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The effects of 34 hr of continuous wakefulness on flight performance, instrument scanning, subjective fatigue, and EEG activity were measured. Ten fixed-wing military pilots flew a series of 10 simulator profiles, and root mean squared error was calculated for various flight parameters. Ocular scan patterns were obtained by magnetic head tracking and infrared eye tracking. Flying errors peaked after about 24 to 28 hr of continuous wakefulness in line with peaks in subjective fatigue and EEG theta activity, and they were not directly attributable to degradation of instrument scanning, which was very consistent across pilots and largely unaffected by the sleep deprivation.

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The Effects of Sleep Deprivation on Flight Performance, Instrument Scanning, and Physiological Arousal in Pilots

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The effects of 34 hr of continuous wakefulness on flight performance, instrument scanning, subjective fatigue, and EEG activity were measured. Ten fixed-wing military pilots flew a series of 10 simulator profiles, and root mean squared error was calculated for various flight parameters. Ocular scan patterns were obtained by magnetic head tracking and infrared eye tracking. Flying errors peaked after about 24 to 28 hr of continuous wakefulness in line with peaks in subjective fatigue and EEG theta activity, and they were not directly attributable to degradation of instrument scanning, which was very consistent across pilots and largely unaffected by the sleep deprivation.

Fatigue due to sleep deprivation is considered a major risk to flight safety (Borowsky & Wall, 1983; Ramsey & McGlohn, 1997; Tormes & Guedry, 1975), with surveys suggesting that up to half of all pilots have actually "dozed off" while flying (Caldwell & Gilreath, 2002). Fatigue degrades not only basic cognitive per-

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formance (Caldwell, Caldwell, Brown, & Smith, 2004; Dinges et al., 1997; Matthews, Davies, Westerman, & Stammers, 2000) but also flight performance, including the ability to maintain designated flight parameters (Caldwell et al., 2004; Caldwell, Caldwell, & Darlington, 2003; LeDuc et al., 1999; Morris & Miller, 1996). Whether the risk to flight safety is due primarily to a reduced general cognitive capacity or to flying-specific factors (e.g., stick control or instrument scanning) has yet to be determined.

Sleep deprivation experiments have generally shown that performance reaches a nadir in the early morning hours, typically after 24 hr of sustained wakefulness and at the trough of the circadian cycle, before improving slightly as the second day progresses (Caldwell et al., 2004; Caldwell et al., 2003). The rebound on the second day is partly due to the effect of the circadian cycle that rises during the day (Eddy & Hursh, 2001) and also to the impending completion of the experiment. In previous simulator studies, helicopter pilots showed an earlier nadir than fixed-wing pilots, possibly because of their different daily schedules (Caldwell et al., 2004; Caldwell et al., 2003).

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One possible correlate of the decrements in flight performance is impaired ocular scanning of the flight instruments. Five basic eye-movement parameters that have been repeatedly studied in conjunction with fatigue are (a) blink rate, which generally increases with sleep deprivation and fatigue (Lal & Craig, 2001; Morris & Miller, 1996; Stern, Boyer, & Schroeder, 1994); (b) pupil diameter, which typically decreases with sleep deprivation (Morad, Lemberg, Yofe, & Dagan, 2000; Ranzijn & Lack, 1997; Wilhelm, Wilhelm, Ludtke, Streicher & Adler, 1998; Yoss, Moyer & Hollenhorst, 1979); (c) saccadic velocity, which has been shown to decrease with sleep deprivation (Caldwell et al., 2004; De Gennaro, Ferrara, Urbani, & Bertini, 2000; Rowland et al., 2005; Russo et al., 2003; but see Morris & Miller, 1996); (d) mean saccade length (fixation distance), which increases with time-on-task (Lavine, Sibert, Gokturk, & Dickens, 2002); and (e) dwell time, which in at least one study was shown to decrease with time-on-task (Lavine et al., 2002). In contrast to the preceding basic eye-movement studies, no previous study has investigated changes in pilot instrument scanning with extended wakefulness, although there have been several studies of pilot scanning behavior under normal wakefulness (Bellenkes, Wickens, & Kramer, 1997; Itoh, Hayashi, Tsukui, & Saito, 1990; Jones, Milton, & Fitts, 1949).

The chief purpose of this study was to investigate changes in flight performance during extended wakefulness of over 30 hr and to determine the relationship between fatigue-related flight performance decrements and both general changes (e.g., increased blink rate) and specific changes (e.g., reduced scanning of specific instruments) in oculomotor behavior. Another objective was to relate changes in flight performance and instrument scanning to changes in subjective and objective fatigue and arousal, the latter being measured by the scalp-recorded electroencephalogram (EEG). Previous research has demonstrated that increases in low-frequency (delta and theta) EEG activity generally parallel changes in performance during sleep deprivation, fatigue, or both (Caldwell et al., 2004; Lal & Craig, 2001; Morris & Miller, 1996).

METHOD

Participants

Ten pilots from the United States Air Force (USAF) participated in this study in an off-duty capacity. Eight of the 10 pilots (all male) were active-duty pilots and the remaining 2 were reserve officers. The average age of the pilots was 34.2 years (range = 23–46 years), with half of the pilots over 35 years and half at 30 years or under. Their average flight experience was 2,806 hr (range = 207 hr–5,800 hr),[1] and the correlation between flight experience and age was almost perfect (r = .96). All pilots signed an informed consent document approved by the Brooks City-Base Institutional Review Board and were compensated for their participation because they served in an off-duty capacity.

All pilots possessed at least 20/25 vision binocularly (they were allowed to wear contact lenses but not glasses for correction), had normal vestibular function as assessed by the Sharpened Romberg Test, and had no previous evidence of vestibular symptoms such as dizziness, vertigo, and disorientation. No pilot suffered from sleep problems or seizures, and none was currently taking any psychoactive medication (e.g., antihistamines, antidepressants, sleep aids, etc.) or was a habitual smoker (i.e., consumed more than one cigarette per day) or caffeine drinker (i.e., consumed more than 100 mg of caffeine per day). All pilots refrained from caffeine, alcohol, and other mild stimulants or sedatives while monitored at home on the night before the sleep-deprivation period as well as during the 34 hr of continuous wakefulness in the laboratory. Nine of the 10 pilots completed a sleep log for the 7 days prior to the start of the experiment and had their final night of sleep (after the first night of training) monitored by a wrist-activity monitor.[2] The sleep duration and quality for the 3 days prior to the beginning of the experiment were analyzed using the Fatigue Avoidance Scheduling Tool (FAST; Eddy & Hursh, 2001), and a baseline "waking efficiency" score was derived for each pilot to predict his level of alertness prior to the period of continuous wakefulness. The average amount of sleep per night was 7.46 hr and was associated with an average "waking efficiency" score of 90.59, with only three pilots scoring below 90 (76.8, 85.2, 85.9).

[1]Three of our pilots had just completed undergraduate pilot training.

[2]One pilot misplaced his sleep log and failed to return it.

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Apparatus: Gyroflight Sustained Operations Simulator

This study was conducted in the Gyroflight Sustained Operations Simulator (GSOS; Environmental Tectonics Corporation, Southampton, PA), a four-axis flight simulator with additional spatial disorientation-producing capabilities. The GSOS was colocated with the Aviation Sustained Operations Laboratory in Building 170 at Brooks City-Base, Texas. The GSOS possesses motion capabilities in pitch (up to ±25°), roll (up to ±25°), and yaw (up to 360° of sustained yaw). The GSOS also features subthreshold washout in pitch and roll as well as limited heave (up to ±12 cm). It has a three-channel high-resolution, noncollimated, out-the-window visual display, with a total field-of-view of 28° vertical by ~120° horizontal. The GSOS aeromodel replicates the T-6 aircraft, with which most of the pilots were familiar, and its reconfigurable instrument panel was also designed to depict as closely as possible the panel on the T-6 aircraft. The GSOS was operated and monitored from a control station in an adjacent room, and its physiological recording capability was configured to record eye movements and EEG.

Eye-Movement Recordings

Eye movements were recorded by means of Eye-Trac 6000 (Applied Science Laboratories, Cambridge, MA), a head-mounted system that consists of a magnetic head tracker and an infrared eye tracker. The “Flock of Birds” head tracker (Ascension, Burlington, VT) provides six degree-of-freedom tracking by means of a 21-Hz magnetic pulse signal directed toward a sensor attached to the head. The position of the eye in the orbit was sampled at 60 Hz using an infrared beam and camera to measure the relative angles of the pupil and corneal reflectance. Together, the head and eye signals determined gaze with an error of < 0.5° during calibration. The eye and head signals were then sent to a computer on the GSOS and relayed through the GSOS slip rings to a monitor located in the control station. Data were stored on a PC and analyzed later.

EEG Recordings

EEGs were recorded using the GRASS-Telefactor Instruments Aurora recording system (West Warwick, RI) running TWin™ collection and analysis software. EEGs were recorded from gold-cup electrodes at two sites (C_z and P_z) and were referenced to linked-mastoid electrodes, while an additional ground lead was attached to the scalp. EEGs were recorded with cutoff filters set at 1 Hz and 70 Hz and were digitized at 200 Hz. Data were then stored on a PC and analyzed later.

Procedures

Flight profile. The GSOS flight profile, shown in Figure 1, consisted of seven major segments: (a) takeoff at 360° and climb to 8,000 ft; (b) a right climb-

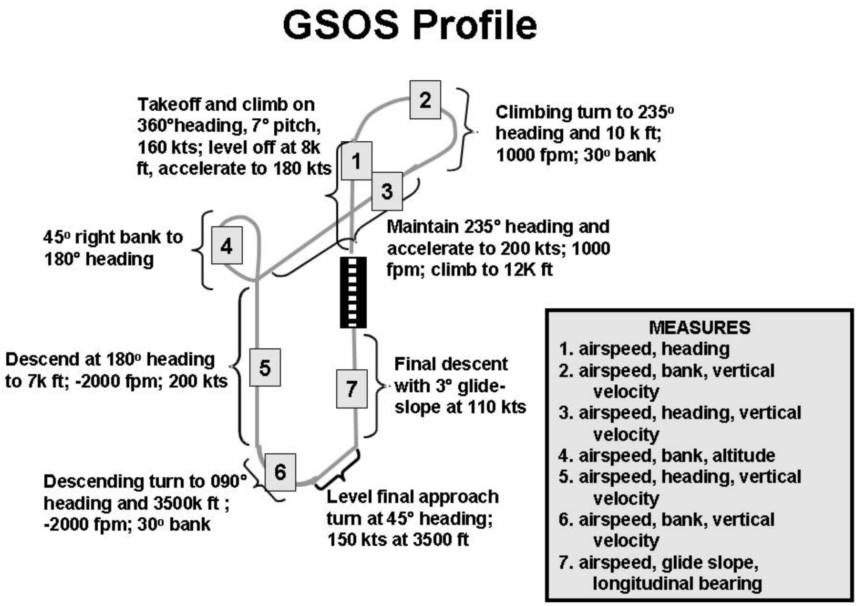

FIGURE 1 The Gyroflight Sustained Operations Simulator (GSOS) profile with the seven segments in which various measures of flight performance were recorded: (a) takeoff at 360° and wings-level climb to 8,000 ft; (b) right climbing turn to 10,000 ft; (c) wings-level climb to 12,000 ft; (d) right level turn to 180°; (e) wings-level descent to 7,500 ft; (f) left descending turn to 4,000 ft; and (g) visual descent and landing at 360°.

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ing turn to 10,000 ft and 235°; (c) a wings-level climb to 12,000 ft; (d) a right level turn to 180°; (e) a wings-level descent to 7,500 ft; (f) a left descending turn to 4,000 ft and 90°; and (g) visual descent and landing.[3] The flight, which required about 19 min to complete, simulated a transition from a dusk takeoff to a nighttime landing and was performed mostly in instrument meteorological conditions (IMC). The exceptions to IMC were during a brief period after takeoff, during a small section of the wings-level climb while pilots searched for traffic, and during the turn to final approach followed by the visual approach and landing. On each segment, the pilot was commanded to maintain a set of previously specified control or performance parameters, including airspeed (all segments), heading (Segments 1, 3, and 5), vertical velocity (Segments 2, 3, 5, and 6), bank (Segments 2, 4, and 6), and longitudinal bearing and glide slope (Segment 7). On odd-numbered flights the pilot flew as already described, and on even-numbered flights the pilot

[3]In an additional segment, which was too variable to allow commanded parameters, the pilot was required to achieve and maintain a heading at 45° to intersect final approach.

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flew a mirror profile, beginning with a climb to the left followed by a wings-level climb at 125° rather than a climb to the right followed by a wings-level climb at 235°. The GSOS profile was designed to be semiautomated and required the operator to directly instruct the pilot only during gross flight errors such as the wrong turning direction, wrong course, or wrong heading.

On four of the flights (1, 4, 7, and 10), seven spatial disorientation conflicts were inserted in during various segments of the flight. These conflicts were designed to test the effects of sleep deprivation on spatial disorientation (Previc et al., 2007). They involved either motion illusions (an excess pitch sensation during takeoff in Segment 1, a Coriolis illusion during head tilt in Segment 4, and postrotatory sensations following rollout from the turns at the end of Segments 2, 4, and 6) or visual illusions (a sloping cloud deck in Segment 3 and a narrow, up-sloping runway in Segment 4). Pilots were instructed to report any discrepancies or conflicts with their instruments but were not informed in advance of the specific illusions. Only two of the conflicts were shown to influence flight performance during measured epochs: the sloping cloud deck on bank during the long wings-level ascent in Segment 3 and the illusory runway on glide slope during the landing in Segment 7. However, the cloud deck effect was very slight (< 1°) and was present for only a small portion of Segment 3, and glide slope in Segment 7 was later removed from the composite error measure. Any remaining effect of conflict versus nonconflict flights was determined to be nonsignificant in a preliminary analysis, so that the data were then collapsed across conflict and nonconflict flights. Because transitions between flight maneuvers had to be eliminated while pilots were in the process of attaining their commanded flight parameters, only about 50% of the total flight was used for data analysis.

Root mean squared error (RMSE) was used as the measure of flight performance. The RMSE values were calculated using Equation 1:

$$\text{RMSE} = \sum_{i=1}^{n} \sqrt{(i-c)^2/n}, \qquad (1)$$

where i is the observed value and c is the commanded flight parameter.

Each segment had three measures except Segment 1, which only had airspeed and heading, and Segment 7, because slope was removed due to the effects of the spatial disorientation conflicts on four of the flights. To compute composite RMSE values for different flight segments and parameters as well as for the entire flight, all RMSE values were divided by the baseline value (the RMSE in Flight 1) and then converted to log units before averaging. The grand composite average was based on a total of 19 individual values.

Eye-movement calibrations and recordings. Eye movements were recorded during all flights. Prior to the beginning of the experiment, the head tracker was calibrated by placing the magnetic sensor in a pointer rod that was aimed at different portions of the GSOS instrument panel. Just prior to each flight, and after the preflight resting EEG recordings session, pilots sat down in the GSOS and the infrared camera was adjusted to obtain a good image of the eye. Then, the GSOS door was closed and the rest of the eye calibration was monitored from the GSOS control room. During the nine-point eye calibration, the pilot scanned most of the GSOS instrument panel while his head remained still. A calibration was considered successful if the calculated gaze was no more than 1° off at any single point (and less than that on average). Typically, the calibration had to be repeated one or more times while the operator optimally adjusted the illumination and sensitivity of the infrared camera. Initial calibrations were successful on 98% of flights; however, many eye-movement records were later discarded because either the pupil or corneal images were lost for more than 15% of the samples during the flight or on visual inspection there was too much variable drift in the eye-movement record from the beginning to the end of the flight (see below).

The eye-movement data collected during each of the seven segments corresponded mostly with the periods in which flight performance data were gathered. Unlike the flight performance data, however, the eye-movement data were recorded even while the pilot rolled down the runway in Segment 1 and they were recorded until touchdown in Segment 7. There were a total of 22 measures obtained from the eye-movement recordings. Five of these were basic measures: average pupil diameter, average blink rate, mean fixation duration (defined as eye position remaining within 1 *SD* [0.5°] for at least six consecutive samples, or 83 msec), average saccade length, and percentage of dwell times greater than 2 sec.[4] Unfortunately, saccadic velocity could not be measured by the Eye-Trac 6000 system because of the relatively slow head sampling rate. There were also 17 measures related to the pilot's instrument scan. These included the percentage of dwells on each of five flight instruments—the electronic attitude director indicator (EADI), airspeed indicator, altimeter, horizontal situation indicator (HSI, also known as the heading indicator), and the vertical velocity indicator (VVI)—as well as the percentage of dwells off the instrument panel altogether. There were also 10 measures of transitioning to and from the five flight displays as well as a measure of transitioning to and from the instrument panel as a whole. In determining the dwell and transition patterns for the five major flight displays, their outlines on the instrument panel space were mapped to the calibration space for the eye tracker and superimposed on the scan pattern from each flight, as shown in Figure 2.

For reasons that are unclear, there was a slight drift of gaze position relative to the calibration in most of the inflight eye-tracking records. However, the drift was almost always constant within a given flight, which allowed us to perform a single

[4]Dwell time refers to the amount of time spent continuously in one area of interest, whether in multiple fixations or not. The 2 sec criterion for long dwell times was based on the fact that, in preliminary data, less than 10% of all dwell times were greater than that value.

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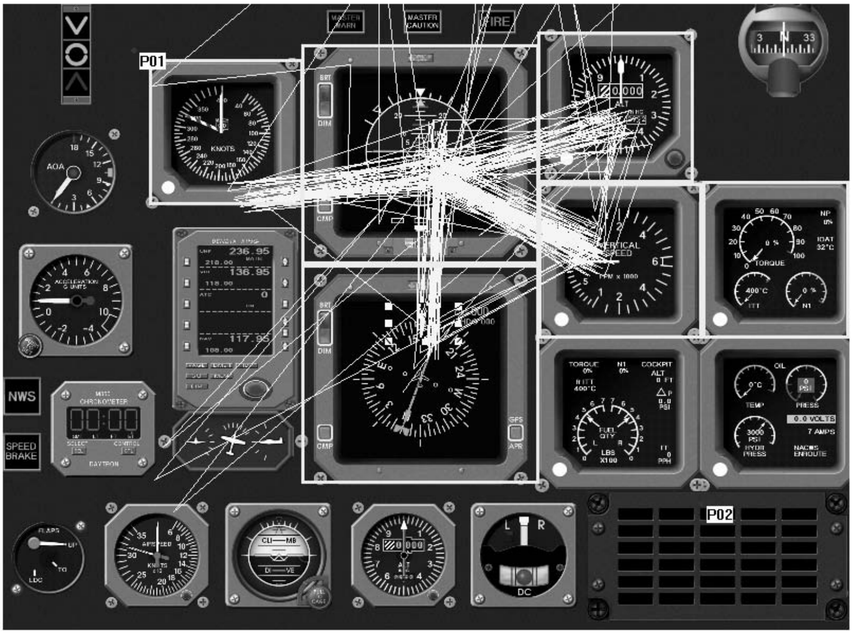

FIGURE 2 A representative scan pattern over an entire flight, with the outlines of the five designated flight instruments shown in white boxes.

recentering of the entire scan pattern for each flight prior to analysis and retain all but four records with excessive variable drift. The recentering was conducted by two of the experimenters (NL and WRE) before any data analysis was performed. Some records with variable drift but normal blink rates were retained for the basic oculomotor analyses, while other records showing blink rates greater than 1/sec (i.e., greater than 3 *SD* above our mean of 0.35/sec) were discarded from the basic oculomotor analyses but retained for the scan-pattern analysis. In the end, 71 of 100 records were retained for the scan-pattern analysis and 64 of 100 records were used in the basic oculomotor analyses, including at least two each from the early and late flights of 9 of the 10 pilots.[5]

EEG recordings and analysis. Electrodes were attached to each pilot after the final training session. Each placement site was cleaned with acetone, after which electrodes were attached to the scalp with collodion and then filled with

[5]Only one eye-movement record was salvageable from the tenth pilot, but it was not statistically analyzable because there were no other records from that pilot. Hence, all of that pilot's gaze data were discarded.

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electrolyte gel. After impedances were checked and determined to be at acceptable levels (< 5 KΩ), the EEG electrodes remained on throughout the entire 34 hr of continuous wakefulness.

Pre- and postflight resting EEGs were recorded for 4 min each, with the eyes open (2 min) and the eyes closed (2 min). Preflight EEGs were recorded in the GSOS control area just before the pilot's gaze was calibrated, whereas postflight EEGs were recorded immediately following each flight in the GSOS and monitored from the control station. In-flight EEGs were also recorded, but these were contaminated by the interaction of the eye tracker's magnetic pulse generator and the movement of the GSOS, as well as by pilots' eye and limb movements. Unfortunately, postflight data were not recorded properly for 19 of 100 flights, so that only the preflight resting EEGs were subjected to analysis, although one pilot with three missing records was removed even from that analysis.

A total of three 3-sec epochs, each selected because they were free of any obvious muscle or blink artifacts, were selected from each EEG record. EEGs from each electrode site and condition were analyzed separately for their Fourier amplitude in each of three bands: deltas (1.5–3.0 Hz), theta (3.0–8.0 Hz), and alpha (8.0–13.0 Hz).

Overall schedule. Pilots arrived the night before the beginning of the continuous wakefulness period for initial training on two versions of the flight profile (neither of which was embedded with spatial disorientation conflicts) and on three cognitive tests: the Psychomotor Vigilance Test (PVT), the Multi-Attribute Task Battery (MATB), and the Operation Span Task (OSPAN). These cognitive tests and their correlations with changes in flight performance during continuous wakefulness are described elsewhere (Lopez, Previc, Fischer, DaLuz, & Workman, 2009). During all training flights, pilots were outfitted with the head-mounted optical device and their gaze measurement was tested for its adequacy.

After their monitored sleep, pilots arrived back in the laboratory at either 0730 or 0830 and flew the GSOS profile for a final practice flight and received additional training on the cognitive tests. At midmorning on Day 1 of continuous wakefulness, each pilot had EEG electrodes attached and, after a period of rest and lunch, began the experiment. During an experimental session, two pilots were run in tandem, with Pilot 1's first flight beginning at 1200 and Pilot 2's first flight beginning at 1300. Successive flights were run at 3-hr intervals (i.e., 1500, 1800, 2100, etc., for Pilot 1; 1600, 1900, 2200, etc., for Pilot 2).[6] Pilots arrived 5 min prior to each flight so their resting EEG could be recorded and their eye-tracking calibration completed, and they remained 5 min following each flight for the postflight resting EEG measurement. The complete sequence of flights is shown in Table 1.

[6]Because the flight times were staggered by 1 hr for the two pilots, the session times in the data figures (next section) are listed as 1230, 1530, 1830, and so on.

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TABLE 1
Schedule of Test Flights for Different Pilots

Flight No.	*Type*	*Pilot 1 Start*	*Pilot 2 Start*
1	Right conflict	1200 (Day 1)	1300
2	Left nonconflict	1500	1600
3	Right nonconflict	1800	1900
4	Left conflict	2100	2200
5	Right nonconflict	2400	0100 (Day 2)
6	Left nonconflict	0300 (Day 2)	0400
7	Right conflict	0600	0700
8	Left nonconflict	0900	1000
9	Right nonconflict	1200	1300
10	Left conflict	1500	1600

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Immediately after completing a flight, each pilot went to a testing area where he completed two subjective fatigue surveys: the Profile of Mood States (POMS) (McNair, Lorr, & Droppleman, 1981), a 65-question survey that scales on six dimensions (tension-anxiety, depression-dejection, anger-hostility, vigor-activity, fatigue-inertia, and confusion-bewilderment), and the Visual Analog Scale (VAS), a computerized scale involving ratings of various dimensions (alertness, anxiety, energy, confidence, irritability, jittery, sleepy, and talkative) with a line and pointer (Penetar et al., 1993). Afterward, pilots underwent testing on the PVT, MATB, and OSPAN.

RESULTS

Subjective Fatigue Ratings

Only the two most direct measures of subjective fatigue—the POMS fatigue-inertia and VAS sleepy scales—were subjected to statistical analysis. The POMS fatigue and VAS sleepiness ratings are shown in Figure 3. The two measures paralleled each other fairly well, although their correlation was not especially high (r = .58). Pilots reported little subjective fatigue or sleepiness over the first four flights, a large increase in fatigue or sleepiness over the next two flights (i.e., in the early morning hours), and continued high subjective fatigue over the final four flights. Analyses of variance (ANOVAs) using Huyn–Feldt corrections for sphericity violations were performed using SPSS (Chicago, IL). Both the POMS fatigue and VAS sleepiness measures varied highly significantly across sessions, $F(1.49, 13.99) = 18.94$, $p < .001$, for POMS; $F(4.24, 38.16) = 27.84$, $p < .001$, for VAS. Increases in both measures occurred beginning with Session 4, with Sessions 4

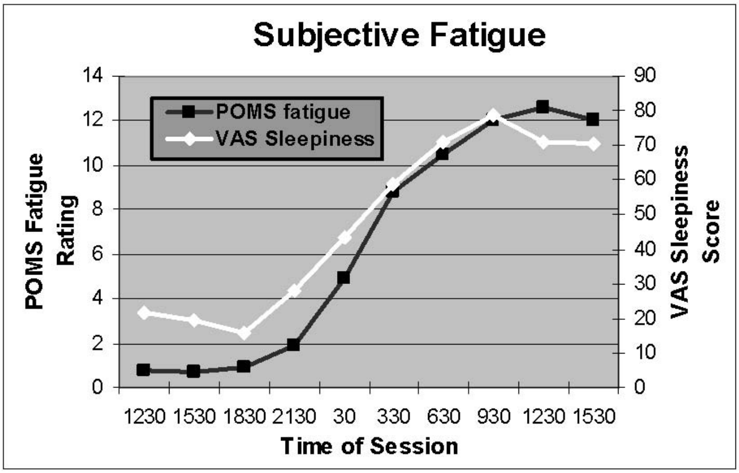

FIGURE 3 Subjective fatigue across 10 flight sessions, as easured by the POMS fatigue scale and the VAS sleepy axis.

through 10 all deviating significantly from baseline (Session 1) for the POMS and Sessions 5 through 10 deviating significantly relative to baseline for the VAS.

Flight Performance

The changes in the composite RMSE during the continuous wakefulness interval are shown in Figure 4. A slight improvement in flight performance occurred over the first five flights, which was followed by a sharp increase in RMSE in the early morning hours that leveled off slightly during the daytime hours on Day 2. The early-morning increase in RMSE was steeper than the rise in subjective fatigue and was slightly delayed relative to it. Despite the decrease in precision flying performance during the final five flights, gross flight errors requiring GSOS operator intervention were fairly rare and occurred no more than three times in any session (summed across all pilots), except for the first session in which six flight corrections were made.[7] Overall, an approximate 25% decrement in performance oc-

[7]It is conceivable that greater flight performance decrements could have occurred in transitioning from one flight segment to another, as we only measured flight performance once the criteria (e.g., a certain bank angle, heading, or airspeed) for entering a maneuver had been met. Fatigue-induced degradation in pilot performance could have prolonged the time required for a pilot to achieve the proper parameters initially and thereby would have been reflected in the total of amount of in-flight data collection time relative to the total time of flight. However, the percentage of data collection time lost due to transitioning varied only slightly across the 10 sessions, from a high of 51.3% in Flight 1 to a low of 48.8% in Flight 2.

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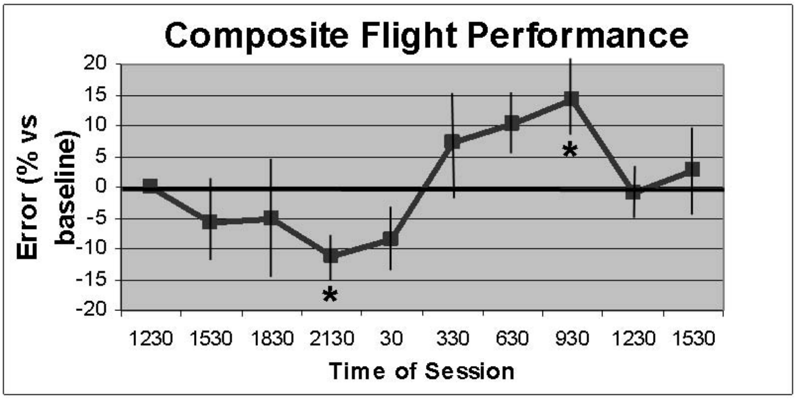

FIGURE 4 Composite log RMSE, converted to percentage relative to baseline (Flight 1), as a function of flight session. *$p < .05$.

curred from the peak performance in Session 4 (1230) to the maximum deficit that occurred in Session 8 (0930). However, this effect masked large individual differences, with three pilots showing a slight reduction in error from the five early to five late flights and two pilots (both of whom showed at least one documented in-flight microsleep) showing decrements of over 30%.[8] The individual differences in fatigue susceptibility did not appear to be related to the recent sleep history as measured by FAST, given that that FAST scores showed essentially no correlation ($r = .03$) with the change in RMSE from the first five to the last five flights. Nor did the age of the pilot predict the increase in RMSE with fatigue ($r = .10$).

A repeated-measures ANOVA, using log RMSE, was performed for the composite flight performance score across the 10 flight sessions. According to Mauchly's test, no correction for sphericity violation was required, $p = .32$. The effect of session was only marginally significant, $F(9, 81) = 1.85$, $p = .07$, partly because not all flight parameters comprising the composite score were significant (see later). Individual pairwise comparisons revealed that only Flights 4 and 8 differed significantly from the baseline flight, with Flight 4 producing a lower mean RMSE ($p = .03$) and Flight 8 producing a higher mean RMSE ($p = .04$).

In addition to the analysis of composite flight performance, four individual flight parameters (airspeed, heading, vertical velocity, and bank) that were measured in at least three of the seven segments were subjected to individual ANOVAs. Figure 5 shows that the change in performance was greatest for vertical velocity and least for bank control. Using Huyn–Feldt corrections for violations of

[8]Microsleeps were determined visually (e.g., prolonged eye closure) and were rare overall in that only six instances in three pilots were recorded during the course of the entire study.

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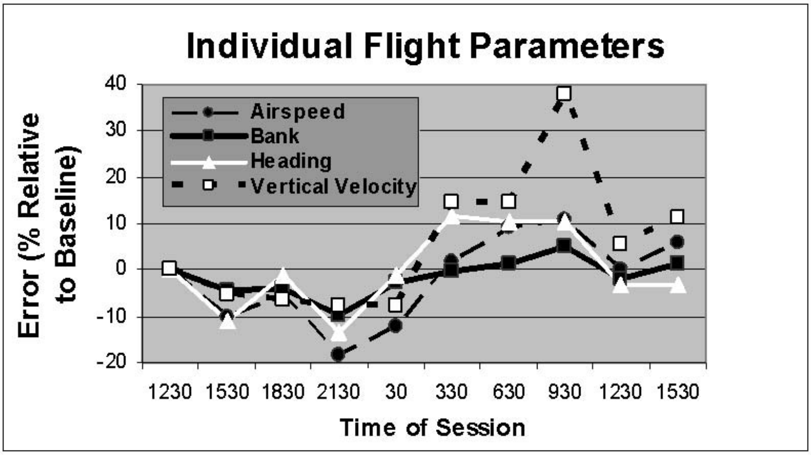

FIGURE 5 Log RMSE, converted to percentage relative to baseline (Flight 1), for airspeed, vertical velocity, bank and heading across flight session.

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sphericity, the individual ANOVAs for each of the four flight parameters revealed that vertical velocity varied significantly across the 10 flight sessions, $F(8.88, 79.99) = 2.95$, $p = .005$, as did airspeed, $F(6.36, 57.25) = 2.45$, $p = .033$. Performance differences across sessions for heading and bank were nonsignificant, $p = .75$ and $p = .84$, respectively.

Eye Movement Analyses

Although 29% of the eye-scan records were excluded from the scan analysis because of various artifacts, the remaining data appeared to be highly valid. For example, the dwell time percentage for each of the five instruments and the off-panel locus were consistent with the type of maneuver being performed (Figure 6). The percentage of overall dwell time away from the instrument panel was greatest for the visual approach, second-most for the takeoff, and third-most for the segment in which pilots briefly looked for traffic. Dwelling on the EADI, meanwhile, was greatest in the three turning maneuvers (Segments 2, 4, and 6), and VVI dwell percentages were greatest in the four climbs and descents in which a specific vertical velocity was mandated (Segments 2, 3, 5, and 6). Overall, pilots were strikingly consistent in their scanning behavior; for examples, the dwell percentage on the EADI across pilots ranged from 43% to 57% ($M = 48.8\%$) and the mean percentage of transitioning to and from the EADI as a percentage of all instrument transitions ranged from 61% to 76% ($M = 69.8\%$).

Because only two pilots had usable eye-movement data from all segments, and because of the sharp demarcation in flight performance between the first five

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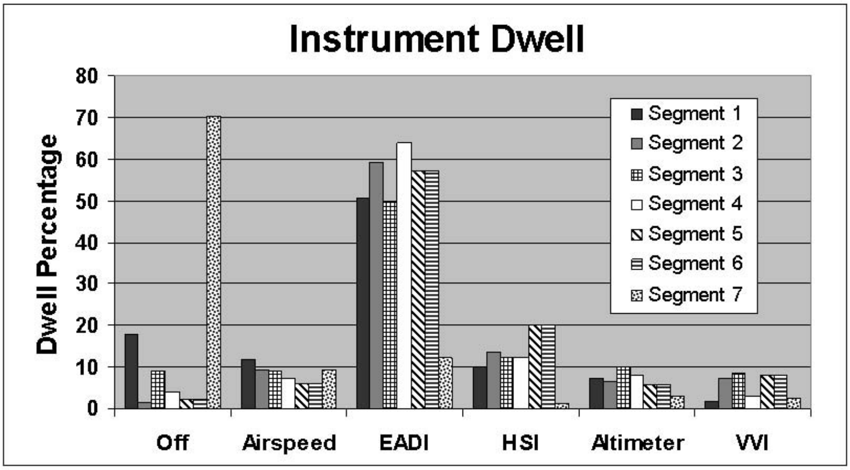

FIGURE 6 Percentage of overall dwell time spent on each flight instrument (as well as away from the instrument panel) for each of the seven flight segments, averaged across data from 10 flights and nine pilots.

flights and the last five flights (see Figure 3), eye-movement measures were collapsed across the five early flights and the five late ones. The differences between the early and late averages were then analyzed by a set of paired *t* tests, one for each of the 22 eye-movement parameters. Overall, the instrument scanning patterns for each pilot were remarkably similar for the early and late flights, and even slight idiosyncrasies in the scanning pattern for each pilot were similarly evidenced in both the early and late flights (Figure 7). The average amount of time spent on the five major flight instruments (the EADI, airspeed indicator, altimeter, HSI, and VVI) never differed by more than 12% in any individual case from the early to late flights, and only 2 of the 10 transitional probabilities among the five instruments differed by more than 10% from the early to late flights. Of the 22 measures, only 2 turned out to significantly differ from the early to late flights: percentage of dwell time on heading, $t(8) = 2.41$, $p = .04$, and transitioning between the HSI and the EADI $t(8) = 3.25$, $p = .01$. However, the actual early–late differences in these measures were very slight, with the HSI dwell percentage increasing only from 11.87% to 12.48% and the HSI–EADI transition percentage increasing only from 20.25% to 20.86%. Had a more conservative *p* value been used to account for the large number of tests performed, neither of these differences would have been significant. No dwell or transition measure achieved statistical significance for the VVI and airspeed indicator, the flight instruments associated with the largest and second-largest changes in RMSE across sessions. However, the two numerically greatest decrements in transitioning from the early to late flights both

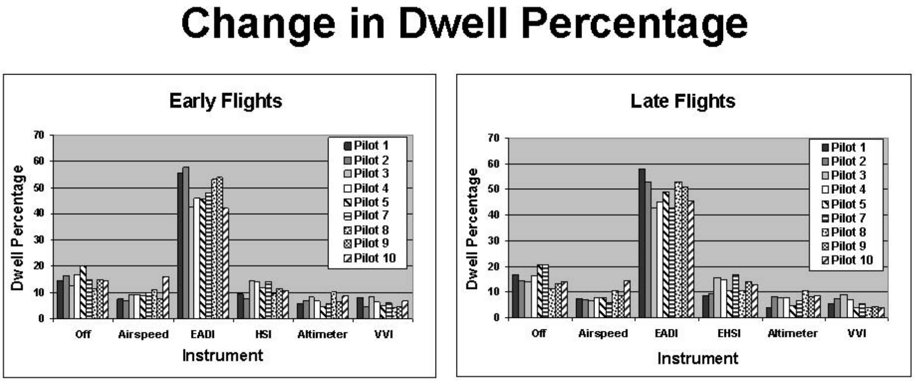

FIGURE 7 Change in percentage of dwell time for each individual pilot on each flight instrument (and away from the instrument panel), from the five early to the five late flights.

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involved the VVI, a 32.68% reduction in airspeed–VVI transitioning and a 30.1% drop in HSI–VVI transitioning.

It should finally be noted that no basic eye-movement parameter of interest (blink rate, pupil diameter, average fixation time, average saccade length, and percentage of long dwells) even approached significance (p = .31, .16, .22, .70, and .48, respectively). In the case of blink rate, the lack of significance was due less to the overall increase (18%) in the blink frequency in the later flights than to the enormous variability in blink rate change. Six of the nine pilots showed increases of 50% or more in their blink rate, including one who had an increase of 163%, whereas two pilots showed very little change and one pilot even showed a decrease of more than 50%.

EEG Analyses

The preflight resting EEG records were analyzed by means of six separate repeated-measures ANOVAs for each of the electrodes (P_z and C_z) and each of the three EEG bands (delta, theta, and alpha). Each ANOVA had two factors: eyes closed versus eyes open, and flight session (1–10). According to Mauchly's test, serious violations of sphericity occurred for flight session and the flight session by eyes closed–open interaction, so Huyn–Feldt corrections were performed in these cases.

Generally, alpha decreased as the period of wakefulness increased, whereas delta and theta activity increased (see Figure 8). The effect of flight session was significant only for theta and alpha at P_z, however: P_z alpha, $F(3.07, 24.54) = 3.13$, $p = .04$ and P_z theta, $F(6.30, 50.42) = 2.35$, $p = .04$. Across flights, the correlation between P_z alpha and theta (both averaged across eyes-open and eyes-closed con-

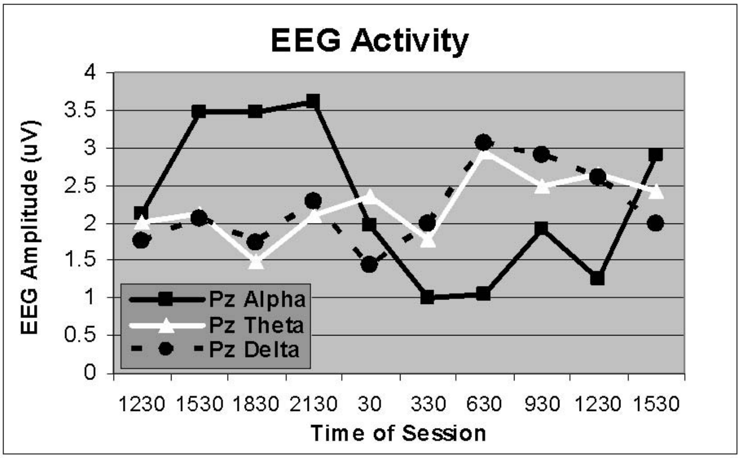

FIGURE 8 The amplitude, in μV, of P_z alpha, theta, and delta EEG activity over 10 sessions.

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ditions) was –.49. There were also significant eyes-closed versus eyes-open effects for C_z theta, $F(1, 8) = 9.36$, $p = .016$, and P_z theta, $F(1, 8) = 5.98$, $p = .04$, both of which reflected higher theta amplitudes when the eyes were closed.

DISCUSSION

The results of this study demonstrate that over 30 hr of continuous wakefulness degrades flying precision in a simulator. This effect proved highly variable across pilots and was not correlated with a deterioration in instrument scanning. In fact, instrument scanning was remarkably unaffected by the pilots' sleep deprivation, which otherwise produced a large increase in subjective fatigue, fatigue-related changes in EEG activity, large decreases in vigilance and cognitive capability (see Lopez et al., 2009), and, of course, degradation of flight performance.

The flight performance deficits began in the early morning hours and peaked at 0930 before waning by noon on the second day. The increased flight error in the early morning hours of the second day was paralleled by an early-morning decline in EEG alpha activity and early-morning peaks in subjective fatigue (as measured by the VAS) and EEG theta activity, all of which exhibited their maximum changes at 0630 or 0930. The subsequent rebound in flight performance suggests that flight performance was affected not only by sleep deprivation but perhaps by the circadian cycle as well. Whether the rebound in flight performance reflected a genuine increase in mental alertness or merely an anticipation of the impending completion of the experiment is not entirely clear, but it should be noted that neither EEG activity nor subjective fatigue ratings rebounded as much as flight performance in the final two flights.

The peak increase in flight error occurred at approximately the same time as for the helicopter pilots in Caldwell et al. (2003) and the F-117 pilots in Caldwell et al. (2004), although the decrements in the latter study began later and continued longer than in either Caldwell et al. (2003) or this study. The difference between the time courses thus appear less related to the type of aircraft flown than to the specific schedules normally flown, because the F-117 pilots in the earlier study normally began their daily schedule later. Another difference between Caldwell et al. (2004) and this study is the later occurrence (at 1330 on Day 2) of their peak EEG changes and the fact that EEG delta activity (unlike theta) did not vary significantly across flight session in this study.

The magnitude of the flight performance deterioration was not large, even at its peak (only about 15%). This was less than in some previous studies, which have shown deficits of up to 45% (Caldwell et al., 2004), and it is less than the 25% reduction in cognitive capacity predicted by the FAST model with one night of sleep deprivation (Eddy & Hursh, 2001). However, the deficit did approximate 25% when compared to the peak of flight performance, which was 10% better than baseline on the fourth flight in the late evening. The best explanation for the improved performance leading up to the early evening hours on the first day was that continued training on the flying task occurred, despite the three training flights and additional free-flying provided during training and familiarization sessions. The “practice effect” is further supported by the fact that neither subjective fatigue ratings (Figure 3) nor EEG alpha and theta (Figure 8) showed a similar trend over the first four sessions. It is worth noting that the MATB, the only one of the three cognitive measures reported by Lopez et al. (2009) to show a similar improvement in the late evening hours of the first day, also required the most training and probably evidenced a similar practice effect.

The segments in which most of the microsleeps were observed and which were most problematic in terms of flight error were those with long wings-level climbs and descents. The fact that bank control was much less severely affected by sleep deprivation than was vertical velocity, which was commanded during the wings-level climbs and descents, indicates that pilots might have been able to increase their arousal level somewhat while turning. So, it might be important to instruct pilots that not all maneuvers are equally problematic from the standpoint of fatigue.

The decline in flight performance, which equaled 25% from Flight 4 to Flight 8, was significant overall but it masked very large differences among individual pilots. For example, the mean percentage change in RMSE was 4.8% from the five early to the five late flights, but two pilots showed changes of greater than 30% and three pilots actually showed improvements in flight performance from the early to later flights. The existence of individual differences in “fatigue resistance” has

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long been noted in the literature and has been attributed mostly to recent sleep history (Caldwell et al., 2005; Neville, Bisson, French, Boll, & Storm, 1994), baseline arousal (Caldwell et al., 2005), or personality factors such as introversion that may be linked to higher levels of baseline arousal (May & Kline, 1987; Smith & Mabien, 1993). Although we did not observe any correlation between flight performance decrements and recent sleep history as measured by FAST, it should be stressed that the data concerning sleep length and quality that we entered into the FAST model were based on pilots' self-reports and not on objective measures. One variable that clearly did not affect flight performance during sleep deprivation was the age of the pilot, based on the very small correlation between pilot age and the change in RMSE from the early to late flights.

The eye-movement results, in terms of both basic eye-movement parameters and instrument scanning, proved somewhat unexpected. Contrary to the previous literature, we did not observe changes in any basic eye-movement parameter even though our average values were comparable to others. For example, our average blink rate across all flights was 0.35/sec, which is highly comparable to the 0.33/sec considered normal for humans (Karson, 1988); our average pupil diameter was 4.79 mm as compared to the ~5.0 mm for Russo et al. (2003); and our average fixation duration of 435 msec was in the range of that reported by Ellis (1986) and was only slightly less than the average fixation duration (~600 msec) reported by Jones et al. (1949) and Bellenkes et al. (1997). The lack of significance of the oculomotor sleep deprivation effects could have been caused at least in some instances by the large variability across pilots in their early versus late oculomotor behavior. For example, the third-largest percentage change from the early to late flights occurred in blink rate, which increased from a mean of 0.32/sec to a mean of 0.37/sec, but the blink rate changes ranged from a decline of 52% to an increase of 163%, with seven of the nine pilots showing increases. The lack of change in pupil diameter, which is inconsistent with most previous findings (Morad et al., 2000; Ranzijn & Lack, 1997; Wilhelm et al., 1998; Yoss et al., 1979), could have partly been due to the fact that our pilots flew under low-to-moderate illumination, whereas previous measurements have usually been made in the dark.[9]

The resilience of instrument scanning during the extended wakefulness period proved highly surprising, given the altered scanning reported by others during sleep deprivation (e.g., De Gennaro et al., 2000), the large increase in subjective fatigue (Figure 3), and the precipitous declines in flying precision (Figure 4) and cognitive performance (Lopez et al., 2009). The remarkable similarity in instrument scanning from the early to late flights did not occur because our measurements were unreliable or of poor validity. Indeed, the overall scanning parameters in this study were consistent with those of other studies (e.g., our pilots looked

[9]In total darkness, for example, baseline pupil diameter typically runs between 7.0 and 7.5 mm (Wilhelm et al., 1998; Yoss et al., 1979), which would have allowed more room for decrease.

~50% of the time at the EADI, as opposed to ~60% in Itoh et al.'s 1990 study of commercial airline pilots) and remarkably consistent across pilots, with similar idiosyncrasies appearing in both the early and late flights (Figure 7). The scanning patterns were also sensitive to the expected demands of particular flight segments, with fixation on the EADI greater during turning and fixation on the VVI greater during climbs and descents (Figure 6). Hence, the maintenance of normal scanning after extended wakefulness associated with high subjective fatigue suggests that instrument scanning, even in pilots recently graduated from USAF undergraduate pilot training, is a highly practiced behavior that is resistant to fatigue. The maintenance of apparently normal instrument scanning is consistent with the fact that susceptibility to Type I spatial disorientation, which increases when pilots break their instrument cross-check (Previc & Ercoline, 2004), did not significantly increase from the early to later flights in our pilots (see Previc et al., 2007).

Hence, the deterioration in flight performance during fatigue, either generally or for specific instrument parameters such as airspeed and vertical velocity, was more likely caused by impaired information processing and decision making rather than by a change in scanning behavior per se. This explanation is consistent with the deterioration of cognitive processing observed in our pilots and the good correlation between fatigue-induced cognitive deficits and flight-performance decrements (Lopez et al., 2009). Although dwell times and transitioning involving the VVI—the most affected instrument in terms of flight performance changes—were somewhat more affected by sleep deprivation than scanning of other instruments, even the VVI scanning trends were not significant.

In conclusion, the results of this study provide an important glimpse of pilot behavior during over 30 hr of extended wakefulness. Although most pilots can maintain reasonable flying precision during sleep deprivation, they appear to do so by relying on training that overcomes large increases in fatigue that substantially impair cognitive performance. For reasons that require further study, a minority of pilots appear less able to overcome their fatigue and consequently evidence microsleeps and more serious flight performance decrements. It is clear, however, that breakdowns in instrument scanning do not cause the deterioration in flying precision, but that the ability to maintain normal scanning in the face of high fatigue and cognitive decline might actually prevent flying performance from deteriorating as much as general cognitive function.

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