Original Article

Effect of cumulative sleep loss on susceptibility to spatial disorientation

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ABSTRACT

Military operations are required to maintain sustained continuous operations throughout the day and the night to gain advantage over the enemy. In such situations, the aircrew cope with reduced hours of sleep over several days. Similarly, airline pilots cope with irregular work schedule to meet commercial requirements. Prolonged hours of work interact with circadian rhythms, thus affecting performance. Besides this effect, an often overlooked factor is the susceptibility of the pilots to Spatial Disorientation (SD) due to cumulative sleep loss. This study was done to assess the susceptibility of cumulative sleep deprived subjects to simulated passive illusions of Semicircular Canals (SCC). 15 non-aircrew volunteer subjects were exposed to passive coriolis and somatogyral illusions in SD simulator (DISO), after 16 hrs of cumulative sleep loss. Parameters measured were latency, Coriolis Time Interval (CTI) and duration response to somatogyral illusion. Besides, psychomotor task performance was assessed daily using validated tests viz. Choice Reaction Time (CRT), Spatial Orientation Task (SOT), vigilance task and visual memory task. Latency, CTI and duration response to somatogyral illusion and coriolis was found to be not significant amongst cumulative sleep deprived volunteer subjects. CRT and SOT did not reveal any significant change after four days. Vigilance tasks showed significant ($p < 0.05$) increase in the total response and the response time on day 5, as also only 'correct response – absent' of visual memory task was found to be decreased, and was significant ($p < 0.05$). The outcome of evaluation of cumulative sleep loss on passive illusions of SCC was inconclusive, which was surprisingly not unexpected, considering the complex interplay of various factors: physical, physiological and psychological. Yet, in operational settings, even in the absence of evidence of altered susceptibility to SD and performance decrement in laboratory based studies, the sleep deprivation induced fatigue and associated performance decrement must always be considered, which could result in unsafe aviation conditions.

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Introduction

Success of military operations depends on maintaining continuous operations through the day and the night. Such sustained operations are meant to gain advantage over the enemy by overwhelming their resources. Modern Air Forces have dedicated night strike squadrons to deny the enemy an advantage by maintaining constant pressure on their air defence systems, degrading their offensive potential and denial of rest and recuperation to men and repair and maintenance of machine. In such situations, the aircrew are known to cope with reduced hours of sleep over several days. Similarly airline pilots cope with irregular work schedule to meet commercial requirements. [1]. The commercial pilots are governed by their duty schedule and the military aviators have the uncertainties of operational deployment to affect their sleep. Changing sleep patterns over a period

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of time is known to induce cumulative fatigue and sleep debt. This, though subtle or covert, may have implications for Spatial Disorientation (SD) and in turn, flight safety. Sleep deprivation has been reported to affect cognitive, psycho-behavioural and emotional measures [2, 3, 4]

Field studies on sleep loss and incident/accident reports do not provide converging evidence to the laboratory studies on sleep/wake pattern showing performance deterioration due to sleep loss [5]. Though, in practice, increase in error rate or delayed reactions may be reported by individuals due to sleep loss, the outcome as per the time-of-the-day is determined by the situation, task and the person related factors [5]. Incidentally, variables in aviation viz.: time of the day, circadian rhythms, alertness states or the task may influence the susceptibility of the pilots to SD.

Effect of acute or cumulative sleep loss has been studied extensively in different settings, and is known to affect the central nervous system, reaction time, vestibular system or memory. Specifically, sleep loss impairs memory, learning, logical reasoning, arithmetic calculations, pattern recognition, verbal processing and decision making [6]. The prefrontal lobe, responsible for attention, coping with novel and unknown situations, divergent, innovative and flexible thinking based on past experiences, contextual and temporal memory, shows slowing of its activity due to sleep loss [6]. The cognitive activities of prefrontal lobe are vital in dynamic tasks such as aviation. Though it has been demonstrated that the adverse effects of sleep loss can be attenuated [6] by increased motivation, in real life a pilot may err while facing cognitively challenging tasks or situations like SD. Research on sleep loss has been conducted using tasks that assessed the basic skill viz. vigilance, reaction time etc. in non-dynamic laboratory setting [6]. However the influence of cumulative sleep loss on susceptibility to SD, akin to disrupted sleep pattern among military pilots, in dynamic simulator based settings has not been studied.

An early study on sleep deprivation [7] reported implications for piloting, especially on situational awareness, where loss of situational awareness, could in turn lead to SD. SD is a major cause of aircraft accidents [8]. Susceptibility of a pilot to the effects of SD, irrespective of age, training or experience, remains an omnipresent threat to flight safety.

This study was conducted to assess the susceptibility of cumulative sleep deprived subjects to SD in SD simulator, with an objective to evaluate if cumulative sleep loss affects the threshold for susceptibility to SD during simulated passive illusions.

Material and Methods

This study was conducted on 15 non-aircrew male volunteers (mean age 31+2.59 years), after obtaining their informed consent. They were selected and age-matched to be representative of intended beneficiary i.e. aircrew. Spatial Disorientation simulator (Airfox DISO®) in the Department of Acceleration Physiology and Spatial Orientation, Institute of Aerospace Medicine (IAM), Bangalore was used to conduct the ground based simulation of passive illusions viz. coriolis and somatogyral illusion, utilizing the continuously rotating system in yaw axis, akin to the Barany's chair.

The experimental protocol was based on the consideration that a normal person may sleep from 2200 h to 0600 h (8 hrs). Thus the volunteer subject was asked to follow his normal routine before day 1. Thereafter, for the next 4 nights, he was asked to follow the defined protocol for sleep deprivation, by sleeping from 0200 h to 0600 h each night. Each subject maintained a sleep diary, to help ascertain the activities before sleeping and the time and duration of sleep. The study was conducted between 0800 h and 1000 h, on Monday (day 1) and Friday (day 5). The psychomotor task performance tests were undertaken by each subject from day 1 to 5; while on day 1 and day 5, after the psychomotor tests, the subjects underwent the DISO runs to record their SD thresholds.

The SD thresholds viz. latency period, persistence of sensations and duration of the selected passive illusions were recorded on two days: day 1 (rested) and day 5 (cumulative sleep deprived). Latency period was measured as time taken for threshold of perception by Semicircular Canal (SCC) in yaw axis, commencing @ 0.5°/sec and gradual increase in steps of 0.2°/sec to both right and left directions. Persistence of sensations was measured by Coriolis Time Interval (CTI), in four positions: head forward, head upward, head right and head left [9]. Duration of illusions was measured as time taken for threshold of perception by SCC in yaw axis, commencing @ 5°/sec, as in somatogyral illusion as per the standard DISO protocol, till 60°/sec and on deceleration, for both right and left directions [9].

In addition, an evaluation of objective alteration in psychomotor task performance, on day 1 (control) and each day thereafter till day 5 (test) was done. This was done to evaluate progressive effects of sleep deprivation on cognitive function tests, as a measure of psychomotor task performance. For an objective evaluation of the performance tasks, validated, PC based, cognitive function tests available at IAM were utilised, including Choice Reaction Time–Visual (CRT), Spatial Orientation Test (SOT) [10], Vigilance Task and Visual Memory Task. The chosen psychomotor tasks are described in brief.

The CRT test is displayed by presenting three visual stimuli as coloured boxes, with a predefined key on the keyboard as the response. The colours displayed are red, green and blue and their respective response keys are 'R', 'G' and 'B'. This test presents the three colours 20 times in random sequence at random intervals. The subject responds to the displayed colour by swiftly pressing the correct key, and is assessed for accuracy of the correct response for the displayed colour.

The SOT [9] is a composite test to evaluate the ability to identify orientation of an aircraft in four different attitudes – nose up-cockpit view, nose up-underside view, nose down-cockpit view and nose down-underside view. This is done by presenting 32 randomly displayed, stimulus pictures of the aircraft, for a stipulated period. In addition, to the displayed image, a strip at the bottom of the monitor contains red and green colours. The subject imagines sitting inside the aircraft cockpit, and then has to identify the central colour of the strip displayed at the bottom, whether the colour is on the port or the starboard wing tip of the displayed aircraft.

Vigilance task is assessed by displaying 90 different geometrical figures flashed on the computer monitor randomly after a short and fixed interval. The subject is to detect immediate repetition of the same figure to which they responded by a pressing the 'space bar'. The figures are of different shapes and of the size 3.75 cm x 2.5 cm. During the test, number of figures is displayed on the top right hand corner of the computer screen. A total of 100 figures in each set were displayed during this study.

VMT is meant to study the working memory. The target, a geometrical figure, with different orientation is displayed, followed by an array of four different geometrical figures, including the target.

The test has the target exposure time of 200 ms followed by pre-array delay of 500 ms, then the array exposure time of 400 ms and then the inter-stimulus delay of 500 ms. Subject has to identify the target from the array, as per the pre-decided choices of the keyboard press. The number of total displayed stimuli in 2 minutes duration varied from subject to subject from 30 to 45 based on their response time.

Utilising the descriptive statistics, all the values are presented as mean and standard deviation. There was significant departure of the data from normality, as assessed through Shapiro Wilk's 'W' statistic. Hence Friedman's ANOVA, a non-parametric analysis of variance, as applicable to

Table 1: Response of the semi-circular canals before and after Cumulative Sleep Deprivation (in seconds)

Day	Mean	SD	F	p
A: Latency				
		Right		
1	14.138	12.587		
5	10.501	8.565	1.496	0.412
		Left		
1	15.043	9.629		
5	14.174	7.897	1.683	0.369
B: Coriolis Time Interval (CTI)				
		Head Forward		
1	14.261	5.638		
5	15.050	6.994	1.444	0.337
		Head up		
1	15.982	7.935		
5	16.436	11.423	1.353	0.388
		Head Right		
1	18.051	10.946		
5	14.731	5.677	1.188	0.610
		Head Left		
1	25.587	14.392		
5	19.632	9.986	95.982	0.078
C: Duration of Somatogyral Illusion (SGyI)				
		Duration to attain steady state during SGyI		
1	21.161	13.971		
5	15.325	8.735	1.277	0.415
		Duration after deceleration during SGyI		
1	22.015	9.410		
5	29.077	13.143	3.319	0.176

Table 2: Choice Reaction Time (CRT) (in seconds)

Day	Mean	SD	Variance	F	p
1	0.864	0.242	0.058		
5	0.938	0.321	0.103	0.050	0.824

Table 3: Spatial Orientation Test (SOT)

Day	Mean	SD	Variance	F	p
A. Total Time (in seconds)					
1	80.539	22.111	488.918		
5	55.267	-0.254	9.089	1.288	0.519
B. Correct Response (number)					
1	13.625	1.668	2.783		
5	13.625	2.028	4.1162	0.419	0.848
C. Incorrect Response (number)					
1	2.375	1.668	2.783		
5	2.375	2.028	4.116	0.419	0.848
D. Selection Time (in seconds)					
1	72.381	21.575	465.520		
5	48.826	8.453	71.459	0.919	0.634
E. Confirmation Time (in seconds)					
1	8.171	3.355	11.256		
5	6.424	2.563	6.571	1.165	0.287

within subject (repeated measure) design was employed. For statistical significance, the 'p' value was set at 5% level of confidence (level of significance < 0.05). The statistical analysis was done using statistical software 'Statistica v.5.

Results

Table 1 shows the responses of the SCC under different conditions. The responses of the SCC under different conditions were found to be non significant after four days of cumulative sleep loss, as compared to the baseline results on day 1.

The results of the psychomotor tasks are presented hereafter.

Table 2 shows the results of the CRT. The results of CRT were found to be non significant after four days of cumulative sleep loss, as compared to the baseline results on day 1.

Table 3 shows the results of the SOT. The results of SOT: total time, responses–correct and incorrect, selection and confirmation time, were found to be not significant after four days of cumulative sleep loss, as compared to the baseline results on day 1.

Table 4 shows the results of vigilance tasks. The total response, the response time and correct response for the vigilance tasks was found to be significant after four days of the cumulative sleep loss, as compared to the baseline results on day 1. Other responses viz. incorrect response, missed response, and repeat response were found to be not significant.

Table 5 shows the results of visual memory task. The visual memory task was found to be not significant after four days of cumulative sleep loss, except correct response–absent, which was significant.

Discussion

In real life situations, occurrence of cumulative sleep loss amongst aircrew may not be uncommon. This could occur due to personal, social or operational reasons. The aircrew may continue coping with such sleep deprivation. However, knowledge about effects of such sleep loss affecting the individual's susceptibility to SD is meagre. Hence, this study was undertaken to evaluate susceptibility to SD during simulated passive illusion

Table 4: Vigilance Tasks

Day	Mean	SD	Variance	F	p
A: Total Response (in seconds)					
1	126.200	65.161	4246.029		
5	139.500	68.495	4691.600	105.423	0.000*
B: Response Time (in seconds)					
1	0.349	0.042			
5	0.326	0.056		4.888	0.045*
C: Correct Response (number)					
1	7.933	4.148	17.209		
5	6.937	2.954	8.729	33.262	0.000*
D: Incorrect Response (number)					
1	1.200	0.941	0.885		
5	2.062	1.806	3.262	0.044	0.956
E: Missed response (number)					
1	3.5	2.030	4.123		
5	4.5	2.220	4.929	2.688	0.199
F: Repeat Response (number)					
1	11.066	2.604	6.780		
5	11.375	2.552	6.5165	0.846	0.012

Table 5: Visual Memory Task

A: Total Response (in seconds)

Day	Mean	SD	Variance	F	p
A: Total Response (in seconds)					
1	49.166	19.880	395.242		
5	43.083	21.865	478.083	12.884	0.213
B (i): Reaction Time – Rt (in seconds)					
1	1.462	0.456	0.208		
5	1.117	0.405	0.164	1.578	0.237
B (ii): Reaction Time – Lt (in seconds)					
1	1.214	0.314	0.099		
5	1.006	0.293	0.085	3.902	0.076
B(iii): Reaction Time – Absent (in seconds)					
1	1.335	0.261	0.068		
5	1.213	0.233	0.054	2.381	0.153
C (i): Correct Response - Rt (number)					
1	14.500	6.037	36.454		
5	13.833	8.032	64.515	7.470	0.123
C (ii): Correct Response – Lt (number)					
1	13.916	5.534	30.628		
5	12.750	7.200	51.840	3.676	0.232
C (iii): Correct Response - Absent (number)					
1	14.166	7.613	57.969		
5	13.000	7.397	54.727	43.318	0.005*
D (i): Incorrect Response - Rt (number)					
1	1.083	1.240	1.537		
5	1.416	2.274	5.174	0.691	0.582
D (ii): Incorrect Response - Lt (number)					
1	0.750	0.753	0.568		
5	0.833	1.193	1.424	0.107	0.898
D (iii): Incorrect Response – Absent (number)					
1	3.833	3.485	12.151		
5	2.000	1.758	3.090	4.406	0.124

among cumulative sleep deprived subjects.

For the purpose of this study, the partial sleep loss over four routine working days amongst non-aircrew subjects was studied, since probability of partial sleep loss during operations is more likely than total sleep loss, and thus has operational consequences. There could be partial sleep loss either due to going to bed late and waking up at the same time or sleeping at the usual hour but waking up early, or there could be sleeping for few hours and then getting up and then falling off asleep again [11]. Partial sleep loss, therefore, occurs whenever there is reduction in the usual amount of sleep during 24 hrs.

In this study, the susceptibility to SD on exposure to passive illusions, as measured by latency, CTI and duration response to somatogyral illusion, was found to be not significant for the cumulative sleep deprived subjects (Table 1). Therefore, cumulative sleep loss did not significantly affect threshold for susceptibility to SD during passive illusions in SD simulator in the present study.

In a sleep deprivation study, utilizing a Stille-Werner rotating device, Wolfe and Brown [12] recorded various SCC related parameters including latency response, the duration of perceived turning, Coriolis sensations and magnitude in degree of perceived climb/dive. Similar results of negligible effects on quantified experience of turning, as reported by Wolfe and Brown [12], were also found in this study.

In another study, Collins assessed the effects of sleep loss on a number of vestibular and vestibular related responses, including nystagmus and sensations, over a longer period of sleep deprivation up to 55 hrs [13]. Based on findings of his study, Collins emphasised that sensation of motion experienced during simple angular accelerations and Coriolis-type (complex) stimulation are especially significant in aviation environment. The same could not be replicated in this study.

Though, psychomotor task performance results in this study did not show any predictable pattern, it has been reported that there could be increase in lapses, affecting vigilance. There could be cognitive slowing, resulting in slower response to tasks demands, though it could also be because of the lapses, which in turn may reduce the speed of response.

Significant decrease in vigilance in correct detections and number of sums completed on addition tasks and digit span tests, respectively, we found when partial sleep reduction reduced to 4 hours. The effect was found to be cumulative over the 4 day period [15]. The negative results from partial sleep-loss studies are believed to be due to tests that are ‘too short’ and not using an experimental paradigm where the schedule of the tests is not a part of the daily workday. This could be the reason for variable results to the psychomotor tasks in the present study.

Deterioration in psychological performance due to sleep is known, whether physiological correlates of the same are evident or not, even though some impairment of Central Nervous System occurs [16]. As is evident in this study, sleep loss leading to performance degradation may not be evident or remain small, not because sleep deficit minimally affects task performance; instead the task performance stays near normal levels with compensatory mechanisms [11]. The sleep deprived subjects, mobilizing and expending their biochemical, physiological and behavioural resources, attempt to maintain their pre-sleep loss performance levels. Yet, it is important to know that a sleep starved subject may function with compromised situational awareness [11].

Unlike most sleep related studies which are performance oriented, susceptibility to SD, besides the psychomotor tasks, was studied in this study. In addition, variables in such an approach viz. task-dependent, individual differences and circadian effects are the confounding factors. Similarly, variables to study SD are related to the situation, personal alertness state or mental reserves, time of the day/night, fatigue, proficiency/skill levels and physiological limitations; and all of them can not either be studied in isolation or quantified. In the laboratory settings, the performance test may apply to a specific task, which may or may not be truly representative; the effect of circadian rhythm may or may not be apparent in the test result; and the sample population of the study, as was the case in this study, may not necessarily reflect the full range of target population [16]. In addition, in laboratory studies, complex interaction of the task, the situation and personal factors make it difficult for the researchers to demonstrate consistent results in studies on partial sleep loss and worse still do not account for real-world variables.

It is difficult to study sleep deprivation in real world conditions. Thus use of simulators and evaluation of aviation specific tests helps evaluate the performance objectively and consistently, especially activities and situation in aviation that could lead to fatigue or cause performance decrement. Compromised mental or physical state leading to SD in flight remains a strong possibility hence such studies under simulated conditions are justified.

Conclusion

The inconclusive outcome of evaluation of cumulative sleep loss in this study and its effect on threshold of SCC to determine the susceptibility to SD during passive illusions in SD simulator, in isolation may not help contribute any further in understanding the dynamics of SD and contribution of sleep deprivation. However, it must be understood that with the complex interplay of various factors: physical, physiological and psychological, such an outcome is not unexpected.

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