USAARL Report No. 2001-02

The Sensitivity of Real-Time, Telemetered Electroencephalographic Data and Actual In-Flight Performance Measurement to Fatigue in a Sleep-Deprivation Paradigm

by
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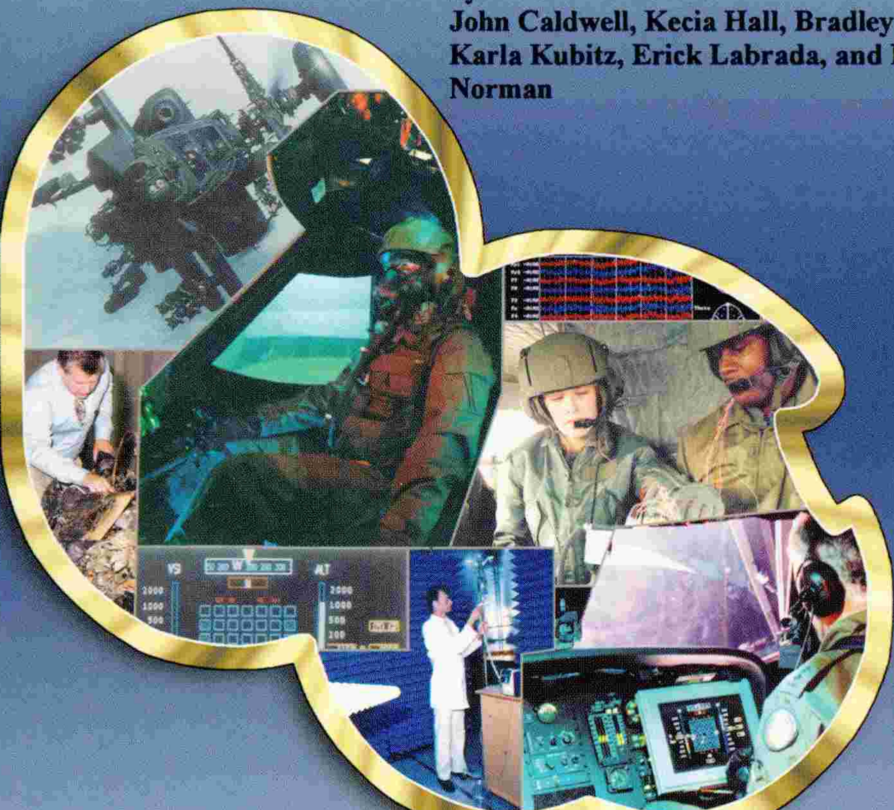

Aircrew Health and Performance Division

December 2000

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release, distribution unlimited
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) USAARL Report No.2001-02	5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION U.S. Army Aeromedical Research Laboratory	6b. OFFICE SYMBOL *(If applicable)* MCMR-UAD	7a. NAME OF MONITORING ORGANIZATION U.S. Army Medical Research and Materiel Command
6c. ADDRESS *(City, State, and ZIP Code)* P.O. Box 620577 Fort Rucker, AL 36362-0577		7b. ADDRESS *(City, State, and ZIP Code)* 504 Scott Street Frederick, MD 21702-5012
8a. NAME OF FUNDING / SPONSORING ORGANIZATION	8b. OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS *(City, State, and ZIP Code)*		10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
622787	869	H	DA361534

11. TITLE *(Include Security Classification)*
(U) The sensitivity of real-time, telemetered electroencephalographic data and actual in-flight performance measurement to fatigue in a sleep-deprivation paradigm

12. PERSONAL AUTHOR(S)
J. Caldwell, K. Hall, B. Erickson, K. Kubitz, E. Labrada, D. Norman

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(Year, Month, Day)*	15. PAGE COUNT
Final	FROM TO		

16. SUPPLEMENTAL NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
05	09	
06	10	

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
telemetry, flight, EEG, mood, performance, fatigue, sleep deprivation

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The present investigation was conducted to determine whether the typical EEG changes recorded from subjects in earlier laboratory sleep-deprivation studies would occur under actual in-flight conditions while aviators are piloting an aircraft. In addition, this study was conducted to examine the extent to which fatigue-related deteriorations in flight performance were associated with increased slow-wave EEG activity.

Ten UH-60 pilots were kept awake for approximately 26 hours so that data could be collected during both non-sleep-deprived and sleep-deprived conditions. EEG data and performance data were collected in the laboratory and while piloting a specially instrumented UH-60 aircraft. Data collected in the laboratory were based on a computerized cognitive task (the Multi-attribute Task Battery or MATB) and the data collected in the aircraft were from computerized monitoring of flight skills during the performance of a standardized flight profile. Self-ratings of mood and alertness were collected only in the laboratory setting via the Profile of Mood States (POMS) and the Visual Analog Scales (VAS).

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE *(Include Area Code)*	22c. OFFICE SYMBOL
Chief, Science Support Center	(334) 255-6907	MCMR-UAX-SS

DD Form 1473, JUN 86 ***Previous editions are obsolete.***

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

Continuation Page
Block 19

EEG theta activity, and to some extent EEG delta activity, increased as a function of sleep deprivation in both settings. EEG alpha activity also was affected in both settings, but the results were dissimilar, possibly due to the fact that testing conditions were more soporific in the laboratory versus the aircraft. MATB indicators of cognitive skill revealed performance decrements that also were associated with sleep loss; consistent with self-reported deteriorations in both mood and alertness as assessed by the POMS and VAS. These findings suggested a variety of fatigue-induced degradations in the functional status of the aviators tested in this study. However, there was only one flight maneuver (out of the eight that were flown) that indicated a problem with actual flight performance capabilities; the left standard-rate turn which was found to be adversely affected at the 0400 flight (during the circadian trough). The flight data collected in the present investigation were not as sensitive to fatigue effects as were the other measures. Future studies will pursue the statistical relationships between flight performance and EEG by testing more participants across a greater number of sleep-deprivation sessions.

It was concluded that it is feasible to monitor aviator status without interfering with the completion of the primary task of flying the aircraft. In addition, it is evident that physiological indices are sensitive to the effects of stressors that may potentially degrade aviator performance. The elevations in EEG theta and delta activity were accompanied by clear fatigue-related performance and mood decrements in the laboratory setting despite the absence of similarly robust findings in the aircraft. It is probable that this less-than-optimal correspondence between laboratory and in-flight data will be overcome in the future by increasing the power of the research design.

Acknowledgments

The authors are sincerely grateful to all of the USAARL aviators who served as safety pilots for this investigation; the members of the USAARL research support staff who maintained, installed, and operated an array of specialized equipment; and those who made the collection and analysis of the flight data possible. In addition, we would like to thank all of our USAARL coworkers who offered their time and support. Lastly, we deeply appreciate the professionalism of each of the aviators who selflessly volunteered to serve as research subjects.

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Background

Military relevance

Sleep deprivation and fatigue degrade aviator performance to the extent that serious problems with regard to safety and effectiveness are likely to result. The ability to predict oncoming performance decrements would enable commanders to implement appropriate countermeasures before the mission is compromised. Unfortunately, in the past, the only viable methods for making such predictions involved the administration of performance-based tests that distracted the pilot from his/her primary job of flying the aircraft. The implementation of physiologically-based monitoring would avoid this difficulty because of the nonintrusive nature of this approach; however, the feasibility of such a strategy has yet to be clearly determined. The U.S. Army Aeromedical Research Laboratory (USAARL) recently completed two investigations which proved that it is in fact possible to obtain valid electroencephalographic (EEG) data from normal, alert pilots under in-flight conditions. Furthermore, it was found that these data could be reliably obtained both while the pilots were tested under resting conditions and while they were actually flying standardized maneuvers. If further work indicates that this EEG-monitoring strategy is sensitive to changes in pilot status (such as would be produced by workload or fatigue), and that the EEG changes are related to the quality of performance, this would suggest that it is feasible to perform nonintrusive, real-time, objective, aviator-status monitoring. The refinement and implementation of such a strategy would ultimately permit aviators and/or their commanders to make accurate, unbiased estimates of flight-performance capabilities in real-world scenarios.

The measurement of aviator status

It is necessary to identify a method for assessing the operational status of individual aviators that overcomes the problems associated with standard performance testing algorithms. Specifically, there is need for an approach which 1) can be conducted during the accomplishment of the operational task (flight); 2) is feasible from an equipment and personnel perspective; and 3) is objective, reliable, and valid. One type of measure which appears to be a reasonable candidate which would satisfy all three of these basic concerns is one that directly measures aviator status via assessments of psychophysiological variables (Caldwell et al., 1994).

Of the psychophysiological variables that are available for measurement, the EEG is the most direct indication of central nervous system functioning. Studies have established the sensitivity of EEG activity to stressors such as sleep deprivation. Comperatore et al. (1993), Caldwell, Caldwell and Crowley. (1996), Lorenzo et al. (1995), Pigeau, Heselgrave and Angus (1987) and others, have, for instance, shown that slow-wave EEG delta and/or theta activity is elevated by even moderate sleep loss. Furthermore, there is a clear time course of EEG changes which occurs as a function of sleep deprivation. Delta and theta are reliably accentuated after 23-26 hours of continuous wakefulness, approximately the same time in which both mood and performance are affected (Caldwell et al., 2000).

However, the advantages of collecting EEGs to assess central nervous system (CNS) neural and presumably "cognitive" activation are somewhat offset by the disadvantages in terms of data collection and analysis difficulties, particularly in the flight environment. In the past, substantial instrumentation difficulties have discouraged investigators from attempting to collect EEG from a subject in flight. Recently, however, there has been a resurgence of interest in examining the electrical activity of the brain during various operational scenarios, and it appears that many of the instrumentation problems may have been overcome.

EEG/Evoked Potentials (EPs) collected in flight

There have been efforts to collect EEGs during both simulator and actual flights, and to directly relate EEG activity to performance accuracy on operational tasks. Sem-Jacobsen et al. (1959) were probably the first investigators to record EEGs during flight. Their initial feasibility study indicated it was possible to obtain usable 8-channel EEG recordings from both pilots and nonpilots in a T-33 jet during operational flight. Sem-Jacobsen (1961) was later able to report the ability to utilize a combination of in-flight EEG analysis and in-flight motion pictures to aid in the selection of pilots for high-performance aircraft. Other authors (LaFontaine and Medvedeff, 1966; Maulsby, 1966; and Howitt et al., 1978) have offered further evidence for the utility of using EEG as a measure during flights. In addition, Sterman et al. (1987) have suggested that EEG activity may be associated with pilot workload and performance. Caldwell et al. (1993) and Caldwell et al. (1997) have shown that, in addition to collecting a limited number of channels of EEG in the fixed wing environment, it is feasible to collect and telemeter spontaneous EEG from helicopter pilots in flight.

Unfortunately, studies examining relationships between in-flight EEGs and in-flight performance are virtually nonexistent. A couple of studies have shown that EEG activity is sensitive to in-flight changes in pilot workload, but the EEG-performance link remains illusive. In the first of these studies, Sterman et al. (1987) found there were elevations in EEG theta power and reductions in EEG alpha power as a function of increased flying demands. In addition, there were increased EEG asymmetries between left and right central regions as a function of increased workload. The authors suggested the existence of a link between the magnitude of EEG asymmetries and performance, but confirmation of this link either was never established or never published. In the second of these two studies, Wilson and Hankins (1994) supported the findings of Sterman et al. (1987) in that EEG theta activity was found to reliably increase during flight segments requiring the highest levels of attention and cognitive processing. Conversely, the segments relying more on psychomotor coordination but less on mental/decision-making capacity were found to be associated with the least amount of EEG theta activity. Unfortunately, flight performance was not measured in the Wilson and Hankins (1994) investigation, so it was not possible to determine whether the observed EEG differences were associated with improvements or decrements in piloting skills.

Thus, there is some evidence that in-flight EEG measures may be useful for assessing pilot status; however, it has not been determined whether the EEG changes that result from aviator stress, workload, fatigue, or any other factors ultimately can be used to predict actual aviator performance. From laboratory studies, it is known that both piloting skills and aviator brain activity are affected by sleep loss (for instance, Caldwell et al., 1996; Caldwell et al., 2000), but since these two dimensions have not been measured concurrently, it remains unclear if there is a clear relationship between the two. Although there are suggestions that this would be the case (based on EEGs collected in the laboratory between flights), a definitive resolution of this issue awaits further investigation. Since USAARL possesses the capability to concurrently monitor both the flight performance and the physiological activity of pilots in flight, it should be possible to determine whether differences in the EEG correspond to differences in flight performance to the extent that these measures can be used to make objective, physiologically-based predictions of oncoming performance losses due to fatigue or high workload conditions in pilots.

Objectives

The present investigation assessed whether the typical increases in theta and reductions in alpha EEG recorded in the laboratory from sleep-deprived aviators occur in the in-flight environment while pilots are at the controls of the aircraft. In addition, this investigation made a first step toward determining the extent to which EEG changes recorded in the aircraft are associated with changes in concurrently-monitored flight performance.

Methods

Subjects

Ten UH-60 current and qualified aviators served as subjects after signing an informed consent agreement and passing an abbreviated medical prescreening. The average age of the participants was 31.2 years (with a range of 26 to 46). The average amount of flight experience was 1153 hours (with a range of 300 to 5000). There were 9 males and 1 female in this study (approximately 2 percent of all Army aviators are female).

Apparatus

Resting (eyes-open/eyes-closed) EEG evaluations were completed both in the laboratory and in the aircraft (while the safety pilot was “on the controls”). Working EEG evaluations (those which were done while the pilot was flying) were completed only in flight, as real-world soldier status monitoring, during completion of realistic duties, is the main thrust of this research. In addition to the EEG evaluations, performance evaluations were conducted both in the laboratory and aircraft. In the laboratory, these evaluations were made with the Multi-Attribute Task Battery (MATB), whereas in flight, these evaluations were made by measuring how well participants performed actual standardized flight maneuvers in a specially-instrumented helicopter.

EEGs

In-flight EEG evaluations were conducted using a Cadwell Laboratory Airborne Spectrum 32.* This device was mounted in the rear of the UH-60 helicopter and connected to the 28-volt power supply available on the aircraft. The Airborne Spectrum is equipped with a 32-channel preamplifier and a control head which can be used to mark special events on the EEG record. In addition, a locally-manufactured event marker which produced a 5 Hz square waveform was used in conjunction with the EEG preamplifier in order to record a pronounced event mark in the actual recorded EEG record (a short pulse marked the beginning of each flight maneuver and a long pulse marked the end). The Airborne Spectrum communicates, via radio transmission, with a standard ground-based Cadwell Spectrum 32 which has been equipped with specialized communications hardware. Laboratory EEG evaluations were made with a standard Cadwell Spectrum 32. The low filters were set at 0.53 Hz, the high filters were set at 100 Hz, and the 60 Hz notch filters were used. Standard Grass E5SH silver cup electrodes, placed on subjects' scalps with collodion, were used to detect EEG. Both the in-flight and the laboratory data were stored on optical disk for later analysis.

Flight performance

In-flight pilot performance evaluations, based on the measures in Table 1, were made via a computerized system consisting of a Sikorsky wiring harness for flight-data collection, an Elexor Associates analog-to-digital converter, and a Paravant hand-held computer for recording the performance results. These components were mounted in the Laboratory's Sikorsky UH-60 helicopter. This system monitored pilot performance during each flight and permitted the transfer of these data to the Laboratory's Digital Equipment Corporation (DEC) VAX 11/785 computer for later analysis. This measurement system is the fourth-generation of a system developed and refined at USAARL (Huffman, Hofmann, and Sleeter, 1972; Jones, Lewis, and Higdon, 1983; Mitchell et al., 1988).

* See manufacturer’s list, Appendix A

Table 1.
Measured flight parameters.

Parameter	Range
1. Barometric altitude	0-10,000 feet
2. Indicated airspeed	30-180 KIAS
3. Vertical speed	0 +/- 3,000 fpm
4. Magnetic heading	0-360 degrees
5. Pitch angle	0 +/- 30 degrees
6. Roll angle	0 +/- 90 degrees
7. Slip	0 +/- 2 balls
8. Localizer deviation	0 +/- 2 dots
9. Glide slope deviation	0 +/- 2 dots

POMS and VAS

In the laboratory, subjective evaluations of mood were made using the Profile of Mood States (POMS) (McNair, Lorr, and Droppleman, 1981). The POMS is a 65-item test which measures affect or mood on 6 scales: 1) tension-anxiety, 2) depression-dejection, 3) anger-hostility, 4) vigor-activity, 5) fatigue-inertia, and 6) confusion-bewilderment. The answers were scored via the same computer on which the test was administered. Subjective sleepiness/alertness was measured via the Visual Analog Scale (VAS). This computerized questionnaire consisted of several 100- millimeter lines, each of which began with the phrase "not at all" and ended with the word "extremely." These lines were centered above adjectives such as “sleepy,” “alert,” “energetic,” etc. The subject was required to mark the line at a point which corresponded to how he/she felt along the continuum. The answer was scored by measuring, in millimeters, where the responses fell on each of the lines (this was accomplished via computer).

MATB

In the laboratory, basic cognitive abilities were examined with the MATB. This test required that subjects perform a tracking task concurrent with monitoring simulated indicators of fuel levels and pump status, as well as a variety of lights and dials designed to simulate aircraft instrumentation. Also, subjects were periodically required to change radio frequencies in accordance with computer-generated audio instructions. The MATB was administered and scored by computer. Outcome measures included reaction times, time outs, correct responses, tracking deviations, etc.

Procedure

Each subject completed three training sessions on the first day of his participation. In addition, he completed three testing sessions which began on the second day of his participation and ended on the morning of the third day, prior to his release. On the training day, subjects arrived at the Laboratory at approximately 1000, and were released by approximately 2200. On the following (testing) day, subjects reported to the laboratory at 1700, and remained in the Laboratory (except for the flights) until approximately 1200 the next day. Thus, subjects spent only 1 night in USAARL, but were not permitted to sleep at any point during this time. Meals and/or snacks were furnished to each subject while they remained in the Laboratory. A medical records review was conducted by a USAARL flight surgeon prior to participation to ensure that each aviator possessed a current up-slip (DA form number 4186) and that he was free from medical conditions or medications that would have impacted his fitness for the study.

On the training day, (following their 1000 arrival at the Laboratory), participants signed the informed consent agreement and received their briefing on the flight profile. Subjects then completed training flights in a the Laboratory's specially-instrumented UH-60 helicopter under the supervision of a USAARL safety pilot. Training flights were scheduled for 1400, 1700, and 2000; however, these times remained flexible to allow for weather or aircraft problems that sometimes created delays. The precise timing of these flights was not considered crucial since the primary reason for their inclusion in the protocol was to ensure that the subjects were trained to asymptotic levels on the maneuvers listed in Table 2 prior to the actual test flights. Every effort was made to ensure that each volunteer experienced at least two day flights and one night flight during the training phase. Although EEG data were not recorded during these flights, objective flight-performance data were collected so that the aviator volunteer could become comfortable with the exact procedures that would be used during the test flights. In between each of the training flights, subjects completed one iteration of the MATB, one VAS, and one POMS for familiarization purposes (these tests were conducted once the volunteer returned to the Laboratory).

On the testing day, subjects were asked to wake up between 0600 and 0700 and to avoid napping prior to arriving at the Laboratory at 1700 for electrode application. In addition, the volunteers were admonished to avoid any types of caffeinated beverages or food products. Once a subject arrived at the Laboratory for testing, 25 scalp placements were marked according to the 10-20 system for electrode placement. Each site was then cleaned with acetone. After thorough cleaning, electrodes were attached to the scalp with collodion, and each electrode was filled with electrolyte gel. Impedances were then reduced to less than 5000 ohms at each electrode prior to testing. Once all 25 electrodes were attached, the subject proceeded to his first EEG test in the Laboratory. The subject was seated in a relatively quiet area while connected to the ground-based Spectrum 32. After impedances were once again checked, the subject was instructed to sit quietly for 5 minutes with eyes open, followed by 5 minutes with eyes closed. Prior to initiating data storage for the initial EEG, a staff member provided copious amounts of feedback to the volunteer concerning how to relax and minimize movements that would have contaminated the saved EEG record. Once a “clean” recording was achieved, actual data collection was accomplished. Following EEG testing, the subject completed one VAS, one POMS, and performed the MATB for 30 minutes. Afterwards, he completed another resting EEG, VAS, and POMS.

Table 2.
Flight maneuvers.

Number	Maneuver Description	Duration
1	360 degree right standard rate turn at 1500 ft	2 minutes
2	Straight and level at 1500 ft	2 minutes
3	360 degree left standard rate turn at 1500 ft	2 minutes
4	1000 foot climb at 500 ft per minute to 2500 ft	2 minutes
5	Straight and level at 2500 ft	2 minutes
6	Right descending standard rate turn to 1500 ft	2 minutes
7	Straight and level at 1500 ft	2 minutes
8	540 deg left climbing standard rate turn to 3000 ft	3 minutes
9	Straight and level at 3000 ft	2 minutes
10	360 degree right standard rate turn at 3000 ft	2 minutes
11	Straight and level at 3000 ft	2 minutes
12	720 degree left standard rate turn at 3000 ft	4 minutes
13	1000 foot descent at 500 ft per minute to 2000 ft	2 minutes
14	Straight and level at 2000 ft	2 minutes
15	Instrument Landing System (ILS) approach	NA

Once laboratory testing for the session was complete, the subject was driven to Cairns Army Airfield (which is located approximately 15 minutes from the Laboratory) where the aircraft departed at 2300 for the first 1.5-hour flight (conducted under night-unaided, visual meteorological conditions (VMC). The aircraft had been preflighted by a USAARL safety pilot prior to the subject’s arrival. After reaching altitude, with the safety pilot at the controls, the subject completed an eyes-open/eyes-closed EEG (10 minutes total) while the safety pilot was in control of the aircraft. Afterwards, the safety pilot transferred control of the aircraft to the subject who completed the maneuvers listed in Table 2. Subjects flew from the right seat of the UH-60 (the pilot-in-command seat in rotary-wing aircraft). The safety pilot instructed the subject when to begin and end each maneuver, and a crew member seated in the rear of the aircraft recorded flight performance and EEG data. In addition, the crew member in the rear of the aircraft communicated constantly with the Laboratory where the EEG data were being recorded in order to ensure that the signal quality was acceptable. If subject-generated muscle or movement artifacts were present, the maneuver would be stopped and the volunteer would be counseled (or taken through relaxation exercises) until the quality of the signal was sufficiently "clean" to continue data collection.

At the conclusion of the flight, the subject was driven back to the Laboratory. The next laboratory test session (EEG, VAS, POMS, MATB, EEG, VAS, and POMS) began at 0200. Following this session, the subject once again departed for Cairns for the second flight (at approximately 0400). After this flight, there was one final laboratory test session at 0700 and one final flight at 0900. At the conclusion of the final flight, the electrodes were removed, the subject was debriefed, and he was released from the study.

In summary, there were three test familiarity sessions and three training flights on the training day and three laboratory sessions and three test flights on the testing day. The laboratory sessions (on the test day) were conducted at 5-hour intervals starting at 2100 (thus, laboratory sessions occurred at 2100, 0200, and 0700). The flights (on the test or deprivation day) also were conducted at 5-hour intervals following laboratory test sessions (thus, flights occurred at 2300, 0400, and 0900). This schedule yielded one predeprivation and two sleep-deprivation tests in both environments, with a 1-hour break in between.

Data analysis

EEG data were initially subjected to power spectral analysis by: 1) scanning the EEG record for each eyes-open, eyes-closed, and/or maneuver segment to develop an appreciation for the overall characteristics of the particular EEG segment; 2) selecting three representative 2.5-second epochs from each segment (a software-driven requirement); and 3) subjecting the epochs to fast Fourier/power spectral analyses utilizing resident software supplied with the Spectrum 32. This procedure yielded data for each EEG segment classified into the four standard activity bands of delta (1.5-3.0 Hz), theta (3.0-8.0 Hz), alpha (8.0-13.0 Hz), and beta (13.0-20 Hz). Once these data were transferred to the main computer system, each band was analyzed in a 2-way, repeated measures analysis of variance (ANOVA) in which the factors were as follows: 1) for the laboratory data-- time (2045, 2140, 0145, 0240, 0645, 0740) and eyes (eyes open, eyes closed); 2) for the in-flight data-- time (2300, 0400, and 0900) and segment (eyes open, maneuver 1, maneuver 2 . . . maneuver 15). Each EEG band was analyzed separately.

Flight performance data were transformed into one performance score per maneuver via locally-constructed software routines. Scores were based on how well the subjects maintained ideal targets for headings, airspeeds, altitudes, etc., with larger scores representing better performance than smaller scores. The exact components of flight performance which made up the composite scores for each maneuver are listed in Table 3. These data were analyzed in a series of either 1-way or 2-way ANOVAs depending on whether the maneuver was flown only once or more than once during each flight profile. The factor for the 1-way ANOVAs was simply time (2300, 0400, and 0900), whereas the factors for the 2-way ANOVAs were time (2300, 0400, and 0900) and maneuver iteration (straight-and-level 1, straight-and-level 2, etc.). Furthermore, following the separate, individual analyses of each maneuver, there was a 1-way ANOVA performed on a combined data set which included all of the maneuvers together.

Table 3.
Components of composite flight scores.

Maneuver	Parameters/components
Straight and levels	Heading, altitude, airspeed, and roll
Right standard-rate turns	Turn rate, altitude, airspeed, slip, and roll
Left standard-rate turns	Turn rate, altitude, airspeed, slip, and roll
Climb	Heading, airspeed, slip, roll, and vertical speed
Descent	Heading, airspeed, slip, roll, and vertical speed
Right descending turn	Turn rate, airspeed, slip, roll, and vertical speed
Left climbing turn	Turn rate, airspeed, slip, roll, and vertical speed
Instrument landing sys. approach	Localizer, glide slope

The scores from each of the 10 items on the VAS (i.e., sleepiness, alertness, energy, etc.) were generated by the computer on which the test was given and then analyzed with a 1-way ANOVA across times (2100, 2155, 0200, 0255, 0700, and 0755). The factor scores from each of the six factors on the POMS (i.e., depression, fatigue, etc.) were analyzed in a similar manner.

The MATB data were initially derived from a computerized algorithm which scored each of the 4 subtests and produced 31 outcome measures. These data were downloaded to a composite file on the main computer for subsequent analysis; however, only a small subset of the variables was ultimately examined because analysis of some of the outcomes would have been meaningless since they were not normalized across testing iterations (i.e., absolute number of correct responses versus the percentage of correct responses). The data set consisted of relevant variables from each subtest–specifically the reaction time, standard deviation of reaction times, and time-out errors for the communications task; the reaction times, standard deviation of reaction times, and time-out errors for the systems-monitoring (lights and dials) subtest; the average deviation of fuel levels from the target value of 2500 in the resource management subtest; and the tracking errors on the unstable tracking subtest. Each of these variables was analyzed with a separate 1-way ANOVA across testing times (2105, 0205, and 0705).

Results

As explained above, each subset of data (EEG, flight, POMS, VAS, and MATB) was analyzed separately to determine the impact of time of testing (or session) on the data of interest. Significant main effects were followed by pairwise contrasts or trend analyses in order to pinpoint the exact nature of the effect. Significant higher-order interactions were explored with analysis of simple effects. The figures depicting noteworthy main effects and interactions are located in Appendix B of this document.

EEG

In the standard laboratory setting, only resting eyes-open/eyes-closed EEGs were collected at each of the three testing periods (prior to the flights). There were two EEG assessments within each period which resulted in a total of six sessions of laboratory tests. However, in the aircraft, EEG data were collected under resting conditions (with a safety pilot on the controls) and during the various flight maneuvers (with the research participant on the controls). Regardless of the testing situation, separate ANOVAs were conducted on the delta, theta, alpha, and beta bands. Although a full montage of electrodes was recorded (a total of 21 active sites referenced to linked mastoids), only the results for Fz, Cz, and Pz will be detailed in the present report. A subsequent report may include findings from the other recording sites if the present analysis indicates that this would yield useful information.

Laboratory data

Delta activity.

The ANOVA on delta activity collected in the laboratory setting included two factors: session (2045, 2140, 0145, 0240, 0645, and 0740) and eyes (eyes open and eyes closed). The analysis indicated session main effects at Fz ($F(5,45)=4.41$, $p=.0023$), Cz ($F(5,45)=4.93$, $p=.0011$), and Pz ($F(5,45)=5.14$, $p=.0008$); and eyes main effects as well at Fz ($F(1,9)=8.31$, $p=.0181$), Cz ($F(1,9)=11.25$, $p=.0085$), and Pz ($F(1,9)=21.13$, $p=.0013$). In addition, there were session-by-eyes interactions at Cz ($F(5,45)=3.30$, $p=.0126$) and Pz ($F(5,45)=4.31$, $p=.0028$). Trend analyses on the session main effects revealed significant linear trends at each of the three electrodes which were due to increases in delta power from 2045 to 0740 ($p<.05$). Also, there was a quadratic trend at Pz which was attributable to a sharp increase in delta power at the final two testing times in comparison with the previous four testing times ($p<.05$). The differences across sessions are depicted in figure B-1 (top left). The eyes main effects were due to increased delta activity from eyes open to eyes closed (the eyes-open versus eyes-closed means across all three electrodes were 4.95 and 8.68, respectively). The session-by-eyes interaction at Cz was due to the fact that there was a small increase in delta from eyes-open to eyes-closed early in the deprivation period (at 2045), followed by a much larger increase later in the deprivation period (at 0645); however, there were no significant differences in the middle ($p<.05$). A similar pattern occurred at Pz, with the exception that the early difference was seen at 2140 and the later differences were observed at 0645 and 0740 ($p<.05$). These interactions are shown in figure B-1 (top right and bottom).

Theta activity.

The analysis of theta activity collected in the laboratory revealed significant main effects and interactions at all three electrodes. The session main effects at Fz ($F(5,45)=10.77$, $p<.0001$), Cz ($F(5,45)=8.06$, $p<.0001$), and Pz ($F(5,45)=6.19$, $p=.0002$) were all primarily due to linear increases in theta activity from the first to the last sessions of the deprivation cycle. However, there also was a single significant cubic trend at Pz and one quartic trend at Fz (see figure B-2, top left). The eyes main effects at Fz ($F(1,9)=29.83$, $p=.0004$), Cz ($F(1,9)=17.51$, $p=.0024$), and Pz ($F(1,9)=25.85$, $p=.0007$) were because the amount of theta at eyes-open was smaller than the amount at eyes-closed (the mean across all three electrodes was 13.23 and 21.84, respectively). The session-by-eyes interactions at Fz ($F(5,45)=3.68$, $p=.0071$), Cz ($F(5,45)=4.26$, $p=.0029$), and Pz ($F(5,45)=2.92$, $p=.0228$) were all because there was slightly more theta under eyes-closed than eyes-open at various points in the deprivation cycle (particularly at 2045, 0145, 0645 and 0740). These interactions are illustrated in figure B-2 (top right, bottom left, and bottom right, respectively).

Alpha activity.

The ANOVA on alpha activity collected under laboratory conditions revealed session main effects at Fz ($F(5,45)=2.93$, $p=.0226$), Cz ($F(5,45)=3.35$, $p=.0117$), and Pz ($F(5,45)=3.44$, $p=.0103$); eyes main effects at Fz $(1,9)=12.49$, $p=.0064$), Cz ($F(1,9)=9.36$, $p=.0136$), and Pz ($F(5,45)=10.34$, $p=.0106$); and session-by-eyes interactions at Fz ($F(5,45)=3.47$, $p=.0098$) and Cz ($F(5,45)=2.61$, $p=.0371$). The session main effects for alpha activity were more complex than those for delta and theta. Trend analysis showed there was a linear component to the effects at Cz and Pz (and marginally at Fz) which was attributable to a decrease in alpha activity from the first to the last part of the deprivation period. However, there also was a cubic component (significant only at Cz and Pz) which occurred because alpha increased from the first to the second testing time; decreased from the second to the third, fourth, and fifth times; and subsequently increased at the last test period (see figure B-3, top left). The eyes main effects were because overall alpha activity was higher under the eyes-closed than the eyes-open condition at all three electrodes. The session-by-eyes interactions at Fz and Cz were essentially the result of large differences between the eyes-open and eyes-closed conditions at 2045, 2140, 0145, and 0740, with smaller or more variable differences at 0240 and particularly at 0645 (there was no significant difference between the two conditions for Fz at 0240 or for Cz at 0645). These interactions are depicted in figure B-3 (top right and bottom).

Beta activity.

The analysis of beta activity from the laboratory testing session revealed fewer effects than were observed elsewhere. A session difference occurred only at Pz ($F(5,45)=2.44$, $p=.0488$), and this was found to be due to a significant cubic trend ($p<.05$) rather than the linear trends that were seen in the other three activity bands. Visual inspection of the means indicated that beta was relatively high during the first part of the deprivation period (from 2045 to 0145) in comparison to what was observed at

0645 (see figure B-4). However, following the drop at 0645, beta activity returned to its previous levels by the last testing time (at 0740). In addition to this session main effect, there were eyes main effects at Fz ($F(1,9)=6.90$, $p=.0275$), Cz ($F(1,9)=11.34$, $p=.0083$), and Pz ($F(1,9)=19.34$, $p=.0017$), all of which were due to greater amounts of beta under eyes-closed than eyes-open. There were no significant interactions.

<u>In-flight data</u>

Delta activity.

The analysis of delta activity for flight (2300, 0400, and 0900) and segment (resting, maneuver 1, maneuver 2, maneuver 3, . . . maneuver 15) indicated there was a flight-related difference only at Pz ($F(2,18)=3.96$, $p=.0376$). Post hoc trend analysis revealed this was due to the fact that delta power changed little from the first to the second flight, whereas it increased substantially by the time of the third flight ($p<.05$). The means for Fz, Cz, and Pz are shown in figure B-5 (top left). In addition to the flight main effect, there was a segment effect at Fz ($F(15,135)=2.35$, $p=.0050$) and Cz ($F(15,135)=2.51$, $p=.0026$). Pairwise post-hoc comparisons indicated this was principally because there were differences between the eyes-open resting EEG (when the participant was not "on the controls") and the EEGs that were collected while the participant was flying the aircraft. For instance, the Fz comparisons revealed differences between the resting condition and 9 of the maneuver segments, while the Cz comparisons revealed differences between the resting condition and all but one of the 15 maneuver segments (see figure B-5, top right and bottom). It is probable that those portions during which the volunteer was "on the controls" simply were not comparable to those during which the volunteer was not. There were no flight-by-segment interactions at any of the three electrode sites.

Theta activity.

The flight-by-segment analysis of EEG theta power revealed significant flight main effects at Fz ($(2,18)=4.56$, $p=.0251$), Cz ($(2,18)=15.92$, $p=.0001$), and Pz ($(2,18)=14.61$, $p=.0002$), all of which were due to significant linear trends. These occurred because theta increased from the first to the last flight ($p<.05$). At Pz, there also was a significant quadratic trend because there was very little difference in the amount of Pz theta in the first and second flights, whereas theta increased substantially by the time of the third flight ($p<.05$). The means for the three flights at each electrode site are depicted in figure B-6. There were no segment main effects or flight-by-segment interactions at Fz, Cz, or Pz.

Alpha activity.

The analysis of alpha activity indicated significant flight main effects at Cz ($F(2,18)=5.29$, $p=.0156$) and Pz ($F(2,18)=6.25$, $p=.0087$), but not at Fz. Post hoc trend analyses showed that these were due to significant linear trends ($p<.05$) that resulted from increased alpha power from the 2300 flight to the

0900 flight. The means for these effects are depicted in figure B-7. There were no segment main effects or flight-by-segment interactions at Fz, Cz, or Pz.

Beta activity.

The ANOVA on EEG beta activity revealed no flight main effects. However, there were segment main effects for Fz ($F(15,135)=2.46$, $p=.0032$), Cz ($F(15,135)=2.94$, $p=.0005$), and Pz ($F(15,135)=2.96$, $p=.0004$); and there was a flight-by-segment interaction at Fz ($F(30,270)=1.73$, $p=.0126$). Pairwise contrasts for the segment effects were performed, but the results were not straightforward and thus may have been the result of sheer chance in several cases (since 136 comparisons were required for each electrode). Thus, these effects should be viewed with caution. The segment main effect at Fz was primarily attributable to the fact that: 1) beta activity was greater during the first left standard-rate turn than during the second left standard-rate turn, the third and fifth straight-and-level, and the second right standard-rate turn; and 2) beta activity was greater during the sixth straight-and-level than during the second, fourth, or fifth straight-and-level, the second left standard-rate turn, and the left climbing turn. At Cz, the segment effect was primarily because the amount of beta recorded during the ILS and the sixth straight-and-level was greater than the beta recorded at several earlier maneuvers (thus, these effects may have resulted from the relative position of the maneuvers within the flight profile). The segment effect at Pz was largely attributable to the fact that the beta recorded during the resting condition was less than the amount recorded during the first right and left standard-rate turns, the first, second, and sixth straight-and-level, the climb and descent, the right descending turn, and the ILS approach. These three interactions are depicted in figure B-8 (top left, top right, and bottom left). The flight-by-segment interaction at Fz was because there was a difference among the three flights only at the right-descending turn, the left-climbing turn, and the second left-standard-rate turn ($p<.05$), but not at any of the other flight segments (see figure B-8, bottom right). Subsequent trend analyses for these effects revealed a linear increase in beta activity from the first to the third flights in the right-descending turn, but the opposite occurred in the left standard-rate turn. None of the follow-up trends was significant for the left-climbing turn. Given the number of comparisons that were involved in exploring this interaction and the fact that the results failed to follow a logical pattern, it is likely that the relatively small number of findings was spurious.

Flight performance

The flight scores for each type of maneuver (i.e., straight-and-levels, climbs, descents, level turns, etc.) were analyzed in two steps. First, each maneuver was analyzed separately in a series of univariate ANOVAs. Two-way ANOVAs (flight x iteration) were performed on the maneuvers which were flown more than once during each flight profile (there were six straight-and-levels, two right standard-rate turns, and two left standard-rate turns), and one-way ANOVAs were performed on the remaining five. Second, all of the maneuvers were assembled into a single data file and analyzed together. In order to accomplish this, the maneuvers that were flown more than once during each flight profile were reduced to a single set of scores (for flights 1, 2, and 3) by averaging the different iterations together (i.e., the results from the first and second left turn were averaged to produce a single set of left-turn scores). Then, a two-way ANOVA (flight x maneuver) was conducted on the composite performance data.

Individual maneuvers

The individual ANOVAs for the straight-and-levels (SLs), right standard-rate turns (RSRTs), left standard-rate turns (LSRTs), straight climb, straight descent, left climbing turn (LCT), right descending turn (RDT), and ILS approach revealed only a single significant effect. There was a deprivation-related difference across the three flights ($F(2,18)=4.38$, $p=.0282$) on the LSRT which was due to the fact that performance declined sharply at 0400, but returned to normal levels at 0900. The mean composite scores for the three flights were 55.7, 49.7, and 53.6, respectively. None of the other flight maneuvers was similarly affected.

All maneuvers combined

The single ANOVA in which all of the maneuvers were analyzed together revealed there was an effect on the maneuver factor ($F(7,63)=67.55$, $p<.0001$) but no effects indicative of deprivation-related changes in performance. Pairwise comparisons across the eight levels of the maneuver factor (referred to as the "segment factor" in the EEG data) revealed SL scores were higher (better) than scores on any of the other maneuvers, whereas RDT and LCT scores were lower than the scores on any of the other maneuvers ($p<.01$). Although RSRT and LSRT scores were higher than RDT and LCT scores, they were lower than climb, descent, and ILS scores ($p<.01$). These differences are likely due to the fact that some flight maneuvers are simply more difficult to perform than others. The mean performance scores for each of the maneuvers are listed in table 4.

Table 4.
Composite flight scores.

SL	RSRT	LSRT	Climb	Descent	RDT	LCT	ILS
74.2	52.5	53.0	66.8	65.8	47.8	46.8	64.5

POMS

The mood scores from the six subscales of the POMS were analyzed with a series of one-way ANOVAs on the session factor (the POMS was given at 2100, 2155, 0200, 0255, 0700, and 0755 in the laboratory prior to each flight in the aircraft). The anger-hostility subscale was dropped from this analysis due to the fact that there were no nonzero responses on this dimension. However, there were noteworthy effects on all but one of the remaining subscales. There were significant main effects on tension-anxiety ($F(5,45)=6.31$, $p=.0002$), vigor-activity ($F(5,45)=29.67$, $p<.0001$), fatigue-inertia ($F(5,45)=27.04$, $p<.0001$), and confusion-bewilderment ($F(5,45)=13.04$, $p<.0001$). Trend analyses indicated these effects occurred because mood deteriorated as the hours of continuous wakefulness increased ($p<.01$). As can be seen in figure B-9, subjective reports of tension, fatigue, and confusion increased from 2100 to 0755, whereas ratings on the vigor dimension decreased. Ratings on the depression scale were unaffected.

VAS

The scores from the eight subscales of the VAS were analyzed with a series of one-way ANOVAs on the session factor in a fashion similar to the POMS. The VAS was administered following the POMS at 2100, 2155, 0200, 0255, 0700, and 0755–prior to each flight in the aircraft. The ANOVA indicated there were significant session differences on six of the eight subscales: alertness ($F(5,45)=17.51$, $p<.0001$), energy ($F(5,45)=15.93$, $p<.0001$), confidence ($F(5,45)=7.74$, $p<.0001$), irritability ($F(5,45)=4.34$, $p=.0026$), sleepiness ($F(5,45)=21.95$, $p<.0001$), and talkativeness ($F(5,45)=9.01$, $p<.0001$). There were no effects on the anxiety scale or the nervousness scale. Trend analyses indicated that the significant effects on the other scales were due to linear deteriorations in mood from the first to the last test sessions ($p<.05$). Also, on the energy subscale, there was a quartic effect which resulted from a more pronounced drop in self-reports of energy during the first half of the deprivation period (from 2100 to 0200) than during the second half of the deprivation period (from 0255 to 0755). Alertness, energy, confidence, and talkativeness declined generally from the beginning to the end of the deprivation period; whereas irritability and sleepiness increased (see figure B-10).

MATB

The MATB consisted of four different subtests (communications, resource management, lights and dials, and tracking), each of which produced separate response measures. For the present report, 11 of these measures were analyzed in a series of one-way ANOVAs to determine whether sleep deprivation affected performance at 3 points in time (2105, 0205, and 0705). There were marginal effects ($p\leq.10$) on seven of the measures, but statistical significance ($p<.05$) was attained only on four. These four were: the reaction times to warning lights ($F(2,18)=8.93$, $p=.0020$), the reaction times to out-of-bounds dial indications ($F(2,18)=3.80$, $p=.0420$), the standard deviation of reaction times to the dials ($F(2,18)=6.88$, $p=.0060$), and the root-mean-square (RMS) errors in the tracking task ($F(2,18)=11.78$, $p=.0005$). Trend analysis indicated a linear deterioration in performance from the 2105 session to the 0705 session in all four cases ($p<.05$). In addition, there were quadratic trends in the reaction times to lights, the standard deviation of reaction times to dials, and the tracking RMS errors which resulted from more pronounced decrements towards the end of the deprivation period than at the beginning (see figure B-11).

Discussion

The primary focus of the present investigation was to determine whether the fatigue-related EEG changes found in earlier studies during standard laboratory testing procedures (Caldwell et al., 1996; Caldwell et al., 2000) could be detected from aviators who were actually flying an aircraft during in-flight operations. Of particular interest, was whether fatigue-related accentuations in EEG theta (3-8 Hz) activity could be recorded from fatigued pilots because, generally speaking, sleepiness and fatigue are known to elevate the amount of slow-wave brain activity (Pigeau, et al., 1987), and increased theta activity has been associated with generalized performance decrements on cognitive tasks (Belyavin and Wright, 1987) and reduced speed of responding to incoming stimuli (Ogilvie and Simons, 1992).

The findings of the present study revealed that there were in fact EEG effects in both the laboratory and the in-flight testing situations, and that there were consistent effects in the EEG theta band across the two settings. Theta activity, recorded from electrodes placed along the midline of the scalp (Fz, Cz, and Pz), progressively increased from the beginning of the deprivation period to the end of the deprivation period, suggesting that fatigue from sleep deprivation was exerting a negative impact on the physiological alertness of the pilots. In addition to these theta effects, lower-frequency delta (1.5-3.0 Hz) activity also was accentuated as a function of sleep deprivation in both testing situations, but the effect was observed only at Pz in the aircraft, whereas it was seen at all three recording sites in the laboratory. Increases in delta activity are primarily associated with sleep in normal adult subjects (Ray, 1990). Differences in alpha activity also were seen in the laboratory and in flight, but the pattern did not show the consistency that was apparent with delta and theta. In fact, alpha power progressively decreased in the laboratory setting while increasing in the aircraft setting. Such a disparity may have resulted from the more soporific nature of the laboratory testing environment versus the noisier and less comfortable in-flight environment. Thus, in the laboratory, participants were more likely to have actually drifted into stage 1 sleep--characterized partially by a diminution of alpha activity (Rechtshaffen and Kales, 1968)--whereas falling asleep “on the controls” in flight would have been less likely to have occurred because of heightened arousal levels (Billings, Gerke and Wick,1975). However, despite this lack of consistency in the alpha data, the uniform effects in both delta and theta strongly suggest: 1) that participants were becoming more fatigued as the deprivation period progressed, and 2) that this increase in fatigue was detectable via EEG recordings both in the more traditional laboratory setting and in the less-well-researched aircraft setting.

Further evidence for a progressive increase in fatigue levels from the beginning to the end of the sleep-deprivation period was provided both by the subjective-mood data and the cognitive-performance data collected in the laboratory (prior to each of the three in-flight sessions). Similar data were not collected in the aircraft. The subjective mood data (from the POMS and the VAS) clearly indicated that the pilots were adversely affected by sleep deprivation. Ratings of fatigue, sleepiness, irritability, tension, and confusion all increased significantly as a function of prolonged wakefulness, whereas ratings of vigor, alertness, energy, confidence, and talkativeness decreased. These findings are generally consistent with reported data from earlier studies in which sleep-deprivation was a factor

(Caldwell and Caldwell, 1997; Caldwell and Caldwell, 1998; Caldwell et al., 2000; Newhouse et al., 1989). These self-reported mood and alertness decrements no doubt contributed to the deterioration in basic cognitive abilities observed on the MATB. Although less than half of the MATB outcome measures apparently were sensitive to the effects of sleep loss and fatigue, the ones that did degrade seem particularly pertinent to aviator performance. Degradations in the reaction time to warning lights and out-of-bounds dial indications, along with more variable performance and increased tracking errors, became more pronounced as the amount of sleep deprivation progressed. Thus, not only were self-perceptions of alertness declining with increased hours awake, but objective measures of performance were deteriorating as well. These findings support those of Caldwell and Ramspott (1998) and Wilkinson (1964) who indicated that tasks requiring vigilance are adversely affected by the fatigue induced by sleep deprivation. It is well known that sleep loss seriously impacts even basic cognitive skills, and the present results are thus consistent with what would have been expected.

Unfortunately, it is this very finding that makes it difficult to interpret the flight performance data that were collected in this research protocol. The analysis of objective flight skills revealed that only one of the eight aircraft maneuvers was affected by the fatigue which resulted from 26 hours of continuous wakefulness, and in this maneuver, the greatest decrements were observed in the middle of the deprivation period rather than at the end. The composite flight scores from the two iterations of the left standard-rate turn indicated a significant reduction in control accuracy at the 0400 flight in comparison to the 2300 and 0900 flights, but similar effects were not observed on the straight and levels, the right standard-rate turns, the straight climbs and descents, the climbing and descending turns, or the instrument landing system approach. The reasons for this lack of consistency with the slow-wave EEG findings and the VAS, POMS, and MATB results remain unclear at this point; however, it may be that the amount of error variance in the flight data was so large that the sensitivity of these data to the effects of fatigue was lost. Alternatively, it could be that the pilots were more aroused in the aircraft (versus the laboratory), and that this enabled them to temporarily attenuate the performance-degrading effects of fatigue in that setting. Both of these explanations are to some degree plausible based on the fact that previous studies have shown actual in-flight testing to be less sensitive to stressor effects than laboratory simulator testing (Billings et al., 1975; and Caldwell and Roberts, 2000). Also, the EEG alpha findings from within the present investigation suggest that alertness may have been slightly improved in the helicopter versus the laboratory setting. In the future, the first of these issues (the sensitivity of aircraft studies) will be addressed by increasing the number of subjects and/or flights in order to increase the statistical power of the study's design, and the second of these issues (possible improvements in alertness) will be addressed by requiring subjects to perform self-ratings of alertness in the cockpit as well as in the laboratory. However, until this future investigation is complete, it will not be possible to know whether these modifications will lead to more favorable results.

In the meantime, it is encouraging to note that it was feasible to monitor overall increases in the fatigue levels of pilots via the real time acquisition of EEG from the in-flight environment. This suggests that it is possible to gain insight into the functional status of aviators without disrupting performance on the primary task of flying the aircraft. However, future studies are needed to establish whether there are significant correlations between in-flight physiological changes and in-flight performance changes. Although, a preliminary examination of this issue will be performed on portions of the present data set in a subsequent report, it will be necessary to collect more in-flight data (for the reasons outlined in the previous paragraph) before this issue can be resolved.

Conclusion

This investigation in which the EEG activity of 10 UH-60 helicopter pilots was monitored during flights in a specially-instrumented aircraft revealed that it is feasible to assess physiological indicators of fatigue without interfering with a pilot's primary task (flying the aircraft). Slow-wave (delta and theta) EEG increased as a function of sleep deprivation, and the increases were consistent with what was observed under standard laboratory conditions. The fact that these EEG changes were fatigue related was supported by concurrent deteriorations in mood and basic cognitive performance (found during laboratory tests conducted between the flights); however, there were almost no degradations in actual flight performance (as measured by a computerized system on board the aircraft). Thus, while it appears useful to monitor basic aviator status via EEG measures, the extent to which these measures correlate with actual operational aspects of performance can be evaluated only after additional study. A follow-on protocol is being prepared to assess the flight performance of a larger number of fatigued pilots in order to overcome the variability associated with in-flight testing.

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Appendix A.

Manufacturer's list.

Cadwell Laboratories
909 Kellog Street
Kennewick, WA 99336

Digital Equipment Corporation
P.O. Box C52008
Tampa, FL 33614

Elexor Associates
P.O. Box 246
Morris Plains, NJ 07950

Grass Instrument Company
101 Old Colony Avenue
Quincy, MA 02169

Paravant
7800 Technology Drive
Melbourne, FL 32904

Sikorsky Aircraft Corporation
6900 Main Street
Stratford, CT 06615

Appendix B.

Figures showing the effects of sleep deprivation.

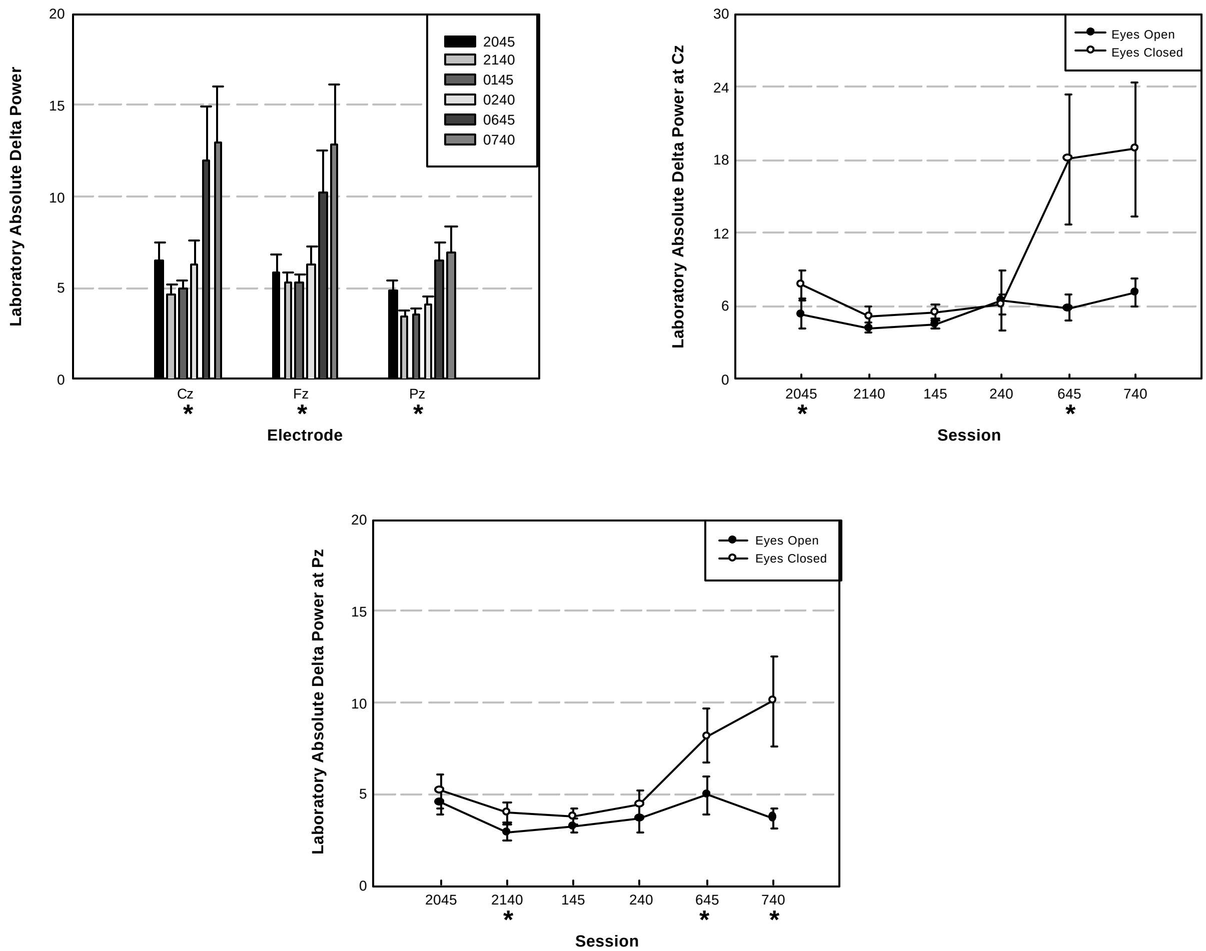

Figure B-1. The effects of sleep deprivation and the combination of sleep deprivation and eyes-open/eyes-closed (for Cz and Pz) on EEG delta activity collected in the laboratory.(Significant effects denoted by asterisk.)

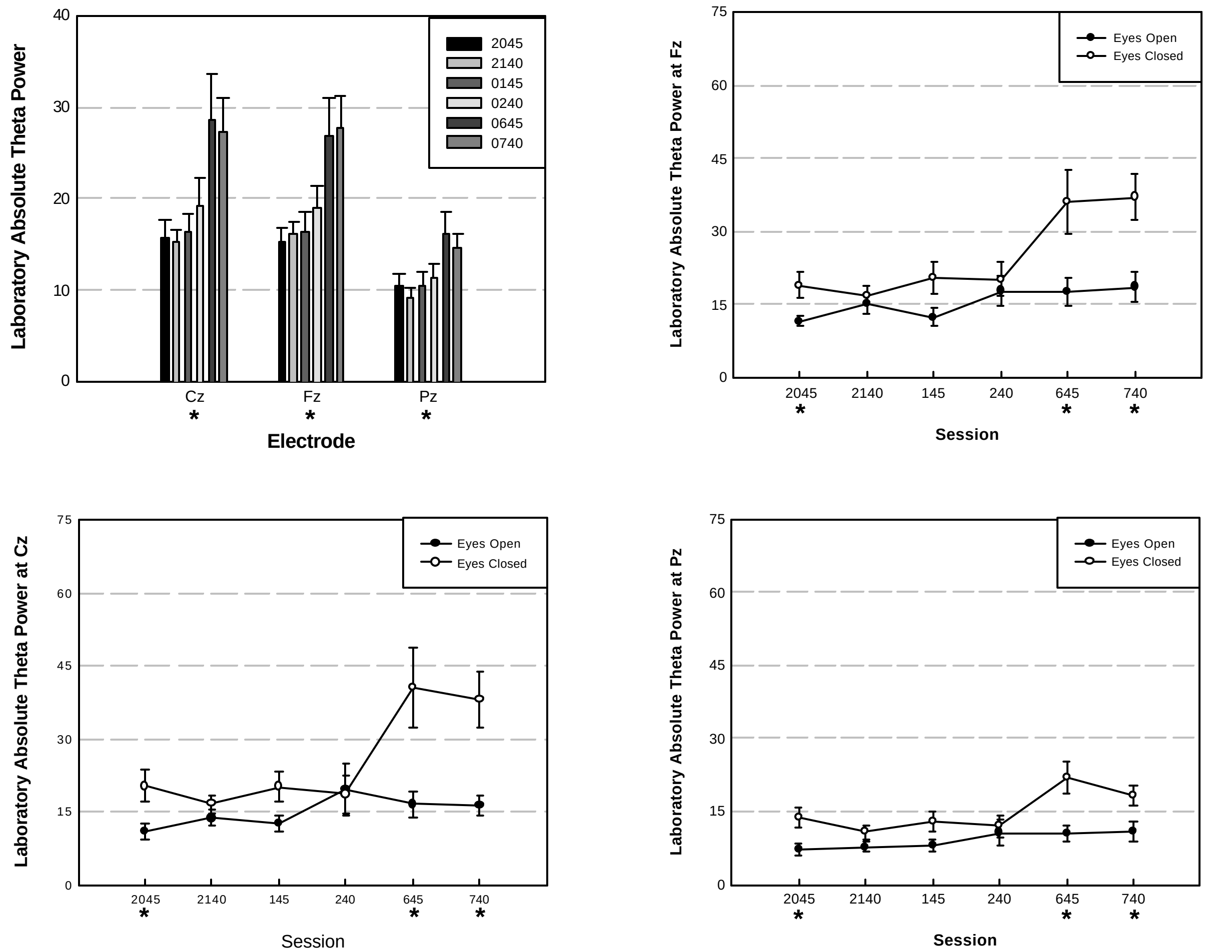

Figure B-2. The effects of sleep deprivation and the combination of sleep deprivation and eyes-open/eyes-closed (for the midline electrodes) on EEG theta activity collected in the laboratory. (Significant effects denoted with asterisk).

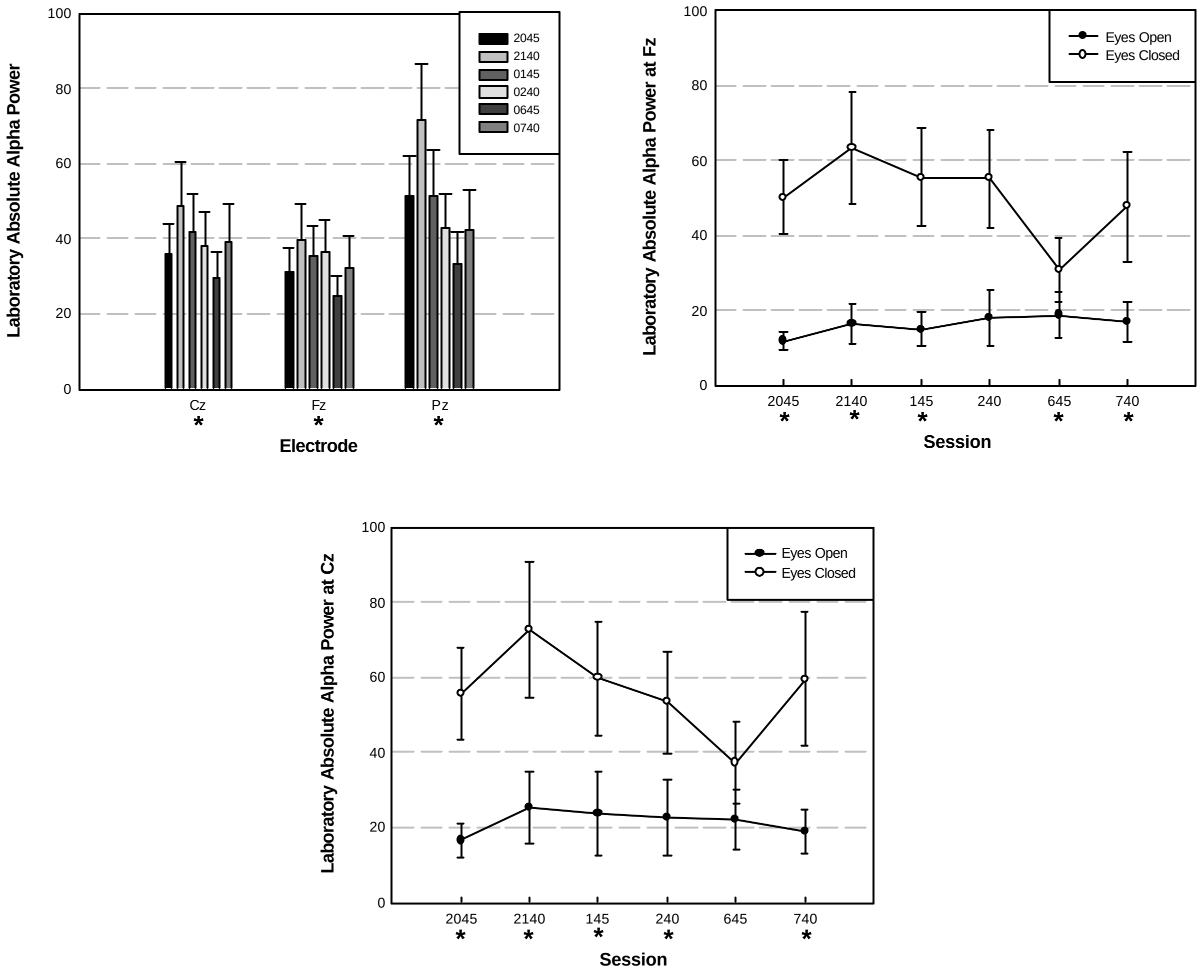

Figure B-3. The effects of sleep deprivation and the combination of sleep deprivation and eyes-open/eyes-closed (for Fz and Cz) on EEG alpha activity collected in the laboratory. (Significant effects denoted with asterisk).

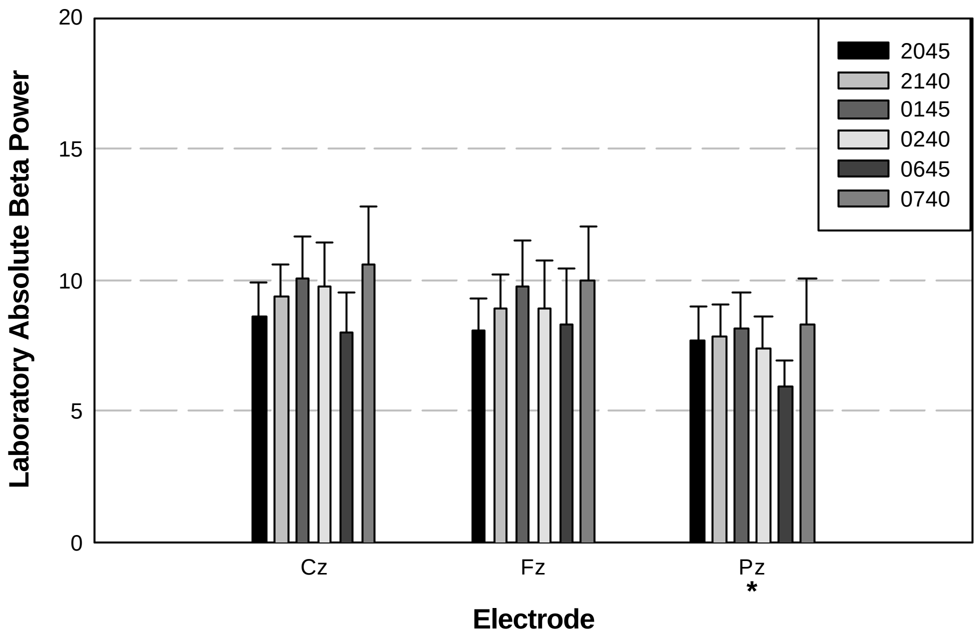

Figure B-4. The effects of sleep deprivation on EEG beta activity collected in the laboratory. (Significant effects denoted with asterisk).

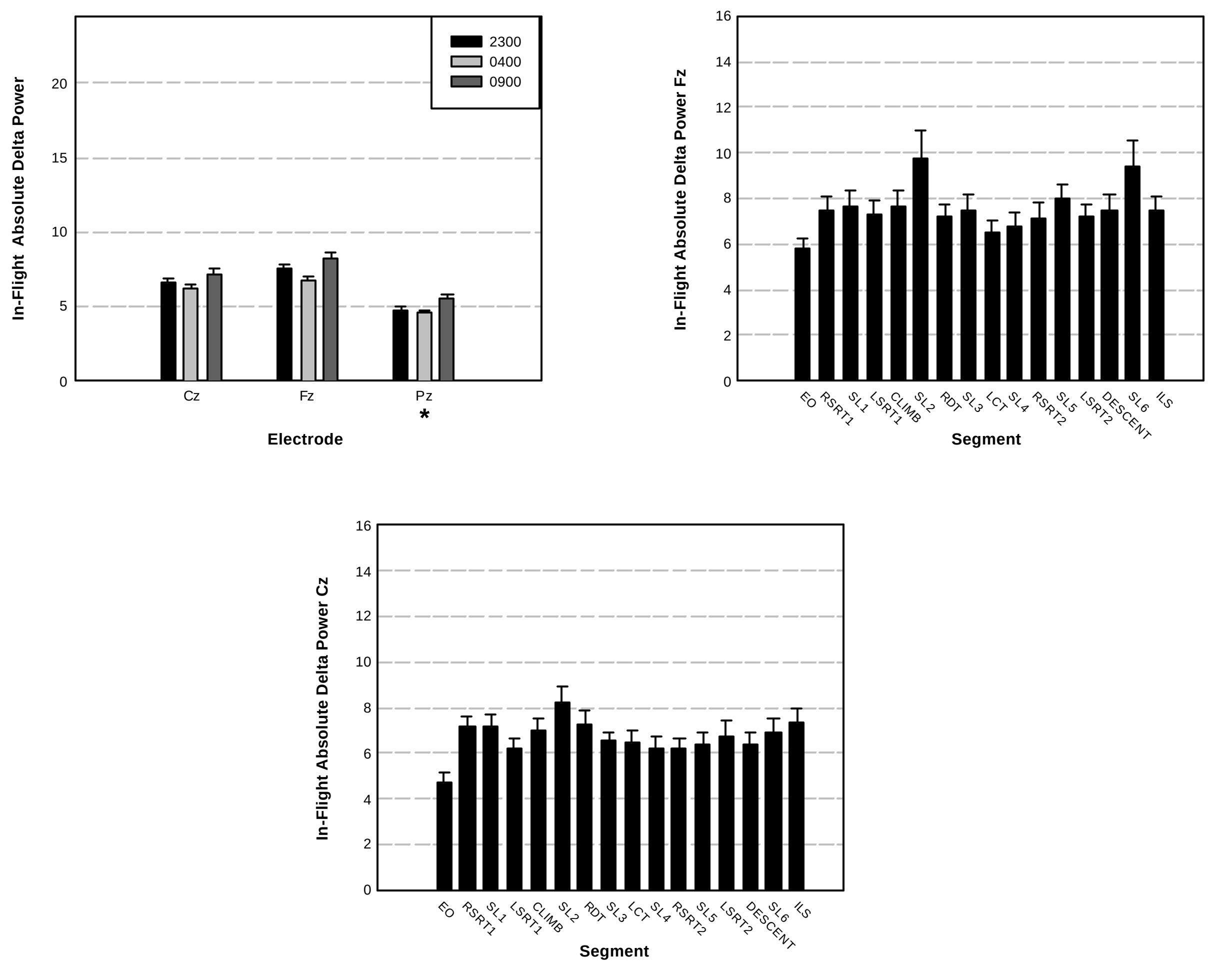

Figure B-5. The effects of sleep deprivation on in-flight EEG delta activity recorded from Fz, Cz, and Pz. (Significant effects denoted with asterisk). Also shown are the differences among the 16 flight segments on delta activity recorded from Fz and Cz.

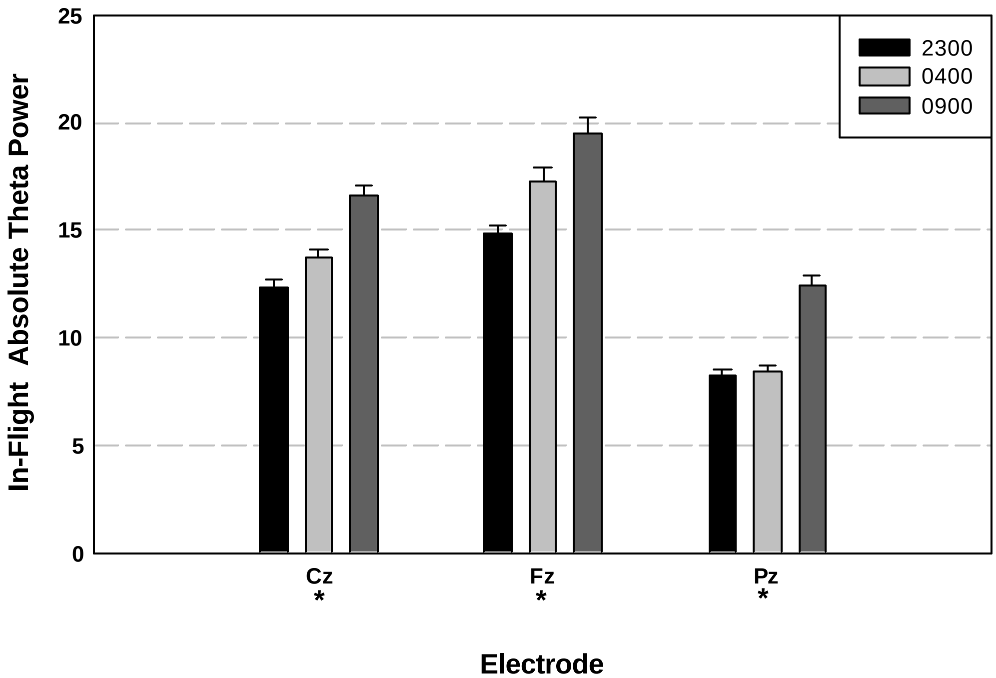

Figure B-6. The significant effects of sleep deprivation on in-flight EEG theta activity recorded from Fz, Cz, and Pz. (Significant effects denoted with asterisk).

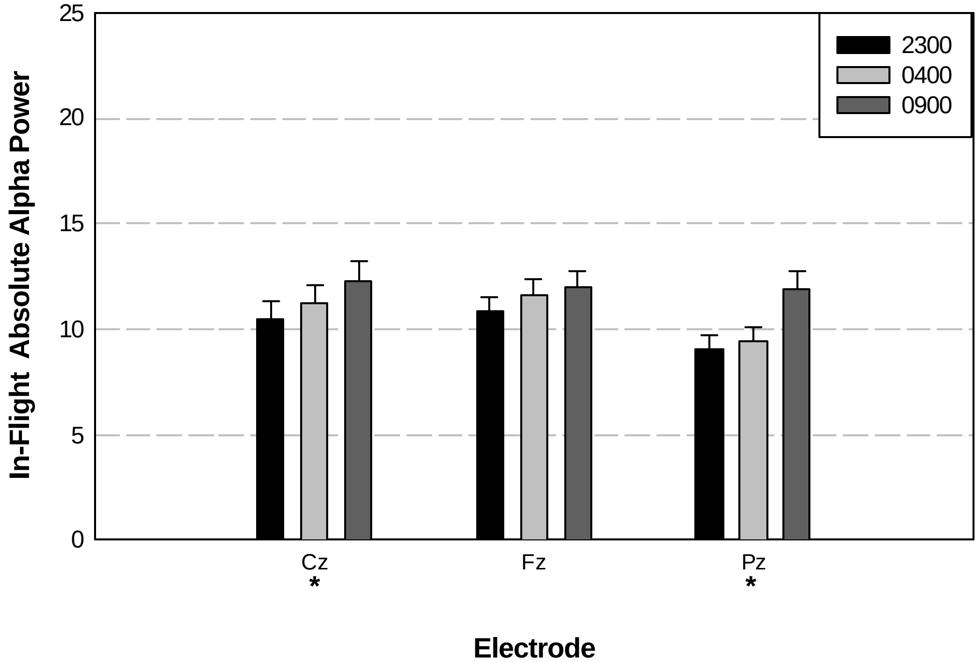

Figure B-7. The significant effects of sleep deprivation on in flight EEG alpha activity (Significant effects denoted with asterisk).

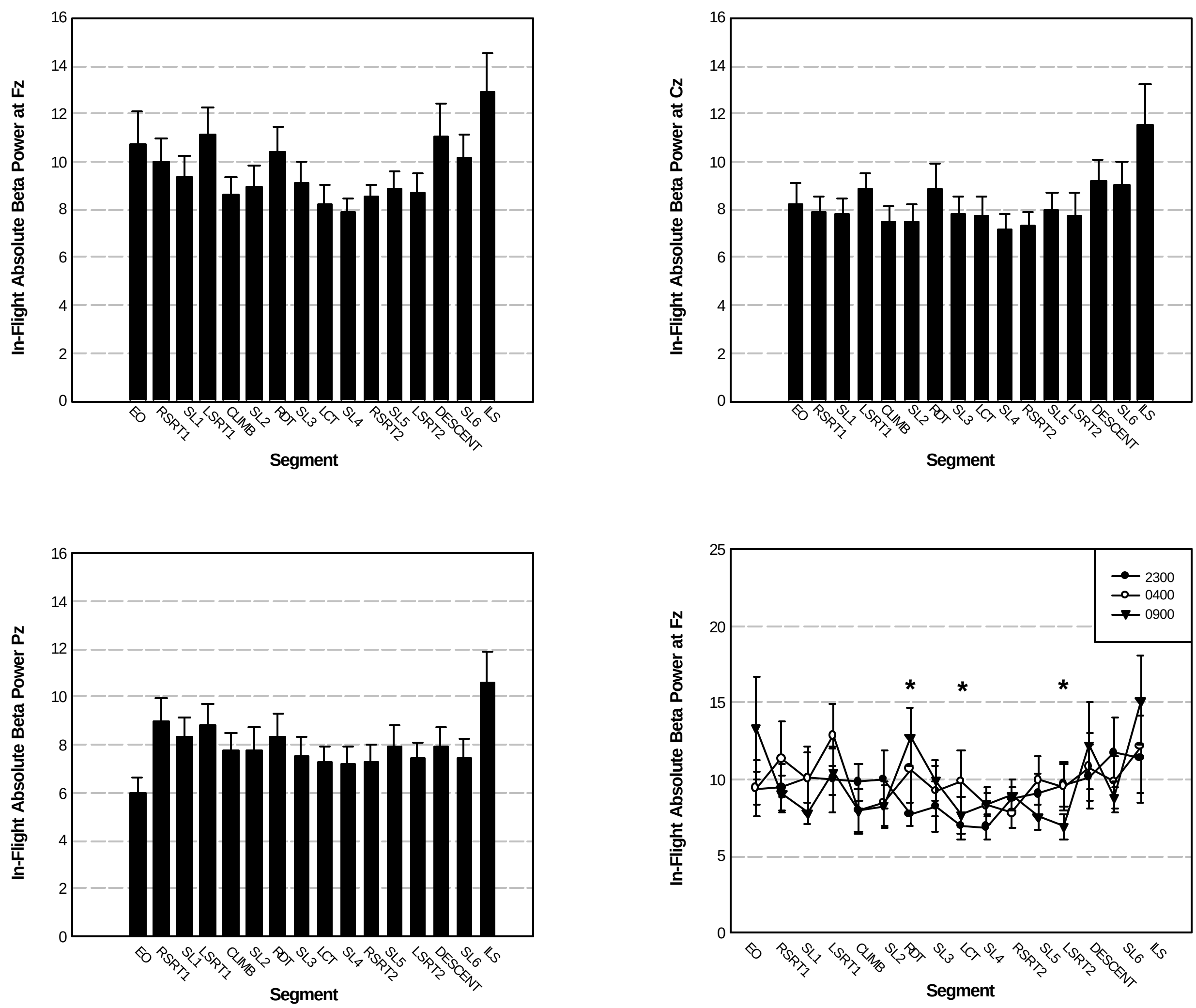

Figure B-8. The mean levels of in-flight EEG beta activity recorded from Fz, Cz, and Pz. There were significant "segment" effects at all 3 electrodes. (Significant effects denoted with asterisk).

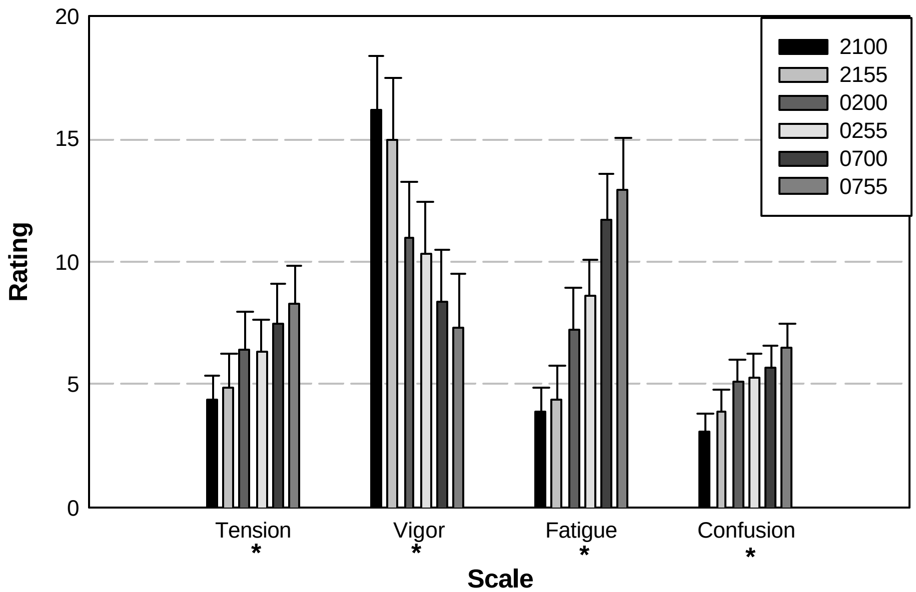

Figure B- 9. The significant impact of sleep loss on subjective ratings from the tension-anxiety, vigor-activity, fatigue-inertia, and confusion-bewilderment scales of the POMS. (Significant effects denoted with asterisk).

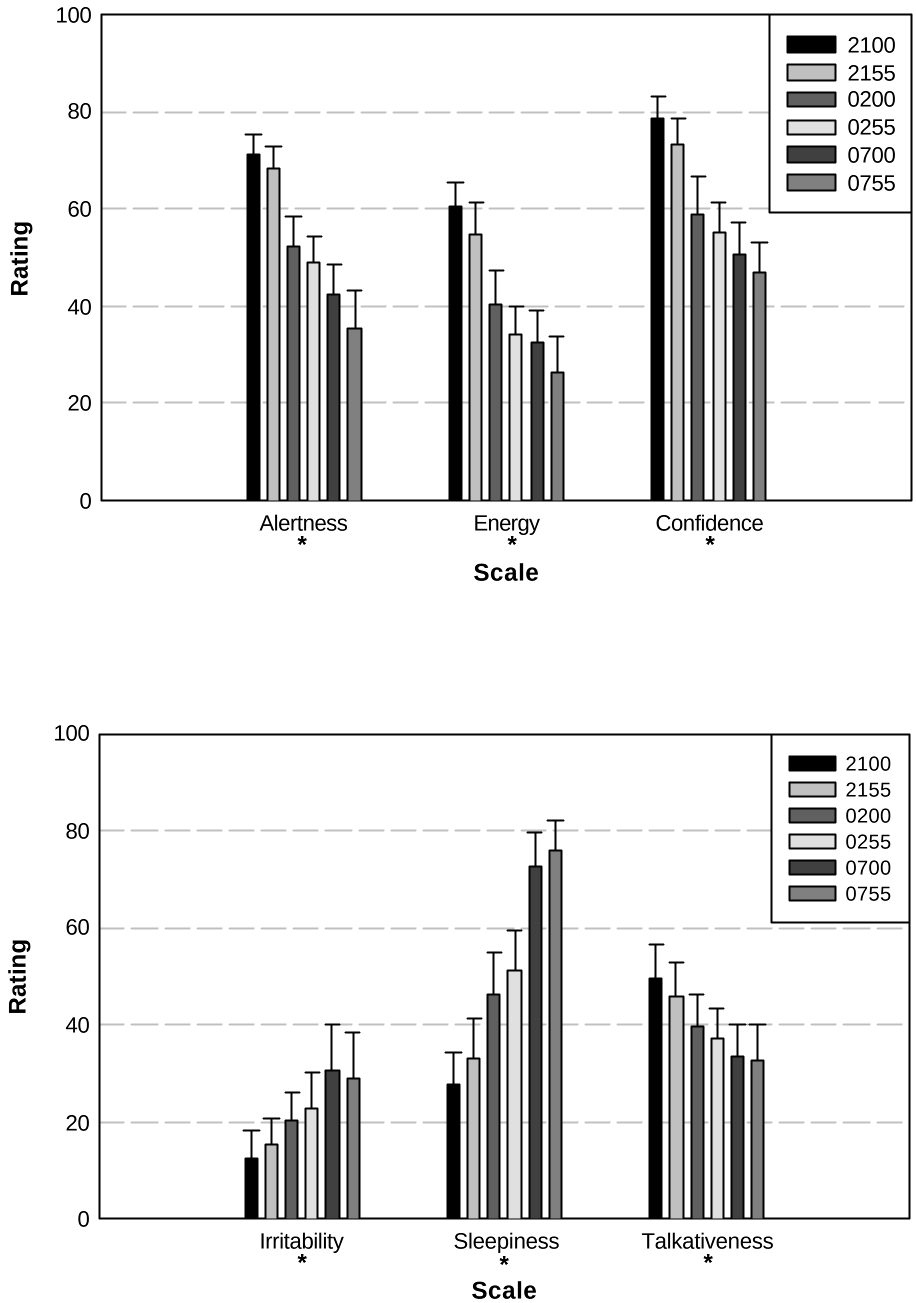

Figure B-10. The significant impact of sleep loss on subjective ratings of alertness, energy, confidence, irritability, sleepiness, and talkativeness from the VAS. (Significant effects denoted with asterisk).

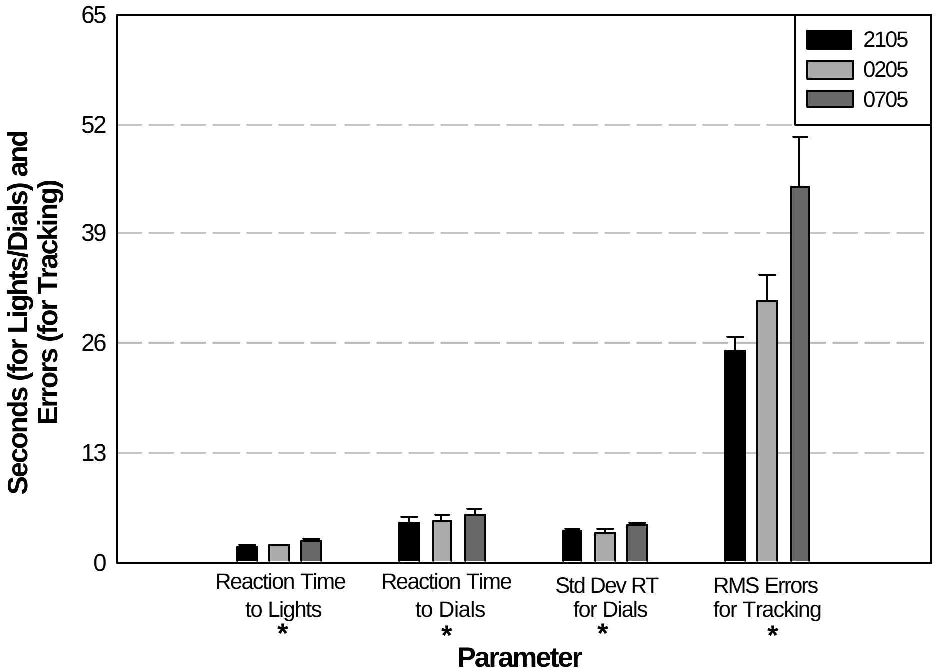

Figure B-11. The effects of fatigue on 4 outcome measures from the MATB–reaction time to warning lights, reaction time to out-of-bounds dial deviations, the standard deviation of reaction times for "dials," and RMS errors from the unstable tracking task. (Significant effects denoted with asterisk).