Fatigue and driving: Disentangling the relative effects of time of day and sleep deprivation

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Abstract

Fatigue is a recognised problem in the transport industry. It has been attributed to two main influences: time of day and the time since last sleep. While the role of these two influences in producing fatigue is not disputed, there is less agreement on how they interact with one another. The aim of this study was to examine the relative effects of time of day and sleep deprivation on fatigue and performance. Two independent groups were exposed to 28 hours of sleep deprivation. For one group (n=39) the sleep deprivation condition began at 06:00 hours and for the second group (n=22), the sleep deprivation condition began at 00:00 hours. By varying the start time for each of the two groups, but keeping constant the duration of sleep deprivation it was possible to examine the effects on performance of variations in the time of day of testing. For the group commencing at 0600 hours the longest period without sleep occurred close to the low point of the circadian rhythm. For the group commencing at 0000 hours, the circadian low point coincided with only around two to six hours of sleep deprivation. Eight computer-based performance tests were used as well as subjective ratings of fatigue. The results showed a clear interaction effect. Both time of day and sleep deprivation factors affected performance but only in combination, neither had independent effects. If the circadian rhythm was not at its low point or trough, there were no effects of sleep deprivation. Performance at the circadian low point was not adversely affected when the study participant was rested. These findings have clear implications for good fatigue management, indicating that night work including driving can be performed if the person is properly rested, but not if night driving is required after long periods without sleep.

Keywords

Fatigue, sleep deprivation, time of day, performance, driving,

Introduction

In the transport industry fatigue is a recognised problem that has been attributed to two main influences: time of day or the circadian rhythm and the time since last sleep. There is good evidence that the daily or circadian rhythm produces a pronounced minimum in the midnight to dawn period and a lesser minimum in the early afternoon in physiological functions such as in temperature, in sleep propensity, in alertness and in performance [1, 2]. There is also good evidence that increasing time awake produces decreasing alertness and performance deficits. For example a number of studies demonstrated that, starting from around 6:00am, a period of sleep deprivation of around 18 hours produces alertness and performance deficits equivalent to that produced by blood concentrations of alcohol at the legal limit for driving in Australia (0.05% BAC) [3, 4, 5, 6].

Unfortunately, there is less evidence and agreement on how these two influences interact with one another. For example, in the sleep deprivation studies cited above, the early morning commencement of sleep deprivation meant that the apparently vulnerable period of 18 hours of sleep deprivation coincides with the circadian low point (0100-0400hrs) when performance capacity and safety are known to be lower. Due to this confounding of time awake and time of day, the relative contributions of each of these influences in producing alertness and performance effects cannot be determined.

This issue needs to be resolved as knowing the source of fatigue is essential for understanding when and why fatigue risk should be of concern for performance and safety. Consequently, the overall aim of this study was to obtain a better understanding of the relative effects of time of day and sleep deprivation on fatigue and performance. This study attempted to disentangle the effects of 28 hours of sleep deprivation from the effects of time of day on performance by comparing sleep deprivation commencing at 06:00 and 00:00hrs. This paper describes preliminary analysis for two of the performance tests used in this study

Methods

Subjects

There were 61 participants in this study in total. All were volunteers in the age range 25-50 years.

Study Design

The design involved two independent groups each of which were exposed to 28 hours of sleep deprivation. For one group (n=39) the sleep deprivation condition began at 06:00 hours and for the second group (n=22), the sleep deprivation condition began at 00:00 hours. By varying the start time for each of the two groups, but keeping constant the duration of sleep deprivation it was possible to examine the effects on performance of variations in the time of day of testing. These start times were selected as they test different aspects of the time of day (circadian rhythm) and sleep deprivation interaction. For the group commencing sleep deprivation at 0600 hours the longest period of sleep deprivation occurred close to the low point of the circadian rhythm. A a six-hour phase delay (sleep deprivation commencing at 0000 hours), meant that the circadian low point coincided with only around two to six hours of sleep deprivation. It would be expected, therefore, that if sleep deprivation degrades performance independently of time of day, the less sleep deprived at the circadian low point the smaller will be the effect on performance and the greater the sleep deprivation the larger the performance deficit regardless of the time of day. If the circadian rhythm has an independent effect on performance, there should be a performance decrement at the circadian low point regardless of the amount of sleep deprivation at that point.

Measures

Eight different computer-based performance tests were used in this study, which took 30-40 minutes total test time at each test occasion. This paper describes the results of two of them; simple reaction time and the Mackworth clock vigilance test. In addition subjective fatigue rating scales were used on each test occasion. Details of these measures are as follows:

- Simple Reaction Time (RT): This is a simple visual-motor response speed test involving a yellow circle moving in an irregular counterclockwise path around the computer screen. The subject's task was to press a key on the keypad as quickly as possible whenever the circle changed colour from yellow to red. The test consisted of 40 colour change trials over a two minute period. The time taken for subjects to respond to the colour change and the number of missed colour changes were both measured.
- Mackworth clock Vigilance test: This task measured the ability to sustain attention in the face of monotonous stimulation. A circle, composed of 24 equally spaced dots, was presented on the computer screen. Each dot flashed briefly in turn at constant 500ms intervals. At random intervals (approximately every minute) one of the dots would be omitted from the flashing sequence. The subjects' task was to respond as quickly as possible via a button press on the keypad whenever a dot was omitted. The task continued for 15 mins during which 15 flashes were omitted. Reaction time to missed flashes and the number of missed responses were recorded.
- Subjective Fatigue Rating Scales: Three visual analogue scales were presented to participants on the computer screen at the beginning and end of each testing session. The three scales focused on different aspects of the fatigue experience and were anchored at the ends by the terms 'fresh – tired', 'clear-headed – muzzy-headed', and 'very alert – very drowsy'. Participants used the mouse to position a cursor at some point between the anchors to reflect their current level of fatigue. The computer recorded cursor position at one of the 20 positions along the dimension. These values were subsequently converted to percentages.

Procedure

All study participants underwent a sleep deprivation regime of 28 hours beginning from either 06:00hours or 00:00 hours. Participants were encouraged to get as much sleep as possible in the period immediately before each condition, including afternoon and evening naps so they were as rested as possible for the first test session. On the test day, participants were asked to wake at 0600 or 0000 and testing began approximately two hours afterwards (08:00 hrs or 02:00hrs). Participants were first asked to complete a brief questionnaire concerning their sleep, eating and drug-taking behaviour since the previous day, and then began the testing regime.

The testing schedule involved tests every hour for the first five tests then regularly every two hours, with the last test session commencing approximately 27 hours (09:00hrs and 03:00hrs) after their waking time. A total of 15 performance test sessions were completed, after which the participants were allowed to retire to sleep.

Analysis

For this analysis two blocks of tests were chosen for each sleep deprivation condition, corresponding to test sessions 1 to 4 (Low sleep deprivation) and 11 to 13 (High sleep deprivation). These test blocks were also chosen as they corresponded to different time windows in the circadian rhythm and provided a counterbalance of sleep deprivation (low and high) and circadian phase (low and high). These time windows were based on the evidence of the circadian trough in the midnight to dawn period and again in the early afternoon [2]. For the 06:00hrs sleep deprivation start condition, the 1 to 4 test session block corresponded to 08:00 to 11:30hrs time window (Low sleep deprivation/High circadian rhythm) and the 11 to 13 test session block corresponded to 01:00 to 05:00hrs time window (High sleep deprivation/Low Circadian rhythm). For the 00:00hrs sleep deprivation start condition, the 1 to 4 test session block corresponded to 02:00 to 05:30hrs time window (Low sleep deprivation/Low Circadian rhythm) and the 11 to 13 test session block corresponded to 19:00 to 23:00hrs time window (High sleep deprivation/High circadian rhythm). The test performance and fatigue ratings were averaged for each of these four sleep deprivation and circadian phase time windows and were compared using MANOVA followed by post hoc t-tests when main or interaction effects were statistically significant. For this analysis the four post hoc comparisons of interest were the effects of high sleep deprivation at high and low circadian points and the effects of the low circadian rhythm at low and high levels of sleep deprivation. For the post hoc analysis the error rate was adjusted for the number of comparisons using a Bonferroni adjustment so alpha was set at 0.013.

Results

Analysis of reaction speed results in the Reaction time test (see Figure 1) showed a significant interaction effect ($F_{(1.59)}=13.18, p<0.001$). Post hoc testing showed significantly slower responding in the High SD/Low Circadian time window compared to Low SD/Low Circadian window ($t_{(58.9)}=3.90, p<0.001$) and in the High SD/Low Circadian window compared to the High SD/High Circadian window ($t_{(59)}=3.21, p<0.002$). Neither of the other two comparisons was statistically significant. These findings indicate that there was no influence of low circadian rhythm on reaction speed during low sleep deprivation and high levels of sleep deprivation were influential only at the circadian low point.

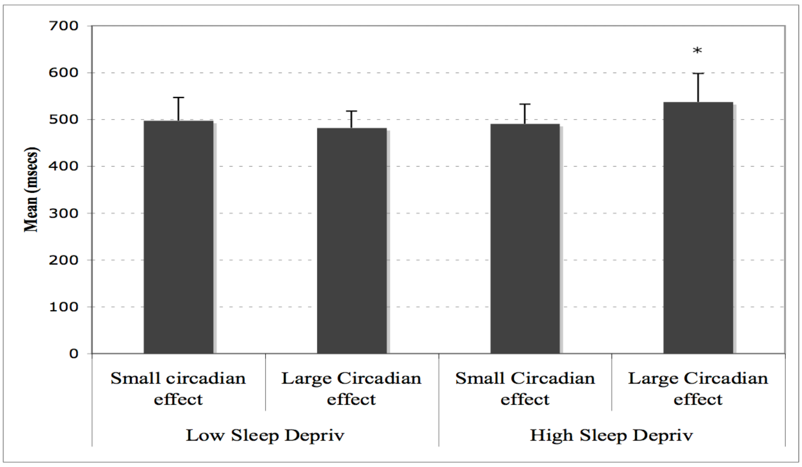

Figure 1: Reaction time test results for each sleep deprivation and circadian time window groups showing mean reaction speed (msecs) and standard deviation with * indicating statistical significance

Similar results were found for the number of missed responses in the Reaction time test (see Figure 2). For this measure the interaction effect was statistically significant ($F_{(1.59)}$=10.14,p<0.002) and post hoc comparisons also showed the same pattern as for response time with no effect of circadian influence on missed responses when sleep deprivation levels were low and high levels of sleep deprivation only showing significantly more missed signals during the circadian low period (High SD/Low Circadian window compared to Low SD/Low Circadian window ($t_{(38.8)}$=5.14,p<0.001); High SD/Low Circadian window compared to High SD/High Circadian window ($t_{(57.8)}$=3.57,p<0.001).

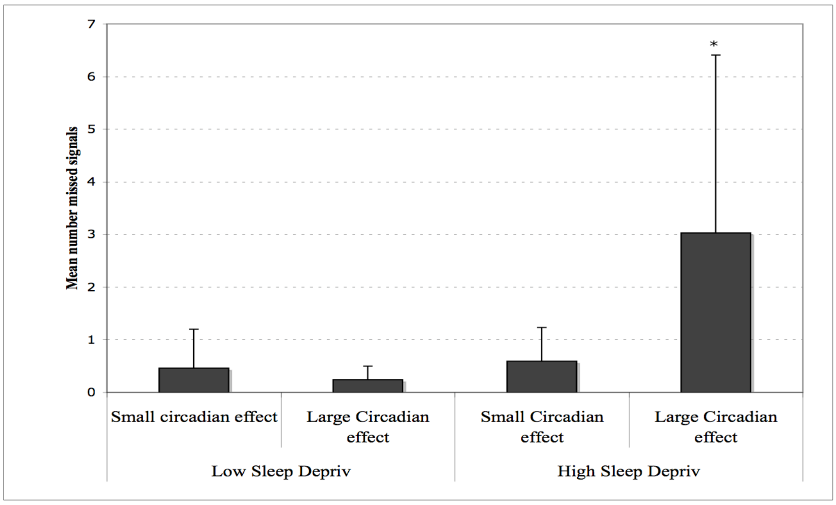

Figure 2: Reaction time test results for each sleep deprivation and circadian time window groups showing mean number of missed responses and standard deviations with * indicating statistical significance

Figures 3 and 4 show the results for the Macworth clock vigilance test. Similar results were found for this test as the Reaction time test. For the Reaction speed measure, a significant interaction effect ($F_{(1.59)}$=16.79,p<0.001) followed by post hoc comparisons showed the same pattern of effects of no effect on speed of response during the circadian low period when sleep deprivation levels were low but significant slowing of response speed when high levels of sleep deprivation coincided with the circadian low point (High SD/Low Circadian window compared to Low SD/Low Circadian window, $t_{(42.6)}$=5.85,p<0.001; High SD/Low Circadian window compared to High SD/High Circadian window, $t_{(41.6)}$=5.58,p<0.001). The Missed signals measure showed very similar results with again, a significant interaction effect ($F_{(1.59)}$=29.59,p<0.001) and significantly more missed signals during the High SD/Low Circadian window compared to the Low SD/Low Circadian window (($t_{(53.2)}$=9.27,p<0.001) and the High SD/Low Circadian window compared to High SD/High Circadian window ($t_{(58.9)}$=6.79,p<0.001). Again, the comparisons for Low SD and circadian window showed no significant effects.

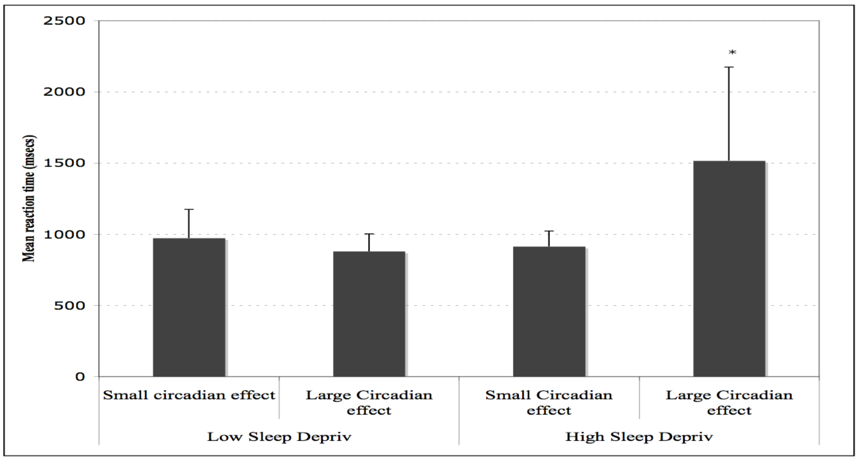

Figure 3: Mackworth clock vigilance test results for each sleep deprivation and circadian time window group showing mean reaction speed (msecs) and standard deviations with * indicating statistical significance

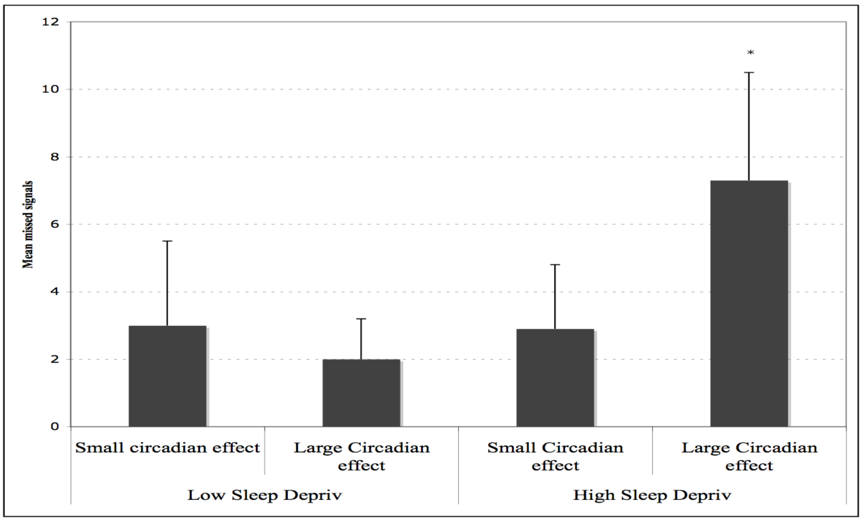

Figure 4: Mackworth clock vigilance test results for each sleep deprivation and circadian time window group showing mean missed responses and standard deviations (in brackets).

The results for subjective ratings of fatigue at each of the sleep deprivation and circadian time windows are shown in Figure 5. As for the performance measures, there was a statistically significant interaction effect ($F_{(1.59)}$=39.47,p<0.001), however post hoc comparisons showed somewhat different findings. Just as for the performance tests fatigue ratings were significantly higher in the High SD/Low circadian time window than in the Low SD/Low circadian window ($t_{(59)}$=8.83,p<0.001) and in the High SD/Low circadian window compared to the High SD/High circadian time window ($t_{(59)}$=4.40,p<0.001). Unlike the performance tests, fatigue ratings were also significantly higher in the Low SD/Low circadian window compared to the Low SD/High circadian time window ($t_{(59)}$=3.06,p<0.003) and in the High SD/High circadian time window compared to the Low SD/High circadian window ($t_{(59)}$=7.59,p<0.001)

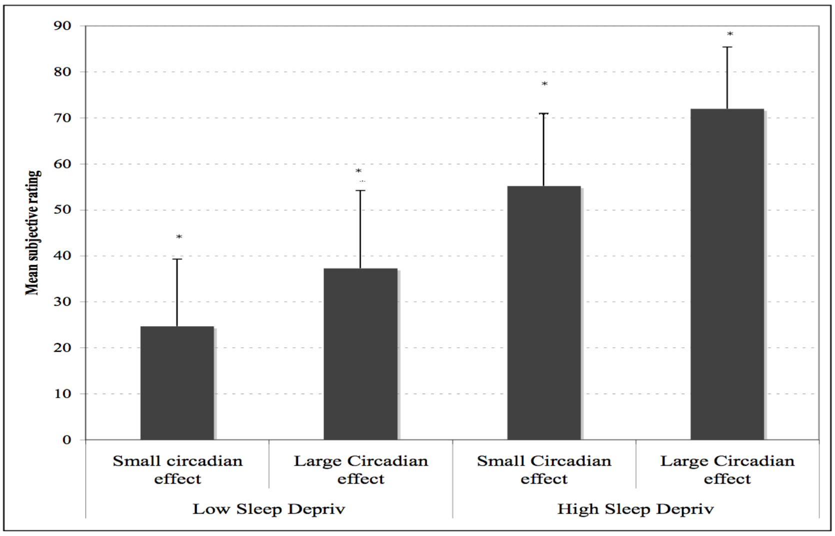

Figure 5: Subjective ratings of fatigue for each sleep deprivation and circadian time window group showing mean ratings and standard deviations (in brackets).

Discussion

In this study both time of day and sleep deprivation factors were determinants of performance but only in combination, neither had independent effects. There was a clear interaction between sleep deprivation and circadian influences on cognitive performance, with the poorest performance occurring when both time of day and circadian influences occurred together. If the circadian rhythm was not at its low point, there were no effects of sleep deprivation. Circadian influences also did not show independent effects. Performance at the circadian low point was not adversely affected when the study participant was rested.

These results are consistent with some mainly indirect findings of previous forced desynchrony studies. In these studies the usual synchrony between time awake and the circadian rhythm is broken by extending the awake period of study participants to longer than 24 hours (usually 28 hours) for a number of weeks. This experimental manipulation has the effect of making waking times occur at almost all times in the circadian rhythm over the study period, but minimizing the extent of sleep deprivation. Studies using this methodology have found that circadian and time awake influences show a non-linear interaction with one another for measures of mood [7] alertness and performance on a continuous addition task [8] and the number of errors but not performance on a modified version of the sustained attention response test (SARTm) [9]. Furthermore, a reanalysis of previously collected data in a laboratory sleep deprivation task also showed a non-linear interaction between circadian and time awake influences using the psychomotor vigilance task [10]. Clearly the results of our study reinforce the role of the interaction of the time of day and time awake processes in producing poorer alertness and performance at the high end of sleep deprivation and the circadian trough.

What has not been demonstrated previously is that the interaction is the only effect of the two influences, on the cognitive functions measured in this study. Previous studies have not compared directly the independent and interaction effects of sleep deprivation and circadian phase. As this study showed, circadian effects only had an influence on performance in combination with sleep deprivation and sleep deprivation effects were only seen at the circadian low point.

Notably, both performance measures of both tests showed the same findings so suggesting that they indicate a more general performance effect. Further analysis of the data from the other tests conducted in this study will reveal the extent to which time awake and circadian influence interact for all cognitive functions. In contrast subjective fatigue ratings did not show the same patterns as the performance tests. Fatigue ratings showed independent effects of sleep deprivation and circadian influences in addition to a larger interaction effect. Other studies have also failed to find consistency between fatigue ratings and neurobehavioural performance [11, 12, 9]. It seems that people respond to body status and the external cues about how tired they should feel and make judgments that are consistent with these influences. Performance, on the other hand, seems to have different origins. Importantly, this disconnect between fatigue ratings and performance effects means that fatigue ratings should not be used as an indicator of potential performance effects.

There are clear implications for fatigue management and the design of driving and rest schedules from this study. The finding that significant performance deficits only occurred when high levels of sleep deprivation coincided with the low point of the circadian rhythm points to the need to avoid driving during the midnight to dawn period if the driver has been awake for long periods. As rested participants did not show the expected circadian effects on performance and sleep deprivation effects on performance were not seen outside the circadian low point these results also indicate that driving at night during the midnight to dawn period can be performed safely and without error if the person is properly rested at the start of the drive. These results provide evidence that for road safety we need to advise drivers of the dangers of working or driving for long hours which culminate in the midnight to dawn circadian period as this combination significantly increases the risk of poor and unsafe performance.

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