Visual Perception, Flight Performance, and Reaction Time Impairments in Military Pilots during 26 Hours of Continuous Wake: Implications for Automated Workload Control Systems as Fatigue Management Tools

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ABSTRACT

INTRODUCTION: Performance data from a visual perception task, complex motor flight task, and psychomotor vigilance task were evaluated in U.S. Air Force Pilots navigating a high-fidelity fixed-wing jet simulator over 26.5 hours of continuous wakefulness.

METHODS: Eight military pilots on flight status performed the primary task of flying a simulated 12.5-hour overnight mission in an Air Refueling Part Task Trainer (ARPTT). Response omission to presentation of single- and double-light stimuli displayed in random sequence across the cockpit instrument panel was the metric used to assess Choice Visual PerceptionTask (CVPT) performance. Deviation from an established azimuth heading in the ARPTT during the CVPT was the flight metric used to assess complex motor performance. Speed, lapse, false start, and anticipation were the metrics used to assess Psychomotor Vigilance Task (PVT) performance during crew rest periods.

RESULTS: Significant visual perceptual, complex motor, and psychomotor vigilance (speed and lapse) impairments occurred at 19 hours awake in the 8-subject group. CVPT response omissions significantly correlated with ARPTT azimuth deviations at r = 0.97, and with PVT speed at r = -0.92 and lapses at r = 0.90. ARPTT azimuth deviations significantly correlated with PVT speed at r = -0.92 and lapses at r = 0.91.

CONCLUSIONS: Acute sleep deprivation degrades visual perceptual, complex motor, and simple motor performance. Complex motor impairments in this task environment strongly correlate with visual perceptual

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impairments. This research provides support for the use of visual perceptual measures as surrogates of complex motor performance in operational situations where the primary cognitive inputs are through the visual system. This research supports the general notion that assessing visual system processes might be a component of cognitive monitoring systems that could potentially be applied to automated workload reduction systems.

1.0 INTRODUCTION

Real-time monitoring for cognitive performance capacity via an approach based on sampling multiple neurophysiologic signals and integrating those signals with performance prediction models, potentially provides a method of assessing decision-making and other operationally-relevant mental processes. Identifying and validating measures of cognitive performance, integrating them into models predicting operational performance, and optimizing the flow of information for decision-making is a goal of the US Army Medical Research and Materiel Command research program known as "Cognitive Performance, Judgment, Decision-making." Integrating validated neurophysiologic correlates of cognition into automated workload reduction algorithms is a goal of the Defense Advance Research Projects Agency Information Processing Technology Office program known as "Improving Warfighter Information Intake Under Stress" (Augmented Cognition). Augmented Cognition seeks to transform the human-machine interaction by making information systems sensitive to the individual warfighter's capabilities and limitations. The Augmented Cognition program seeks to utilize neurophysiologic measures in concert with workload reduction algorithms as part of an effort to improve information processing ability by an order of magnitude. Integrating varied physiological measures, prioritizing signal transmissions and information content for immediate consideration of intervention, and developing suitable algorithms to automatically engage workload reduction systems continue to be non-trivial issues receiving considerable investigation. The Cognitive Performance, Judgment, Decision-making research program intends to provide Augmented Cognition with operationally-relevant correlations among metrics, neurophysiologic indices, and operational performance under stress.

The goal of this paper is to describe relationships among visual information processing impairments and operational performance as they occur during sleep deprivation and in a high workload aviation environment for the purposes of integrating visual indices into future automated workload reduction systems. Visual perception during an air refueling mission was studied in an air refueling trainer for its sensitivity as a surrogate or marker of operational performance.

Research discussed herein was originally published in Russo et al. (2004), and Russo, Kendall, Johnson et al. (2005). This paper discusses the occurrence of the phenomena of visual neglect and correlations of neglect to patterns of performance on complex and simple cognitive tasks.

1.1 Visual Neglect Phenomenon

Visual neglect is a person's inability to recognize or acknowledge some visual information despite a structurally intact visual system. Visual neglect occurs if the visual stimuli are not fully or correctly processed by the parietal lobes, not forwarded to or processed by the thalamic relays, or not forwarded to or attended to by the prefrontal regions. Based upon clinical cases in patients with brain damage, parietal lobe dysfunction can result in patterns of impairment where primarily peripherally located visual stimuli are neglected, and one or more of several simultaneously presented visual stimuli are neglected (Balint, 1909; Russo et al., 1999). Due to the "executive" attentional focusing functions of the prefrontal regions, prefrontal dysfunction may result in a pattern of neglect to stimuli from all fields of visual regard.

The finding of visual neglect in patients with parietal lobe dysfunction is consistent with the findings of Thomas et al. (2000, 2003) who found hypometabolism in the parietal regions in a flurodeoxyglucose positron emission tomography (fdgPET) study of the effects of total sleep deprivation. Thomas et al. showed significant decreases in cerebral glucose utilization in brain regions responsible for visual attention and visual cognition in awake volunteers at 24 hours of continuous wakefulness. The prefrontal regions are involved in executive functions, such as prioritizing and selecting tasks, and maintaining attention on a selected task. The bilateral parietal regions are responsible for processing and interpreting visual information, developing complex visual-spatial relationships, appreciating multiple visual images simultaneously, and with aspects of eye movement.

Multiple studies investigated the deterioration of perceptual and oculomotor function under conditions of fatigue or extended wakefulness (Behar, 1976, De Gennaro, 2000). Studies that examined perceptual function reported a decrease in visual vigilance, visual acuity, visual detection and visual scanning (Hatfield, 1971; Lieberman, 1998), while studies that examined oculomotor function reported sympathetic-parasympathetic mediated fluctuations in pupil size, saccadic velocity, oculomotor fixation, and initial pupil diameter (De Gennaro, 2001). McLaren et al. reported decreased sleep latency and correlations with pupilometric variables (2002).

Several authors discussed relationships between impairments in visual perception and attentional processes in sustained task performance and prepared the foundation for exploration of visual perceptual impairments in sustained wake (Meeteren, 1983; Miura, 1986). Rogé et al., (2003) described a tunnel-vision phenomenon during total sleep deprivation in an automotive simulator. We recently described the occurrence and patterns of visual neglect beginning at 19 hours of continuous wake (Russo et al. 2004, 2005).

Researchers at Walter Reed Army Institute of Research, using a choice visual divided attention task during a driving simulator, reported a relationship between visual impairments and operational performance failure, with declines in recognition of the visual stimuli, and lapses and errors of commission beginning at 20 hours of continuous wake. While microsleep events (up to 15 seconds of Stage 1 theta) increased with sleep deprivation, the lapses rarely correlated temporally with operational performance, suggesting that the impairments observed were resulting from functional neural changes other than those attributable to frank sleep. These Walter Reed Studies lead to the design of our choice visual perception task to assess for possible visual neglect due to acute sleep deprivation.

Stern’s (1998) study of visual attentiveness in a truck simulator, using commercial drivers, showed eye-gaze shift impairments. The study examined divided attention in a moderate cognitive loading environment influenced by sleep deprivation. Results showed that sleep deprivation decreased the frequency of eye movements towards simulated side-view mirrors.

Studies using a restricted sleep design to assess vigilance and operational performance reported significant increases in reaction time and lapsing on a psychomotor vigilance task. In a sleep-dose response study where subjects received 3, 5, 7 or 9 hrs of sleep a night for 7 nights, Belenky et al. (2003) reported a decrease in response speed for the 3, 5 and 7 hr groups and an increase in lapses in the 3 and 5 hr groups. After 3 nights of recovery sleep, the 3, 5 and 7 hr groups did not return to baseline performance. In a 7-day sleep restriction study where sleep was restricted to 4-5 hrs per night, Dinges et al. (1997) reported that, by the second day, response time and lapses increased significantly from baseline. Another study, conducted by Doran et al. (2001), compared performance on a vigilance task between an 88 hour total sleep deprivation group and a group that received a 2-hour nap. Results showed that the 2-hour nap group sustained vigilance at baseline levels, whereas the total sleep deprivation group had an increase in reaction time and errors.

In the field of human factors-related aviation research, performance studies focused primarily on elucidating pilot flight performance decrements. Possible reasons why real-world flight performance decrements occur are less-than-optimal controls and displays, pilot over- and under-stimulation, loss of situational awareness, operations tempo- or workload-related fatigue, continuous wakefulness, time-zone crossings, and shift changes. Several authors have reported changes in visual motor systems but minimal discussion related these changes to performance impairments. Some authors studied the effects of pharmacological aids on reversing sleep-deprivation-induced pilot performance decrements. Caldwell et al. (1998, 2004) found that both modafinil and dextroamphetamine maintained performance and alertness in fatigued rotary wing pilots in simulated flights, even during the circadian trough. In a study of F-117 Stealth Fighter pilots in simulators, Caldwell et al. (2000) showed that modafinil improved mood and flying performance on some tasks as early as 20 hours of continuous wake, with greater gains seen from the stimulant with increasing periods of wake. A study conducted by Neri et al. (2002) investigated controlled waking rest-breaks as a countermeasure for the effects of fatigue. The treatment group exhibited decreased slow eye movement 15 minutes after break with no significant difference on objective vigilance when compared to the control group.

Paul et al. (2001) reported on the fatigue effects of pilots flying transatlantic flight re-supply missions. Administration of neuropsychological tests occurred during the transatlantic sortie. Results showed that performance decrements occurred over the three days of the transatlantic re-supply missions. Prior to the transatlantic flight, pilots reported an average of 8 hours 40 minutes of sleep, which decreased to 6 hours and 40 minutes of sleep during the flight sortie. Subjective measures of sleepiness also predicted flight performance decrements in fatigued pilots.

In a case study of how fatigue from the demands of the operational world can affect pilots' performance, Armentrout and Holland (2004) conducted multi-discipline investigations into a USAF large transport near-mishap where the pilots were so tired that they fully stalled the very large USAF transport aircraft on a dark, quiet night approach to an island. The pilots fell over 4,000 feet in their stalled and fully functional cargo aircraft during a mixed visual-instrument approach. Armentrout and Holland utilized information from a variety of sources (including pilot recollections) to show that the aircrew experienced a loss of situation awareness, channelized attention, and spatial disorientation-- with fatigue from days of sleep interruption as a critical over-arching enabler. The fatigued pilots did not fully appreciate the relevance of visual instrument panel indications of slowly deteriorating airspeed, vertical velocity increases, and an increasing angle of attack that lead to the stall condition. The pilots barely recovered the aircraft just 773 feet above the water's surface after passing through more than 90 degrees of wing bank twice during the ensuing free-fall of the stalled condition. This case study highlighted that fatigue can directly affect not only the ability to adequately process and integrate a wide variety of stimuli, including visually-presented information, but also that fatigue increases the chance that reductions in situation awareness will occur. This reduction can impede flying safety under some scenarios due to the brain's inability to process and integrate information from disparate sources into a meaningful, relevant whole with regard to the state of the aircraft.

Regarding perceptual and operational performance in aviation research, Behar et al. (1976) and Morris and Miller (1996) noted different results in visual impairment and its relation to flight performance. Behar reported that although oculomotor decrements occurred in the pilots (n=4) , their ability to sustain flight performance remained unaffected by fatigue under the conditions tested. Morris and Miller, however, showed that flight performance impairments correlated with long eyelid closures and increases in blink amplitude in a simulator study of military pilots under conditions of extended wake. Differences in results could be due to length of sleep debt period and familiarity with the simulator. This leads to the question of visual impairment being a possible predictor for flight performance decrements.

In the aforementioned studies, the visual measurements used did not measure fixed visual deficits, but rather transient attentional deficits under a moderate cognitive loading environment. We demonstrated visual neglect in U.S. Air Force pilots beginning at 19 hours of continuous wake. The visual neglect preceded and correlated with shutdowns of the fixed wing simulator due to erratic flying. Impaired flight performance began at 21.5 hours of continuous wake. The present paper is an extension of Russo et al. (2004) and reports on the relationship between visual perception and motor performance (complex: deviations from an established course heading; and simple: psychomotor vigilance) under conditions of high cognitive loading and modest sleep deprivation (across 26.5 hours of continuous wakefulness). The high cognitive loading environment is created by the complexity of the primary task: flying a simulated C-141 aircraft at approximately 275 knots and within approximately 30-50 feet of a KC-135 air tanker.

2.0 EXPERIMENTAL DESCRIPTION AND METHODS

2.1 Task Description

This study evaluated visual perception and motor performance in U.S. Air Force pilots in a simulated overnight aerial refueling flight, following a day of continuous wake (Russo et al., 2004; Russo et al., 2005). Although pilots do not normally fly long missions after a day-long period of wakefulness, this design was selected to reflect a possible course of action available to military commanders and planners in times of high operational tempo. Because pilots often have only seconds to interpret and act upon visual information, small visual errors or neglect occurring over brief periods of time could possibly result in catastrophic mission failures. Indeed, two C-141 starlifters collided several years ago while aerial refueling with the loss of both aircraft and all lives on board, resulting in a high level of interest in the perceptual and situation awareness aspects of aerial refueling.

A choice visual perception task (CVPT) was designed and integrated into a U.S Air Force C-141 simulator cockpit to assess for possible impairments in a high cognitive loading environment. The simulator used in this study was an Air Refueling Part Task Trainer (ARPTT). The non-digital visual representation of high-fidelity dynamic motion KC-135 and KC-10 tanker models is reported to be as realistic as flying behind a real tanker under dusk and night-time simulator conditions. Pilots who use this simulator routinely to train for actual aerial refueling operations say flying behind this extremely realistic looking aircraft in the simulator is very compelling and is about as difficult as the real world task (personal communication with pilots). **Figure 1** shows (left frame) a view from the cockpit of the ARPTT and (right frame) a view from the cockpit of an actual U.S. Air Force C141.

Figure 1: View from Air Refueling Partial Task Trainer (left frame) and Actual C141 (right frame).

2.2 Subjects

Eight right-handed male pilots between the ages of 31 and 52 years old (mean age 37 years) from the 305th and 732nd Air Mobility Command Wings, McGuire Air Force Base, N.J, participated in this study. All volunteers were qualified to fly the C-141 airframe and the ARPTT. All were currently on flight status, indicating recent verification of good health, including visual and color acuity in accordance with Air Force Pamphlet 48-133, 1 June 2000, Chapter 5 (Visual Acuity Testing) and AFI 48-123, Attachment 7 (medical standards for flying duty) paragraph 7. Vision was tested using the Optec 2300 Vision Tester that assesses far vertical and far lateral phoria, distant visual acuity, fusion and depth perception. The pseudoisochromatic plate set (PIP) was used to establish normal color vision. Air Force pilots qualified on both the C-141 airframe and the ARPTT represented a small and geographically dispersed group of individuals. To increase the probability of obtaining qualified pilots, and to more closely reflect realistic operations, the investigators permitted the use of caffeine (<400mg/day) and nicotine in moderation. Thus, the risk of possibly introducing an uncontrolled variable was acknowledged, but pilots in the operational world often use caffeine or other stimulants on occasion, so this moderate caffeine use is rather generalizable to the real operational environment. Those on daily medications were automatically excluded.

Three of the pilots were active duty U.S. Air Force personnel, four were reserve U.S. Air Force personnel who primarily flew transcontinental and transoceanic flights for commercial airlines (United, US Airways, and American Airlines) on Boeing 747s, Boeing 777s, and Air France Airbus, and one was a reserve commissioned pilot on full-time active duty. Two of the commercial airline pilots and one of the active duty pilots were air-refueling instructor pilots. The eight pilots reported a mean of 7.75 actual refueling aircraft hours in the three months prior to the study with ranges from 0.5 to 30 hours. The eight pilots also reported a mean of 63.75 total simulator hours with ranges from 40 to 100 hours. The pilot volunteers were paid for their participation.

2.3 Measures

Complex motor performance was measured using an Air Refueling Part Task Trainer (ARPTT). The ARPTT is a U.S. Air Force high fidelity optical simulator configured to represent the cockpit of the C-141B (cargo) airframe and is used to train only the refueling component of an actual air-refueling mission. To refuel, the C-141B pilot was expected to maneuver into a prescribed position behind and below a KC-135 tanker aircraft.

The image of the KC-135 tanker was reflected into the forward visual field of the C-141B cockpit through a series of mirrors, and the relationship of the C-141B receiver aircraft to the moving KC-135 tanker was highly responsive to the controls of the simulator. The C-141B receiver aircraft was set to a gross weight of 240,000 lbs and programmed within the simulation to commence the flight scenarios at 190 ft aft and below the KC-135 tanker in a standard following distance. The KC-135 was programmed to automatically maintain an optimal altitude of 24,000 ft and airspeed of 275 knots. Throughout the study external conditions were dusk light, zero atmospheric turbulence, and 10 mile visibility. Internal cockpit conditions were set to dim light (260 Lux), full simulator motion effects for turbulence, and 70% engine and airflow sounds. The setting of 70% represented a realistic noise level by accounting for the cockpit and helmet sound attenuation properties.

Three flight patterns were repeated during the study. In an initial entry maneuver, upon simulator activation, the C-141B flew a closure starting at 190 ft aft and 1,000 ft below the tanker. In a subsequent maneuver, the receiver continued closure at a rate of 1 to 2 ft per sec until the pre-contact position (50 ft aft, slightly below and in trail of the tanker) was achieved. In this study, the simulated refueling time was 15 min. The actual sequence of flying maneuvers began with instructions for the pilot to fly at a comfortable position, approximately 190 ft aft and below the tanker. This was the resting position for the flight. The pilot entered into the pre-contact position and the 20-minute visual perception task was administered. Immediately following completion of the choice visual perception task, the pilot then returned to a comfortable and less demanding flying position. When a refueling was scheduled, the pilot entered into the pre-contact position then closed to contact. After each 15-min refueling period, the pilot again returned to a more relaxed and comfortable flight position.

Azimuth Deviation (drift from established course heading) was recorded via the ARPTT, and deviations from the established azimuth were taken from the data output range from 0 to +/-30 off primary heading. Azimuth Deviations were scored as the total number of times the aircraft crossed the 0 deg heading and at each additional 5 deg crossing, that is at 5, 10, 15, 20, 25, and 30 deg. The mean of the Azimuth Deviations during the 20-minute visual perception task performed on Day 2 was used for data analysis.

The Choice Visual Perception Task (CVPT) was designed and installed onto the instrument panel of the ARPTT cockpit to assess central and peripheral visual field awareness along the horizontal meridian in a high cognitive loading, multi-task environment. The display was a semicircular, small-caliber (approximately 1.5 cm diameter) high-grade aluminum tube with light stimuli 18 in from the center of the pilot's head just below eye-level. During this 20-min task, 150 sequential single- or double-light stimuli were presented, and each stimulus lasted 0.25-sec. The pilots divided their attention between performance of the task and active flight. Stimuli spanned 75-deg left to 75-deg right of center at 15-deg intervals just below the simulated horizon and against the instrument panel's black background. A full description of the task may be found in Russo et al. (2004, 2005).

The volunteers flew individually in the ARPTT and performed the pre-contact position maneuver and CVPT simultaneously, 15 times on Day 2 over the 24-hour testing period. Each session provided a unique combination of stimuli sequences and inter-stimulus intervals. For the primary task, the pilots were instructed to fly safely at the pre-contact position, and for the secondary task to verbally acknowledge the light stimulus.

One infrared cockpit camera recorded pilot voice and facial movement, a second recorded the view appreciated by the pilot of the air tanker, and a VCR recorded flight parameters.

The Advanced Tri-Mode Actigraph (Precision Control Design, Inc, Fort Walton Beach, Florida), utilized to document sleep/wake history during the study, used a linear piezoelectric accelerometer to record human movement in 1-min epochs for distinguishing wake from sleep.

2.4 Procedure

Volunteers arrived at the ARPTT trainer, McGuire Air Force Base for training on Study Day One. The subjects provided their written informed consent during the enrollment phase of recruitment. After training and re-familiarization, the pilots returned home, went to bed at midnight, awoke at 0600 h on Study Day Two, and reported to the ARPTT building by 0800 h. The pilot volunteers complied with the requested sleep schedule (confirmed by the wrist-mounted actigraph) by sleeping an average of 5.8 h with a range of 5.62 – 6.15 h of sleep. On Study Day Two, volunteers arrived at the simulator building at 0800 h, began testing, and pursued ad lib waking activities. The volunteers ate dinner between 1815 and 1930 h. From 1930 until 2000 h, they tested and received a pre-flight and mission brief. From 2000 h on Study Day Two to 0830 h on Study Day Three, the volunteers tested and flew the mission scenario.

In an actual flight operation, a copilot would be present. In order to simulate a copilot sharing flight operation responsibilities, each volunteer was permitted three scheduled breaks: 2130-2320, 0130-0320, and 0530-0650 h. In a departure from normal operational procedures, the subjects did not nap during these scheduled breaks. Actual flying time for each volunteer was 7.5 h. The pilots performed four 15-min fueling sequences during flight at 2040, midnight, 0400, and 0730 h. The scenario of an overnight flight after a day without sleep was intended to simulate a possible scenario that may exist in a high operational tempo environment, where there may be limited opportunity for crew-rest.

A timeline for the testing is shown in **Figure 2**.

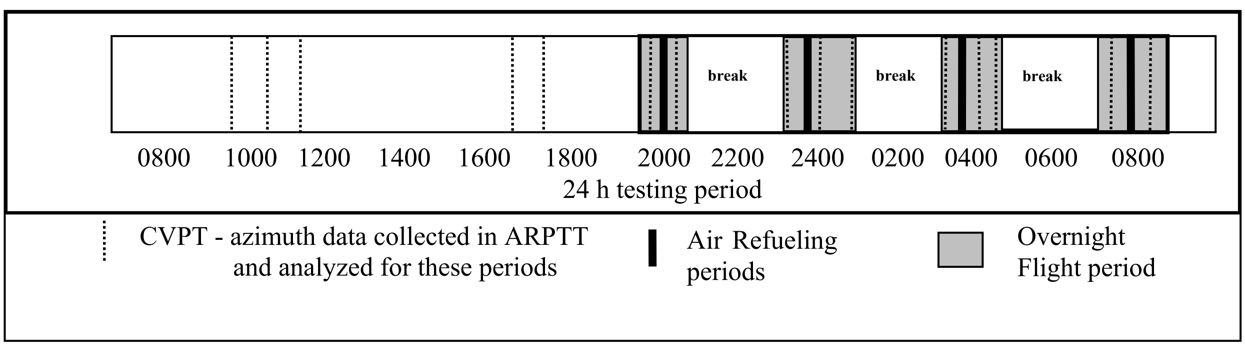


Figure 2: Testing Timeline. Adapted from Russo, Kendall, Johnson et al, (2005).

3.0 RESULTS

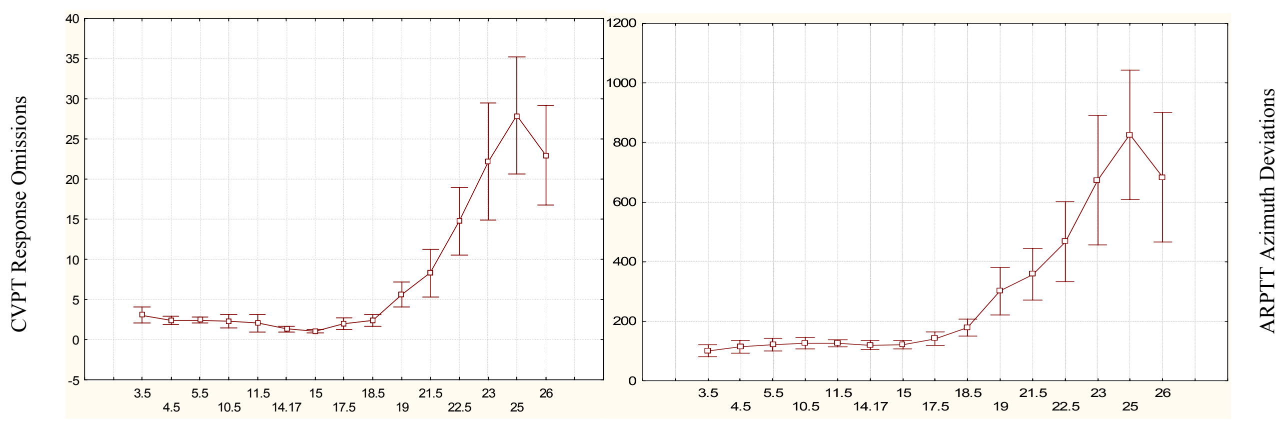
CVPT Response Omissions occurred at 19 h of continuous wake (p = 0.018) (**Figure 3a**). Declining performance at 19 h of wake was shown as well for ARPTT Azimuth Deviations (p = 0.046) (**Figure 3b**). CVPT Response Omissions and ARPTT Azimuth Deviations were positively correlated (r = 0.97, $p \leq$ 0.0000). For the CVPT metric, 2250 stimuli were presented to each volunteer over the course of the study.

Total errors included both Errors of Omission and Wrong Responses. Omission of a single stimulus occurred when the subject failed to respond to the single light. Omission of a double stimulus occurred when the subject failed to respond to one or both of the presented lights. Total Errors of Omissions were 963, with 760 to single stimuli and 203 to double stimuli. The average (mean) number of errors of omission for the 8 pilots are used for comparisons.

ARPTT Azimuth Deviation was measured by the number of crossings at zero, 5 degrees, 10 degrees, 15 degrees, 20 degrees, 25 degrees, and 30 degrees. The number of zero crossings was 13,023, the number of 5 degree crossings was 2356, 10 degree crossings was 438, 15 degree crossings was 177, 20 degree crossings was 78, 25 degree crossings was 33, and 30 degree crossings was 27. The total number of Azimuth Deviations was 16,132. The average (mean) number of Azimuth Deviations for the eight volunteers presented across time is presented in **Table 1**.

Table 1: Mean Number of Deviations from Established Course Heading (Degrees Azimuth) across Trials and Hours Awake (N = 8).

Trial # / Hrs awake	**1 / 3.5**	**2 / 4.5**	**3 / 5.5**	**4 / 10.5**	**5 / 11.5**	**6 / 14.1**	**7 / 15**	**8 / 17.5**	**9 / 18.5**	**10 / 19**	**11 / 21.5**	**12 / 22.5**	**13 / 23**	**14 / 25**	**15 / 26**
Degrees															
± 30											1	1	1.25	1.95	1.5
± 25											1	1	1.25	2.21	2
± 20											1.25	2	2.87	3.43	2.5
± 15			1	1						1	1.67	3.83	6.17	6.38	5.25
± 10			1	1	1			1.25	1	7.17	3.92	6.5	1.1	8.96	6.97
± 5	5.5	3	3.75	2	2.33	2.67	4.3	4.8	8.08	19.4	19.21	24.79	29.79	31.85	29.78



Hours of Continuous Wake (0 thru 26; 0600 h Day Two through 0800 h Day Three)

Figure 3: Changes across Time for Mean ±SEM (left, Figure a) Visual Perceptual (CVPT) Response Omissions and (right, Figure b) Complex Motor (ARPTT) Azimuth Deviations. Adapted from Russo, Kendall, Johnson et al 2005.

4.0 DISCUSSION

Significant decrements in visual perception and complex motor performance occurred with <19 h of being continuously wake. These findings are consistent with findings from earlier studies and reaffirm that acute sleep deprivation impairs multiple aspects of performance. Analyses performed individually for each metric showed significant changes at 19 h of wakefulness. There was no difference in time of onset of impairments among the two metrics, Visual Perception (CVPT) and Complex Motor Performance (ARPTT).

An important finding in this study is that visual perceptual impairment and complex motor performance are correlate strongly with each other. The choice visual perception task simulated the visual input a pilot might experience during normal flight operations—that is, the random appearance of a light stimulus along the instrument panel. The task required active visual perception, that is, both recognition of the stimulus and a relatively rapid acknowledgement of its location. Multiple thalamic nuclei relayed the afferent signals and modulated the efferent responses. Thomas et al. (2000, 2003) found cerebral deactivation in the prefrontal, parietal, and thalamic regions in a PET study beginning at 24 h of total sleep deprivation. These brain regions are primarily responsible for visual attention and visual cognition.

The complex motor performance task of flying in the pre-contact position behind the KC-135 tanker clearly required far more involved neural circuitry. Pilots perceive the relative location of their aircraft using multiple visual cues, such as the signals presented by the boom operator and the relative wing position of the tanker. Pilots perceive acceleration and deceleration through proprioceptive and vestibular systems. The cerebellar system provides integration between proprioception and fine motor coordination. All sensory inputs relayed through, and were interpreted by, the thalamus. The pilot responded accordingly through the frontal motor systems with actions by both hands and feet. During a complex maneuver, such as is represented by the pre-contact and refueling activities, a pilot would often remain silent in order to conserve and focus cognitive abilities on the delicate and demanding flight task.

As continuous wake impaired responses to both the visual perception task and the complex motor task, a relatively close neurophysiological relationship may be hypothesized. The close relationship between decrementing sensory perception and decrementing motor performance would lead one to consider the possibility that impaired visual information processing contributed to the impaired motor responses. When the pilot maintains a steady pre-contact or contact position, he/she relies heavily, although not exclusively, on visual cues. Once information processing of visual cues degrades, motor performance dependent upon these cues would logically degrade as well. Alternatively, sleep deprivation may be decrementing independently both sensory and motor systems, and the impairments may be representing a simultaneously occurring global impairment of higher-order cognitive functions.

Impairments of visual information processing also may be a contributing cause of ground vehicular accidents in awake but sleepy drivers. As visual information impairments develop, the ability to appreciate changes in the road (curves, narrows or intersections) and to appreciate fully and integrate that information into situational awareness, could result in failure to adjust speed properly and direction in a timely manner, even in the presence of an intact motor system. Impairments of visual attention resulting from total sleep deprivation may contribute to the occurrence of accidents during flight maneuvers that require tight formations, rapid responses, and quick decision-making. Pilots may not be as attentive to the relative location of their wingtips as they would be when fully rested because they are not able to fully "capture" all of the relevant inputs needed in time to avoid difficulties. Similar comments could be made with regard to flying instruments or complex visual approaches. As fatigue increases, the odds of having problems with spatial disorientation and of improperly handling visual illusions may increase as well. Fatigue affects situation awareness levels in general, because one critical component of situation awareness is the ability to project current aircraft states into the near future (Endsley, 1995). Extreme fatigue short-circuits this process because the higher integrative functions of the brain do not work as efficiently to process disparate pieces of information into a unified whole, as is required for a global assessment of the operational situation. Possible future research could address the effect on pilot performance by incorporating crew-rest condition variables to assess the impact of restricted and shifted sleep schedules on visual perception and complex motor performance.

For cognitive monitoring, assessment of visual information processing would have to occur unobtrusively, that is, without a dedicated stimulus-response requirement. Measurement of visual perception as an indicator of visual awareness and cognitive performance may be accomplished through two mechanisms: 1) visual evoked potentials or occipital-parietal electrocortical signals, or 2) pupillary hippus. With the advent of dry-application high-impedance electrodes, evoked and electroencephalographic indices may be captured unobtrusively in pilots and soldiers. The electroencephalographic information may be able to provide evidence of failing cognition. Pupil size changes appear to reflect recognition and cognitive processing of visual information. Measurements of these pupil oscillations can be made unobtrusively in that eye tracking devices may be mounted into instrument panels, helmet displays, or eyeglass frames. More likely is that future neurophysiological monitoring systems will integrate electrocortical information with pupil and oculomotor information into algorithms that interpret visual perception as an input for models that predict cognitive performance.

The visual impairments seen under conditions of sleep deprivation occurred in some but not all of the pilots in this 24-hour sleep deprivation study. The study design intended that cognitive load and multi-tasking remain relatively constant. Out of the eight pilots who participated in this study, three individuals did not manifest the visual neglect. These individuals were air-refueling instructor pilots. We speculate that the instructor pilots were over-trained or had attained expert level performance on the ARPTT and hence subject to a lower level of cognitive challenge. From a multiple resource theory standpoint, they were so over-trained that even when fatigued, they had to use less cognitive attentional resources to accomplish the same task, thereby “freeing up” other attentional resources for the visual and other tasks we tested. We speculate based upon the data fit to the polynomial equations shown earlier that if the instructor pilots were subject to further sleep deprivation, they too may demonstrate the same impairments as their non-instructor colleagues. Other explanations are under consideration for the maintenance of performance in these pilots. A histogram of the average number of omissions and the total number of simulator shutdowns by pilot, with age of pilot and instructor status, is presented in **Figure 4**. One can see from this histogram that there is no relationship between age and performance impairment as measured by either simulator shutdowns or by the occurrence of omissions on the visual perception task.

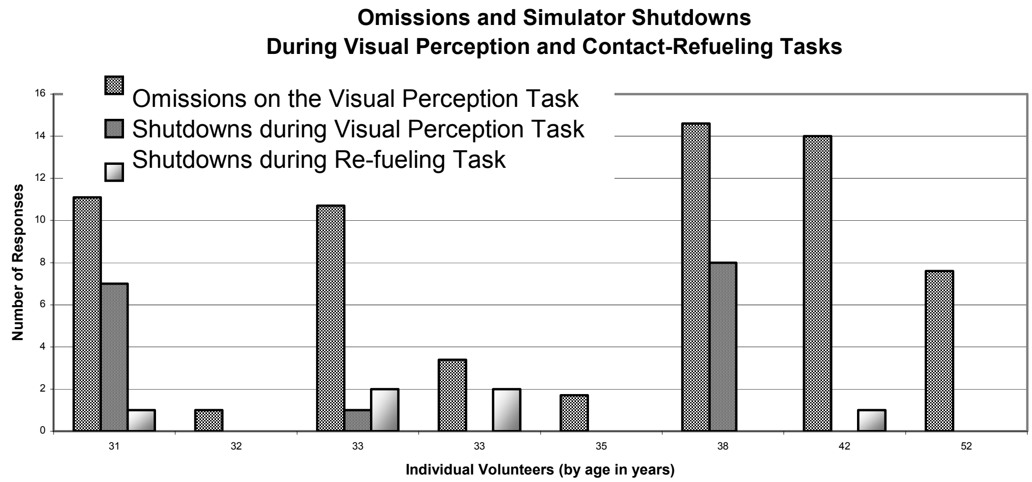


Figure 4: Distribution of Average Number of Omissions on the Visual Perception Task and of Total Number of Simulator Shut Downs by Individual Pilot. Age Indicated for Each Pilot along y-axis and IP Status Indicated in Pilot Area (adapted from Russo et al., 2004).

A design consideration that may have contributed to the findings is the influence of the circadian rhythm on the occurrence of impairment. The continuous wakefulness began at 0600. The impairments on both the visual task and the flight measure occurred during the hours of 0100 to 0700 when circadian support was minimal. Whether these findings would be the same had the study begun at 1800, thereby completing the continuous wakefulness at a time when circadian support would be high, is unknown.

5.0 CONCLUSIONS

In summary, significant visual perceptual, complex motor, and simple reaction time impairments began in the 19th hour of continuous wake. Visual perceptual impairment and complex motor performance decrements strongly correlated with each other. As such, measures of visual perception and information processing in general may be sensitive surrogate indicators of operational performance during complex motor tasks under conditions of sleep deprivation under these conditions. This research suggests that there is a possibility for the use of visual perceptual measures under fatigued conditions as an additional measure by proxy of complex motor performance measures, in situations where the individual is dependent on primarily visual information.

6.0 U.S. DEPARTMENT OF DEFENSE DISCLAIMER

Human volunteers participated in these DoD studies after giving their free and written informed consent. Protocols for these studies were approved in advance by the Walter Reed Army Institute of Research Human Use Review Committee. Investigators adhered to AR 70-25 on the use of volunteers in research. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations. The views expressed in this paper are those of the authors and do not reflect the official policy or position of the Department of the Army, Department of Defense, or the U.S. Government. This manuscript is not subject to copyright restrictions and portions have been previously published in peer-reviewed medical journals. The materiel is unclassified and approved for full public release.

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