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Effects of sleep deprivation on cognitive performance by United States Air Force pilots

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ABSTRACT

This study examined the effects of 35 h of continuous sleep deprivation on performance in a variety of cognitive tasks as well as simulated flight. Ten United States Air Force pilots completed the Multi-Attribute Task Battery (MATB), Psychomotor Vigilance Task (PVT), and Operation Span Task (OSPAN), as well as simulated flight at 3 h intervals over a 35 h sleep deprivation period. Performance declined on all tests after about 18–20 h of continuous sleep deprivation, although the degree to which performance degraded varied. During the second half of the sleep deprivation period, performance on the simulated flight was predicted by PVT and OSPAN reasonably well but much less so by the MATB. Variance from optimal flight performance was predicted by both PVT and OSPAN but each measure added incremental validity to the prediction. The two measures together accounted for 58% of the variance in flight performance in the second half of the sleep deprivation period.

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In August of 1997 a Korean Airline 747 in good working order flew into a hillside in Guam killing all 227 people aboard. The investigation concluded that the accident occurred because of reduced situation awareness on the part of the pilot leading to 'controlled flight into terrain'. The pilot was apparently unaware of the mountain in his path. But why would an experienced senior pilot make such an error? One possible reason is fatigue. As noted in one account of the accident, "Prior to the flight to Guam he had flown from Seoul to Australia, back to Seoul, then to Hong Kong, and then back to Seoul again before his fateful trip to Guam, all with only a few hours of rest." (http://www.airlinesafety.com/editorials/PilotFatigue.htm). Though this paper will focus on the aviation industry, assessment and prediction of effects of fatigue and sleep deprivation on performance of complex multi-tasks is a quite general issue.

The effects of fatigue on performance have long been a safety concern to terrestrial and air transportation, medicine, and industrial settings such as nuclear plants. Between 1974 and 1992, 25% of major mishaps involving US Air Force tactical fighter jets and 12% of US Navy major mishaps involved fatigue as a contributing factor (Ramsey & McGlohn, 1997). Fatigue played a role in over 12% of all US Air Force mishaps (Luna, 2003) and is a recurring concern throughout the aviation industry (Caldwell, 2005). Caldwell and Gilreath (2002) surveyed Army aircrew personnel, who reportedly worked an average of 65 h per week but obtained only 6.4 h of sleep per night. In the absence of sufficient sleep, response accuracy and speed degrades, and aircrews are more likely to lower their standards of performance, suffer impairments in the ability to integrate information, and experience a reduced attention span that may lead to forgetting or ignoring important aspects of flying (Perry, 1974). Therefore, it is important to better predict when personnel are likely to experience fatigue-based decrements using quick and easy-to-administer cognitive tests.

Various studies have shown significant performance decrements on basic cognitive tasks in fatigued subjects (Caldwell et al., 2003; Dinges et al., 1997; Matthews, Davies, Westerman, & Stammers, 2000). And, there is great potential for using such tasks to predict when a fatigued individual might be prone to performance decrements on real-world tasks such as flying airplanes or driving long-haul trucks. However, the extent to which simple cognitive tasks can be used to predict performance decrements on real-world tasks remains unclear. Caldwell et al. found physiological measures obtained from eye tracking and EEG are often difficult and expensive to incorporate into real-world military missions. Further, those measures do not appear to reliably predict fatigue decrements or performance on criterion tasks. Even if they were

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more reliable or more valid, there is little connection between the theoretical constructs underlying those assessments and error in the real-world tasks.

However, several cognitive tasks do have promise. One is the Multi-Attribute Task Battery (MATB) (Comstock & Arnegard, 1992), a computerized aviation simulation test. This test has been considered desirable because of its complexity, face validity, and sensitivity to fatigue (Caldwell et al., 2003; Caldwell & Ramspott, 1998). MATB tracking accuracy may also have the ability to predict flight performance changes since Caldwell et al. found it significantly related to changes in overall flight performance accuracy after 37-h of continuous sleep deprivation.

A test widely used to assess fatigue in the aviation industry is the Psychomotor Vigilance Task (PVT) developed by Dinges and Powell (1985) (see also Lim & Dinges, 2008). This test typically involves a visually presented object that periodically changes and the subject's task is to rapidly indicate when each change occurs. For example, one typical object is a display of zeros either on a computer screen or wrist-worn display that suddenly begin counting up each millisecond and the subject is to press a button as quickly as possible to keep that number as small as possible. The logic behind the task is that if fatigue leads to a lapse of attention it should be reflected by slowed responding to the change in the stimulus event. In fact, performance on the PVT has been shown to reliably decline with reduced sleep (Dinges et al., 1997; Kamdar, Kaplan, Kezirian, & Dement, 2004; Russo et al., 2005; Whitmore et al., 2004). The PVT also reflects reliable individual differences in putatively rested individuals (Unsworth & Spillers, 2010). The PVT has rapidly become somewhat of a 'gold standard' for measuring fatigue in aviation studies but there still is much that we do not know about the task and what it measures. While there is considerable literature showing that detection time on the PVT degrades with sleep deprivation, there is a scarcity of work showing the relationship of those measures with performance on real-world tasks. Further, there is a dearth of published studies comparing the PVT with other potential measures of cognitive fatigue and how they predict performance on real-world tasks.

The Operation Span Task (OSPAN; Unsworth, Heitz, Schrock, & Engle, 2005) is a test which measures cognitive control aspects of working memory. While the OSPAN has been used to assess abiding trait-like aspects of cognitive control, it also reflects momentary state-like aspects of cognitive control and self-regulation (see Ilkowska & Engle, 2010, for a review). There is reason to believe that working memory performance as measured by the OSPAN may correlate well with flight performance during fatigue. General cognitive ability is the best predictor of pilot and navigator overall performance (McHenry, Hough, Toquam, Hanson, & Ashworth, 1990; Olea & Ree, 1994; Ree & Earles, 1991; Ree, Earles, & Teachout, 1994). Further, there is an extensive literature showing a strong relationship between working memory capacity and fluid intelligence (Engle & Kane, 2004; Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004; Kyllonen & Christal, 1990). Whether these findings in the absence of systematic sleep deprivation are related to performance under conditions of fatigue is yet to be determined. The purposes of this study were to (1) investigate overall changes in performance in fatigued USAF pilots, and (2) compare different cognitive tests as predictors of flight performance over a period of continuous sleep deprivation.

Method

Ten male active-duty, reservist, or retired pilots for the USAF served as subjects after signing an informed consent agreement that detailed the procedures of the study. The mean age of the pilots was 34 years, ranging from 23 to 46 years old. All subjects were screened for near-vision acuity, vestibular function, and eye tracking quality prior to their participation. The subjects reported an average of 2805.7 total flight hours (ranging from 207 to 5000 h). Subjects self-reported an average of 7.46 h of sleep per night the week prior to the study. None were taking any type of medication known to impact mental alertness (i.e., sedating antihistamines, sleep medications, prescription stimulants, etc.) nor were they heavy nicotine (>1 cigarette per day) or heavy caffeine (>100 mg of caffeine per day) users. Subjects completed the study in groups of two. Subjects were compensated for their participation.

Apparatus

This study was conducted in the Aviation Sustained Operations Laboratory at Brooks City-Base, Texas. In addition to the cognitive tests and flight performance measurements described in this paper, EEG and eye tracking data were collected in the Gyroflight Sustained Operations Flight Simulator (Environmental Techtonics Corp., Southampton, PA). Methodology for EEG and eye tracking movements are discussed in detail in a companion paper (Previc et al., 2009). Flight performance measurements were collected in the flight simulator. The cognitive measures were collected on desktop computers in a sound-attenuated testing room as were two additional measures of subjective fatigue: the Profile of Mood States (POMS) (McNair, Lorr, & Droppleman, 1981) and the Visual Analog Scale (VAS) (Penetar et al., 1993). Subjective measures of fatigue are discussed in detail in Previc et al. (2009).

Multi-Attribute Task Battery (MATB)

The MATB (Comstock & Arnegard, 1992) is a computerized aviation simulation test that required subjects to perform an unstable-tracking task with a joy stick while concurrently monitoring warning lights and dials, responding to computer-generated auditory requests to adjust radio frequencies, and managing simulated fuel flow rates (using various key presses) for 30 min.

Data on tracking errors, response times, time-outs, false alarms, and accuracy rates were collected by means of the MATB processing software. However, only four MATB measures – communications reaction time, systems monitoring reaction time to dials, systems monitoring reaction time to lights, and tracking root mean square error (RMSE) – were analyzed because these measures are the only ones shown to be sensitive to fatigue in past studies (J.A. Caldwell, personal communication, 2006).

Operation Span Task (OSPAN)

On each trial of the automated version of the Operation Span Task subjects first see an arithmetic equation, then indicate whether an answer following the equation is correct, and finally they see a letter to remember for later recall (Unsworth et al., 2005). Three to seven such processing-and-storage presentations constitute a trial. After the trial, a recall grid is presented and subjects use a mouse to click on the letters they saw during the trial in correct serial order. To ensure subjects attended the math problems and did not rehearse the letters during that time, a 75% accuracy criterion was required on the math portion of the task. OSPAN produced an "absolute OSPAN score" (OSCORE) and a "total number correct score" (TSCORE). The OSCORE was the sum of letters in all sets of data for which the entire data string was recalled correctly. The TSCORE was the total number of letters recalled in the correct position, regardless of whether or not the entire set was perfectly recalled. Since a high criterion is used for the math problems the math score was not analyzed.

Psychomotor Vigilance Test

The PVT-192 (Ambulatory Monitoring, Inc., Ardsley, NY) is a portable hand-held device with a test requiring 10 min to

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