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7. Author(s)	
William E. Collins, Ph.D.	

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16. Abstract

The influence of approximately 34 and 55 h of sleep deprivation on performance scores derived from manually tracking the localizer needle on an aircraft instrument was assessed under both static (no motion) and dynamic (whole-body angular acceleration) laboratory conditions. In each of two experiments, 20 young men were equally divided into groups of control and sleep-deprived subjects. All tests were conducted in an enclosed Stille-Werner rotator in total darkness with the exception of the illuminated tracking display. In both experiments, significant decrements in dynamic tracking performance were uniformly obtained after 24 h and more of sleep loss. Static tracking scores were also impaired but less consistently so. In Experiment II, administration of d-amphetamine after 53 h of sleep loss produced a sharp drop in error for both static and dynamic tracking. Although performance at both types of tasks remained poorer for sleep-deprived subjects, their static tracking scores did not differ significantly from control subjects 2 h after drug ingestion. Thus, while the drug benefited performance, the benefits were only partial ones. Attentional lapses and inefficiency in perceptual-motor and information-processing mechanisms seem to account for the deleterious effects of sleep deprivation on performance. Thus, the study indicates clear declines in performance scores for an aviation-related task after a night without sleep. These negative effects become generally greater with increasing amounts of sleep loss and are more pervasive in motion environments.

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SOME EFFECTS OF SLEEP DEPRIVATION ON TRACKING PERFORMANCE IN STATIC AND DYNAMIC ENVIRONMENTS

I. Introduction.

Several studies[1,7,10] of the effects of sleep deprivation have indicated that attentional lapses are related to performance decrements and that these lapses increase in frequency and duration with increases in sleep loss. Johnson and Naitoh[5] suggest that such lapses could account for performance decrements on tasks that require vigilance or motor performance; for other types of tasks, a change in information-processing capability or deficiencies in the formation of memory traces may be more adequate explanations of sleep loss effects. Moreover, many of these performance measures are influenced by diurnal rhythms[10] such that effects of sleep loss are likely to be more evident in early morning hours.

Assessments of the influence on performance of altered psychological and physiological states including those produced by sleep loss usually are made in stationary environments. However, in aviation, important aspects of modified mental and physical conditions are the effects of these conditions on performance during motion. Recent work has shown that impeditive effects of alcohol[2,4] and other drugs[8,9] on laboratory tracking performance were more pronounced when the trackers were undergoing whole-body angular stimulation than when they were stationary. While motion might influence performance simply as an additional general stressor, the drug-induced increase in tracking error was correlated with a loss of ability to maintain visual fixation and thereby inhibit the ocular nystagmus provoked by angular stimulation. It is possible that the consequences of sleep loss may produce similar effects; some perceived difficulty in maintaining visual fixation following even mild degrees of sleep deprivation is a relatively frequent anecdotal report.

The present study comprised two experiments. In the first, the effects of approximately 34 h of sleep loss were assessed by using performance and motion conditions identical to our previous work with alcohol and other depressant drugs.[2,7,8] The second experiment involved three modifications: (i) The magnitude of the angular stimulus was halved, (ii) the time of sleep loss was extended to about 55 h, and (iii) the influence of an alerting drug was assessed.

II. Method.

A. *Subjects.* Forty male college students, paid volunteers ranging in age from 21 to 30 yr, served as subjects. None had previous laboratory experience involving vestibular stimulation. Half the men performed in Experiment I and the other half in Experiment II. Within each experiment, the 20 subjects were assigned at random to one of two equal-size groups, either a control group or a sleep-deprived group. Subjects were asked to abstain from alcoholic drinks for 48 h prior to the study and to arrange to have 8 or more h of sleep on the night prior to the first experimental day. Subjects were not allowed to consume caffeine drinks or to smoke throughout the study.

B. *Apparatus.* The subjects were required to perform on a one-degree-of-freedom compensatory tracking task (i) during angular acceleration and (ii) under stationary conditions. The tracking task system, described in detail elsewhere,[3] consisted of an aircraft localizer glide slope indicator and a joystick. The vertical needle of the indicator was in constant left-right motion, driven at changing rates of speed by a sinusoidal forcing function with a 14–s period. The subject was instructed to keep the needle in the center or null position by making compensatory movements with the joystick.

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Angular movement of an enclosed cockpit (a modified Stille-Werner rotation device) was accomplished by a Wavetek signal generator that programed a triangular waveform stimulus with a period of 48 s. A peak angular velocity of 120°/s (Experiment I) or 60°/s (Experiment II) was attained in both the clockwise and counterclockwise directions. Thus, for Experiment I, the rate of angular stimulation was 10°/s² and for Experiment II the rate was 5°/s². The subject was accelerated at the prescribed rate until he reached a velocity of 120°/s in one direction; he was then decelerated through "0" to a velocity of 120°/s in the opposite direction, then accelerated again through "0" to 120°/s in the original direction, etc. The room was in total darkness throughout the testing session with the exception of a light source that was focused on the tracking instrument and provided approximately 1.0 fL of illumination.

C. *Scoring.* Deviations of the localizer needle from the null position were considered errors; a voltage proportional to these deviations was electronically integrated over 1–s intervals during the test period and was recorded on a Beckman Type T electroencephalograph. The same device was used to record the eye movements of the subjects. Horizontal ocular deviations were obtained by means of electrodes taped near the outer canthi of the subject's eyes; a reference electrode was secured on the forehead. Calibrations of eye movements were accomplished with two small, alternately flashing lights, horizontally separated to subtend a visual angle of 15°. The quality and quantity of nystagmus evidenced in the tracings was rated on a 0–5 scale by an experienced rater who had no knowledge of the subject, group, or session being rated.

D. *Procedure.* A day or two before the start of the experiment, all subjects received instructions and then participated in a set of familiarization trials that involved 2½ min of static tracking and 2½ min of dynamic tracking. This was followed by a formal practice session comprising five cycles of static tracking and five cycles of dynamic tracking (i.e., tracking during five 48–s periods of angular acceleration) separated by 3 min of rest. The performance requirements of experimental sessions conducted on subsequent days were identical to those of the formal practice session.

In the first experiment, the 2 experimental days comprised tests given at about 0900, 1300, 1700, and 2100 on Day 1 and 0900, 1300, and 1700 on Day 2. Subjects were exposed to the experimental protocol in groups of five. Half the control and sleep-deprived subjects always performed static tracking prior to dynamic tracking; the order was reversed for the remaining subjects.

In the second experiment, 3 experimental days comprised tests given at about 0900, 1300, and 1700 on Day 1; 0900, 1300, and 1700 on Day 2; and 0900, 1300, and 1400 on Day 3. Subjects were exposed to the experimental protocol in groups of two or three. Each subject was administered a 10–mg capsule of d-amphetamine sulphate at 1200 on Day 3. The only information subjects had about the drug was that it was one sometimes used to prevent motion sickness.

In both experiments, nystagmic eye movements and performance were recorded throughout the experiment; one of the groups of 10 men was kept awake throughout the experiment while the other group slept at the laboratory (from 2300 to 0700). The group kept awake was provided with a variety of challenging games and activities to prevent soporific states. A monitor was constantly with the subjects. Subjects were always encouraged to do their best immediately before each static and dynamic performance test. Both groups expected the experiment to continue for 3–4 h longer than the actual schedule (to reduce possible effects of knowing which was the last session).

III. Results.

Means and standard deviations for tracking error scores and nystagmus ratings appear in Tables 1 and 2 (Experiments I and II respectively). In both experiments, analyses of variance (repeated measures design)[6] were conducted with difference scores for each measure by using scores during the 0900 session on Day 1 as the base from which differences were calculated. Sessional differences between groups were assessed with simple effects tests.[6] In all cases, the .05 level of probability was used as the criterion for significance. Static tracking error scores for the practice session and for the first session on Day 1 were about 63 percent of the dynamic tracking error scores in Experiment I (10°/s²

angular stimulus) and about 90 percent of the dynamic tracking error score in Experiment II ($5°/s^2$ angular stimulus). That is, performance was better (less error) in the static situation than in the more demanding condition of angular motion.

TABLE 1. Means and Standard Deviations for Tracking Error and Nystagmus Ratings Obtained in Experiment I

		Control Group						Sleep-Deprived Group					
		Static Tracking		Dynamic Tracking		Nystagmus Rating		Static Tracking		Dynamic Tracking		Nystagmus Rating	
Session		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Day 1	0900	809	168	1421	565	1.40	0.88	1226	482	1667	567	1.60	0.61
	1300	964	436	1617	795	1.31	0.90	1285	578	1756	633	1.45	0.64
	1700	949	515	1497	772	1.18	0.74	1257	615	1612	750	0.95	0.50
	2100	1055	608	1294	681	1.08	0.68	1210	513	1584	684	1.13	0.69
Day 2	0900	936	531	1372	704	0.98	0.93	2021	1273	2664	1592	2.00	1.08
	1300	938	472	1169	639	0.98	1.04	1470	766	2180	1066	1.23	0.74
	1700	823	408	1111	595	0.80	0.67	1467	763	2020	1314	1.48	1.15

TABLE 2. Means and Standard Deviations for Tracking Error and Nystagmus Ratings Obtained in Experiment II

		Control Group						Sleep-Deprived Group					
		Static Tracking		Dynamic Tracking		Nystagmus Rating		Static Tracking		Dynamic Tracking		Nystagmus Rating	
Session		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Day 1	0900	1216	462	1317	426	0.61	0.37	1278	403	1413	456	0.95	0.44
	1300	1029	388	1129	439	0.53	0.29	1113	374	1384	448	0.75	0.26
	1700	975	366	1044	436	0.32	0.19	1282	376	1399	367	0.55	0.44
Day 2	0900	926	344	1131	482	0.51	0.30	1621	385	2051	461	1.15	0.71
	1300	867	378	1015	453	0.44	0.35	1772	599	2346	809	1.00	0.75
	1700	1119	590	1279	859	0.30	0.35	1609	589	2236	855	0.85	0.67
Day 3	0900	687	327	827	436	0.53	0.29	2688	1070	3096	1020	1.67	0.53
	1200	DRUG											
	1300	644	284	742	326	0.44	0.10	1487	1014	1687	1259	1.00	0.67
	1400	588	254	652	279	0.66	1.04	1027	408	1429	521	0.56	0.28

A. *Experiment I.* Significant differences were obtained during experimental sessions by analyses of variance for both static and dynamic scores. For the latter, there were significant F-ratios for groups ($p<.05$), for sessions ($p<.05$), and for the sessions × groups interaction ($p<.01$). For static tracking, only the interaction term was significant ($p<.05$).

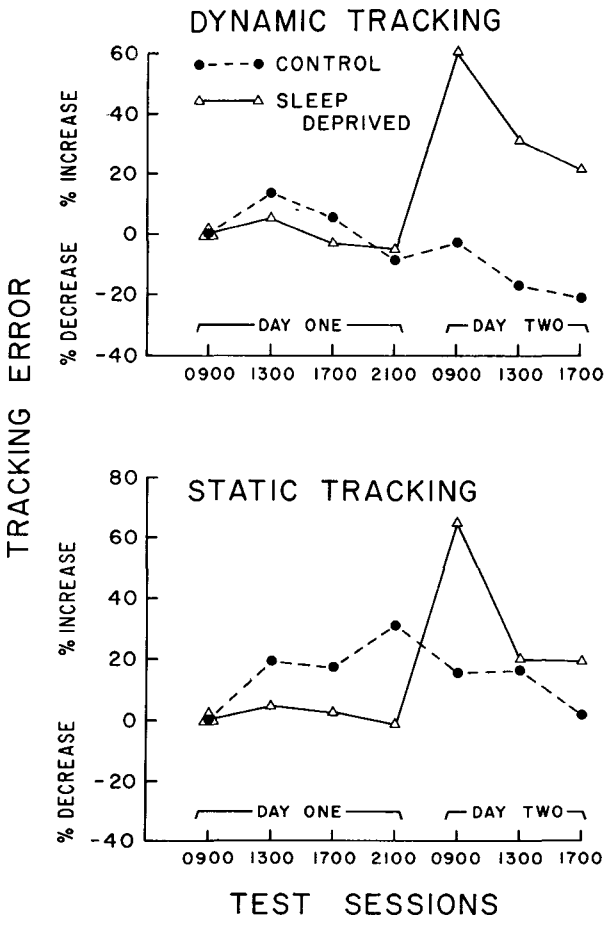

FIGURE 1.—Changes in tracking error under static (stationary) and dynamic (10°/s² angular accelerations) conditions. Tracking error during the 0900 session on Day 1 was set at "0"; error scores for subsequent sessions were converted to percentages of increase or decrease from the "0" level.

There were no significant differences between the control and sleep-deprived groups for either static or dynamic tracking on Day 1. However, as shown in Figure 1, clear differences between the groups became apparent on the second day. Control subjects, in general, showed continued performance improvement from the previous day, whereas the error scores for sleep-deprived subjects increased sharply during the morning session for both static ($p<.01$) and dynamic tracking ($p<.001$). These increases were moderated during the two afternoon sessions such that the differences between the groups in static tracking were not significant, while differences between groups in dynamic tracking, although reduced, were still significant for both afternoon sessions ($p<.01$ in both cases).

Plots of nystagmus scores during dynamic tracking are presented in Figure 2. Analysis of variance yielded no significant difference among the difference scores between the two groups, but simple effects tests showed that sleep-deprived subjects had significantly more nystagmus ($p<.01$) on Day 2 during the 0900 session.

B. *Experiment II.* Analyses of variance yielded significant differences on experimental days for both static and dynamic tracking scores across sessions ($p<.01$), between groups ($p<.001$), and for the sessions × groups interaction ($p<.01$).

There were no significant sessional differences in comparing the difference scores of the two groups on Day 1 for either static or dynamic tracking. Clear differences between the groups became apparent on the second day (Figure 3). Control subjects, in general, showed continued performance improvement, whereas the error scores for sleep-deprived subjects increased markedly. These increases in error yielded significant differences between groups for the dynamic tracking condition for all sessions on Days 2 and 3 ($p<.05$–$p<.001$). Static tracking scores differed significantly ($p<.01$–$p<.001$) between the groups for all sessions except those at 1700 on Day 2 and 1400 on Day 3. The ingestion of d-amphetamine on Day 3 had no apparent effect on scores for the control group (which continued to show some improved performance) but did serve to reduce errors for the sleep-deprived group during the sessions held 1 and 2 h after drug ingestion. Although error scores remained significantly higher for sleep-deprived subjects during dynamic tracking ($p<.01$ and $p<.05$ respectively for sessions 1 and 2 h after drug ingestion), the drug was effective in reducing the static tracking error of sleep-deprived sub-

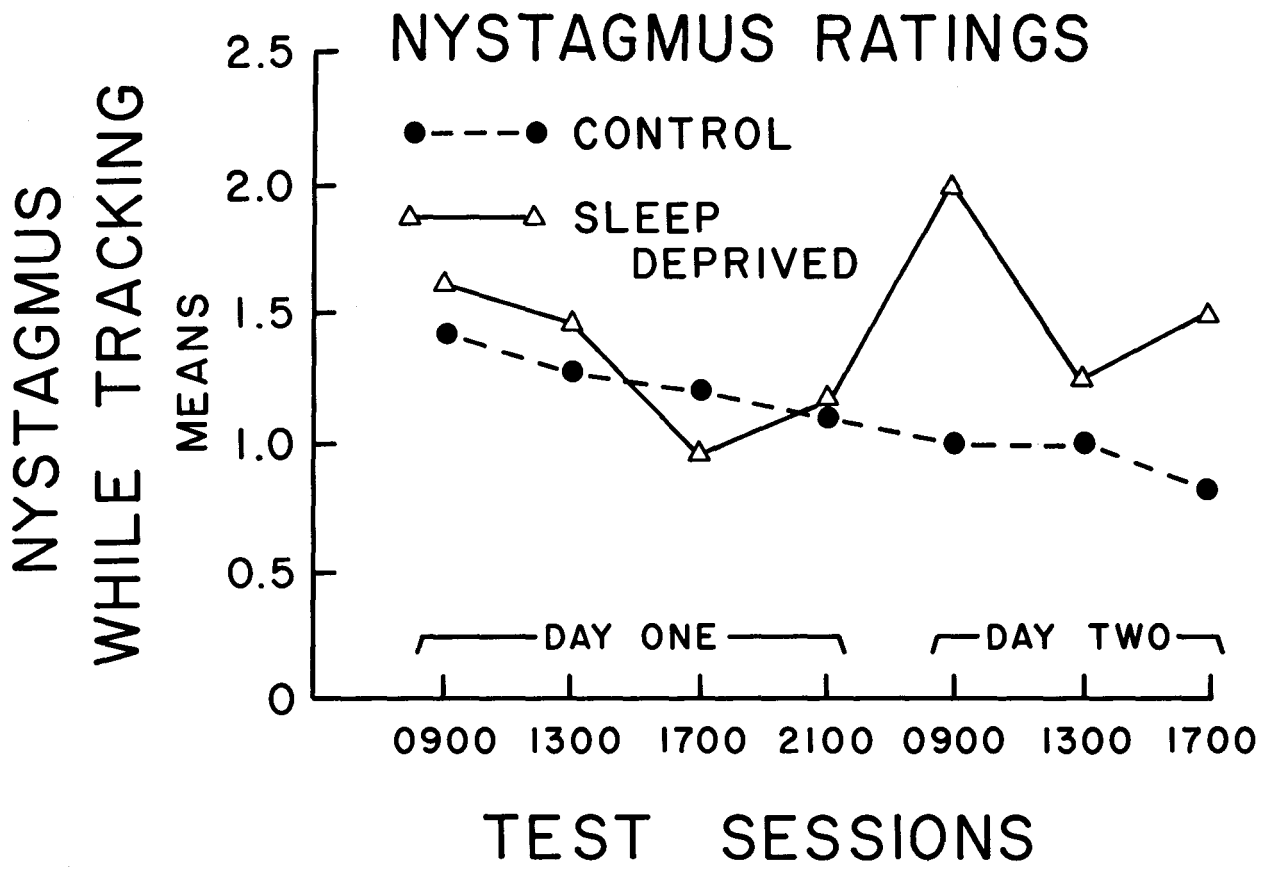

FIGURE 2.—Ratings of nystagmus obtained during dynamic (10°/s² angular accelerations) tracking.

jects to an insignificant difference from that of control subjects during the 1400 session (differences were significant at the .01 level during the 1300 session).

Plots of nystagmus ratings across sessions appear in Figure 4. No statistically significant differences were obtained for the difference scores by analyses of variance. However, simple effects tests indicated that sleep-deprived subjects had significantly more nystagmus output than did controls during the 0900 session of Day 3 ($p<.001$).

IV. Discussion.

In both experiments, significant decrements in dynamic tracking performance were uniformly obtained after 24 h and more of sleep loss. Static tracking scores were less consistently affected; viz, sleep-deprived subjects showed a marked increase in tracking error during the morning session after a night without sleep—probably influenced by a circadian effect—but they recovered sufficiently to be not significantly different from control subjects during the late afternoon sessions in both experiments.

Following 48 h of sleep loss (Experiment II), another marked increase in error scores was apparent for both static and dynamic tracking. While a circadian component probably was a contributing factor, the magnitude of the error increase argues against the likelihood that enough recovery would have occurred to cancel the significant differences between sleep-deprived and control subjects for either dynamic or static tracking in later sessions had an analeptic drug not been administered. It is also unlikely that an improvement (reduction in error) would have occurred among sleep-deprived subjects for both static and dynamic tracking at 1300 on Day 3 as compared with 1300 on Day 2 if the drug had not been administered (the improvement was significant at $p<.01$ for dynamic tracking error by a least significant difference test[6]).

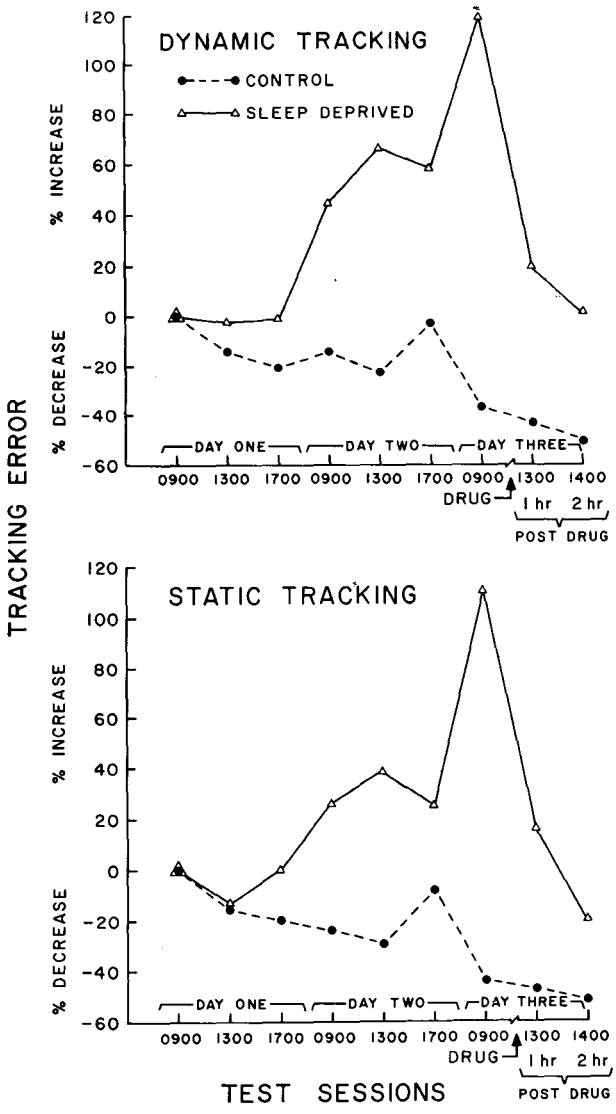

FIGURE 3.—Changes in tracking error under static (stationary) and dynamic (5°/s² angular accelerations) conditions. Tracking error during the 0900 session on Day 1 was set at "0"; error scores for subsequent sessions were converted to percentages of increase or decrease from the "0" level. Ten mg of d-amphetamine were administered to all subjects at 1200 on Day 3.

The ingestion of 10 mg of d-amphetamine after approximately 53 h of sleep loss produced a sharp drop in errors for both static and dynamic tracking. Although some of the performance improvement from the morning session may be attributable to motivational and circadian factors as well as to the drug, the static tracking performance of sleep-deprived subjects recovered sufficiently (although it was still inferior) to be not significantly different from that of control subjects 2 h after drug ingestion. Dynamic tracking scores also improved for sleep-deprived subjects but remained significantly poorer than the scores of control subjects. Thus, the effect of the alerting drug was limited; that is, performance of the sleep-deprived subjects improved in both static and dynamic situations but not to the levels of the control group, and less effect was obtained for dynamic as compared with static tracking. While an alerting drug may have some beneficial performance consequences when used to oppose effects of 53 h or more of sleep loss, present data indicate that the benefits are only partial ones.

While it would be inappropriate to equate the sleep loss of the present experiments to small doses of depressant drugs, comparisons of these performance results with results obtained following the ingestion of alcohol[2,4] and other depressants[8,9] suggest points of difference in the way that performance decrements are mediated. Subjects who had ingested alcohol, secobarbital, dramamine, or phenergan in previous studies showed significant decrement in performance during motion but little or no decrement in performance during static tests (it is, of course, likely that higher doses of these drugs would have significantly reduced static scores). Eye-movement recordings revealed that these depressants interfered with the ability of the subjects to use visual-fixation mechanisms to inhibit the nystagmus occasioned by angular accelerations; thus, nystagmus-induced blurring of the visual field could account for the increases in dynamic performance errors and the absence of deleterious performance changes in the static situation. However, sleep loss produced a different effect in that (i) both static and dynamic tracking performance declined significantly (although dynamic tracking scores were more consistently affected) and (ii) increased nystagmus activity was not reliably associated with significant performance decrements during motion. In the present study, it would appear that both information-processing and attentional mechanisms may have been more prominently involved. Clearly, the sleep-deprived group occasionally experienced the lapses noted in other research.[1,5,7,10] Several of the sleep-deprived subjects reported as early as 0900 on Day 2 that the tracking instrument would occasionally

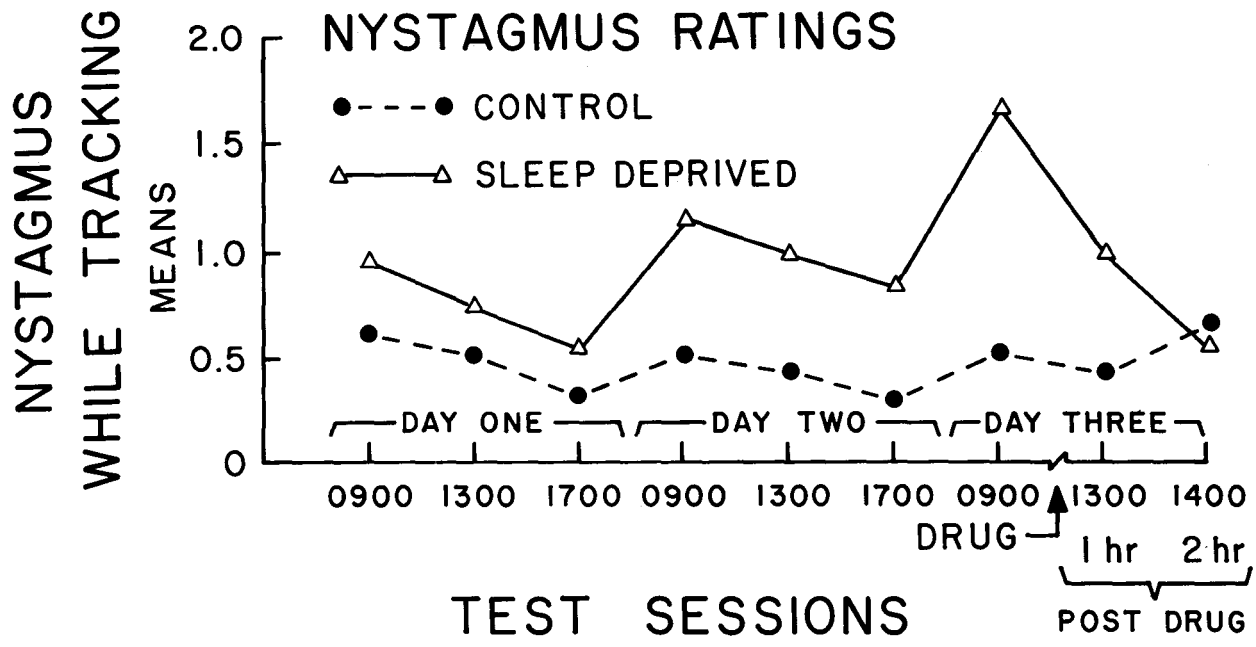

FIGURE 4.—Ratings of nystagmus obtained during dynamic (5°/s² angular accelerations) tracking.

"black out" or the localizer needle would disappear for brief periods, or that the fixed glide slope indicator on the instrument would be mistaken for the localizer needle. By Day 3, some visual hallucinations were reported; e.g., the localizer needle appeared to be "dripping," the needle took on the appearance of a man, and visual scenes appeared to be superimposed on the tracking instrument. On some occasions, these lapses might have caused a loss of visual fixation and thereby increased nystagmic output during dynamic tests. But the fact that increased nystagmus of the sleep-deprived subjects was not a reliable correlate of increased tracking error in the dynamic tests (as well as the static tests) suggests some additional interference in performance by mechanisms associated with information processing or with perceptual-motor systems.

Thus, this study indicates clear declines in performance scores for an aviation-related task after a night without sleep. These negative effects become generally greater with increasing amounts of sleep loss and are more pervasive in motion environments.

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