have now shown that two separate mechanisms of attention underlie the ability to attend to and estimate rising expectancies over seconds, as opposed to the cognitive control necessary to allocate attention to maintain task performance over minutes. Interestingly, although these data indicate that different forms of attention underlie the vigilance decrement and the RSI effect, there is still some question as to the origin of the RSI effect and, consequently, which form of attention is here found to be spared by sleep deprivation.

Early work on the RSI effect suggested that it arose from the refractory period of a limited-capacity system.[4] That is, after making a response, processing kinesthetic feedback was thought to impede processing of a subsequent stimulus for a fixed duration of time (about half a second). However, this explanation cannot support the present demonstration of an RSI effect using 2- to 10-second intervals, which exceeds the maximum proposed refractory period. Instead, the current findings, with RSI values an order of magnitude greater than those used in previous studies, suggest time-scale invariance to the RSI effect and, thus, provide the first evidence for Rabbitt's suggestion that it may arise from the use of temporal context to shape response preparation.[6]

Two previous studies found no change in the RSI effect after 1 night of sleep deprivation.[4,5] Our results extend this finding to a test highly sensitive to sleep deprivation,[2] the PVT, and through a second night of sleep deprivation. Combined with our thorough analysis of multiple performance measures, we now believe that this null effect is indicative of true resistance of rising expectations over seconds to the effects of 48 hours of sleep deprivation, rather than a lack of statistical power, lack of sensitivity of the test, insufficient sleep deprivation, or other uninteresting explanations.

These results have two important implications for future research. First, the successful behavioral dissociation of vigilance and rising expectations over seconds suggest the possibility that these two abilities are supported by different neural mechanisms. This question could be pursued in neuroimaging studies. Second, theories of sleep deprivation should consider how the unique sleep deprivation–induced pattern of spared and impaired aspects of attention may affect the ability to perform in real-world settings.

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REFERENCES

1. Dinges DF, Powell JW. Microcomputer analyses of performance on a portable simple visual RT task during sustained operations. Behav Res Methods Instrum Comput 1985;17:652-5.
2. Doran SM, Van Dongen HP, Dinges DF. Sustained attention performance during sleep deprivation: evidence of state instability. Arch Ital Biol 2001;139:253-67.
3. Rabbitt P. Psychological refractory delay and response-stimulus interval duration in serial, choice-response tasks. Acta Psychol 1969;30:195-219.
4. Wilkinson RT. Response-stimulus interval in choice serial reaction time: interaction with sleep deprivation, choice, and practice. Q J Exp Psychol 1990;42A:401-23.
5. Smulders FTY, Kenemans JL, Jonkman LM, Kok A. The effects of sleep loss on task performance and the electroencephalogram in young and elderly subjects. Biol Psych 1997;45:217-39.
6. Belenky G, Wesensten NJ, Thorne DR, et al. Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: A sleep-dose response study. J Sleep Res 2003;12:1-12.