Accident Analysis and Prevention 43 (2011) 690–697

Contents lists available at ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Investigating the relative effects of sleep deprivation and time of day on fatigue and performance

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ARTICLE INFO

Article history:
Received 12 June 2009
Received in revised form 7 September 2010
Accepted 15 October 2010

Keywords:
Fatigue
Time of day
Circadian rhythm
Sleep deprivation
Performance

ABSTRACT

Time of day and the time since last sleep are acknowledged causes of fatigue, but comparatively little is known about how they interact. This study examines the relative effects of time of day and sleep deprivation on fatigue and performance. Two independent groups were exposed to 28 h of sleep deprivation beginning at 06:00 h for one group ($n = 39$) and at 00:00 h for the other ($n = 22$). By varying the start time for the two groups, but keeping constant the duration of sleep deprivation, the effects of variations in the time of day of testing could be examined. For the 06:00 h start group the longest period without sleep occurred close to the low point of the circadian rhythm. For the 00:00 h start group the circadian low point coincided with only two to six hours of sleep deprivation. Performance was evaluated two-hourly using eight computer-based tests and subjective fatigue ratings. The results showed a clear interaction effect. Both time of day and sleep deprivation affected performance but only in combination; neither had independent effects. These findings have implications for fatigue management.

1. Introduction

Fatigue is a recognised problem in industry, especially the transport industry. It has been attributed to two main influences: time of day or the circadian rhythm and the time since last sleep. Evidence on the existence of the circadian rhythm demonstrates that there is a daily rhythm in physiological functions such as temperature, sleep propensity, alertness and performance that has a pronounced minimum in the midnight to dawn period and a lesser minimum in the early afternoon (Czeisler et al., 1980; Monk, 1987). Similarly, there is considerable evidence that increasing time awake also produces decreasing alertness and performance deficits. For example a number of studies demonstrated that, starting from around 06:00 h, a period of sleep deprivation of around 18 h produces alertness and performance deficits equivalent to that produced by blood concentrations of alcohol at the legal limit for driving in Australia and a number of other countries (0.05% BAC; Dawson and Reid, 1998; Williamson and Feyer, 2000; Arnedt et al., 2001; Falleti et al., 2003).

While the role of these two influences in producing fatigue is not disputed, there is less evidence and agreement on how they 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 h of sleep deprivation coincides with the circadian low point (01:00–04:00 h) when performance capacity and safety are known to be lower. This confound between time awake and time of day means that it is not possible to interpret the relative contributions of each in producing alertness and performance effects. It is possible that the apparent effects of sleep deprivation are due to the combination of sleep deprivation and time of day effects (so over-estimating the effects of sleep deprivation), to sleep deprivation effects alone or solely to circadian influences.

It is important to resolve this question as knowing the source of fatigue is essential for designing work–rest schedules that will be effective for fatigue management. 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. The aim of this study was to disentangle the effects of 28 h of sleep deprivation from the effects of time of day on performance by comparing sleep deprivation commencing at 06:00 and 00:00 h.

2. Method

2.1. Study design

The design involved two independent groups, one collected in 1997 and the other in 2006 each of which were exposed to 28 h of sleep deprivation. For one group ($n = 39$) the sleep deprivation condition began at 06:00 h and for the second group ($n = 22$), the sleep deprivation condition began at 00:00 h. By varying the start

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doi:10.1016/j.aap.2010.10.013

Table 1
Overview of approach to data analysis.

Time in sleep deprivation period	Details	Early (2.00–5.5 h)	Late (19:00–23:00 h)
Test time			
Start 06:00		Neither effect (A)	SD and Circ effect (D)
	Sleep deprivation (SD)	Low SD	High SD
	Circadian phase (Circ)	Circ high	Circ low
	Test period	0800–1200	0100–0500
Start 00:00		Circ effect (B)	SD effect (C)
	Sleep deprivation (SD)	Low SD	High SD
	Circadian phase (Circ)	Circ low	Circ high
	Test period	0200–0600	1900–2300

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 06:00 h the longest period of sleep deprivation occurred close to the low point of the circadian rhythm. A six-hour phase delay (sleep deprivation commencing at 00:00 h) 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, less sleep deprivation will result in a smaller effect on performance and greater sleep deprivation will produce performance deficits, 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. The overall study design is summarised in Table 1. The results for the group beginning at 06:00 h were described previously (Williamson and Feyer, 2000; Williamson et al., 2001).

2.2. Study participants

There were 61 participants in total in this study. All were volunteers. They were recruited through word of mouth and advertisements. All were paid for their time either as a normal part of their work or as a one-off payment of $1000 at the end of their participation.

Table 2 shows the demographic characteristics of study participants in each study group. There was no difference between the early morning and midnight sleep deprivation start groups on age, with very few participants in the most extreme age categories (<20 and 50–59 years) so most participants were in the 30–49 years age group (53% and 51% for 06:00 and 00:00 start groups respectively). There were also no statistically significant differences between the groups on gender, educational background or Epworth Sleepiness Scale (ESS) score. In addition ESS scores were low for both groups.

Table 2
Summary of demographic characteristics for participants beginning sleep deprivation in the early morning (06:00 h) and midnight.

	Sleep deprivation start 06:00 h	Sleep deprivation start 00:00 h	Significance
Age			
<30 years	35.9%	36.4%	$\chi^2_{(2)} = 2.71$, ns
30–39 years	28.2%	45.5%	
40+ years	35.9%	18.2%	
Gender			
Male	94.9%	86.4%	$\chi^2_{(1)} = 1.35$, ns
Education level			
<7 years	2.6%	0.0%	$\chi^2_{(4)} = 1.88$, ns
7–10 years	57.9%	45.5%	
11–12 years	15.8%	18.2%	
Tertiary technical	13.2%	18.2%	
Tertiary academic	10.5%	18.2%	
Epworth score			
Mean (/24) (s.d.)	6.69 (3.74)	6.40 (2.99)	$F_{(1,59)} = 0.09$, ns
Lag between last sleep and start testing			
Mean hours (s.d.)	2.3 (2.74)	3.03 (2.73)	$t_{(58)} = 1.55$, ns

2.3. Measures

Eight different computer-based performance tests were used in this study, totaling 30–40 min test time at each test occasion. In addition subjective fatigue rating scales were used on each test occasion. Details of the measures are provided in Williamson et al. (2001), and are as summarized below. All tests were computer-based and involved stimulus presentation on the screen and responses using either a keypad (Genovation Micropad 622) or a standard serial mouse.

- *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 2 min 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 500 ms 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 min during which 15 flashes were omitted. Reaction time to missed flashes and the number of missed responses were recorded.
- *Unstable tracking*: This test assessed hand–eye coordination and required participants to keep a small green dot inside a moving yellow circle on the computer screen. The task was adaptive in that it became more difficult (movement became less predictable) as the participant became more accurate in keeping the dot within the circle. The test duration was 3 min and measured task difficulty level achieved.
- *Dual task*: This test assessed the ability to attend to two tasks simultaneously by combining the unstable tracking and simple Reaction time tests. The tracking task was the same as when conducted alone and reaction time was assessed by requiring participants to respond to colour changes in the circle being tracked using the same keypad as in the RT test alone. The test duration was 3 min and the same measures were collected as for the two component tasks alone.