Intern. J. Neuroscience, 116:1125–1138, 2006

ISSN: 0020-7454 / 1543-5245 online
DOI: 10.1080/00207450500513922

informa
healthcare

EFFECTS OF SLEEP DEPRIVATION ON LATERAL VISUAL ATTENTION

ATHENA P. KENDALL
MARY A. KAUTZ

Walter Reed Army Institute of Research
Silver Spring, Maryland, USA

MICHAEL B. RUSSO

United States Army Aeromedical Research Laboratory
Fort Rucker, Alabama, USA

WILLIAM D. S. KILLGORE

Walter Reed Army Institute of Research
Silver Spring, Maryland, USA

Sleep loss temporarily impairs vigilance and sustained attention. Because these cognitive abilities are believed to be mediated predominantly by the right cerebral hemisphere, this article hypothesized that continuous sleep deprivation results in a greater frequency of inattention errors within the left versus right visual fields. Twenty-one participants were assessed several times each day during a 40-h period of sustained wakefulness and following a night of recovery sleep. At each assessment, participants engaged in a continuous serial addition task while simultaneously monitoring a 150° visual field for brief intermittent flashes of light. Overall, omission errors were most common in the leftmost peripheral field for

Received 9 June 2005.

The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Army, the Department of Defense, the U.S. Government, or any of the institutions with which the authors are affiliated.

Address correspondence and reprint requests to MAJ William D. S. Killgore, Ph.D., Department of Behavioral Biology, Division of Psychiatry and Neuroscience, Walter Reed Army Institute of Research, 503 Robert Grant Avenue, Silver Spring, MD 20910, USA. E-mail: william.killgore@na.amedd.army.mil

all sessions, and did not show any evidence of a shift in laterality as a function of sleep deprivation. Relative to rested baseline and postrecovery conditions, sleep deprivation resulted in a global increase in omission errors across all visual locations and a general decline in serial addition performance. These findings argue against the hypothesis that sleep deprivation produces lateralized deficits in attention and suggest instead that deficits in visual attention produced by sleep deprivation are global and bilateral in nature.

Keywords attention, cognition, laterality, right-hemisphere, sleep deprivation, vigilance, visual field, visual perception

Normal, healthy individuals need adequate sleep for optimal cognitive functioning (Himashree et al., 2002). Without adequate sleep, humans show reduced alertness (Penetar et al., 1993) and impairments in cognitive performance (Thomas et al., 2000, 2003). Prolonged sleep deprivation is associated with decrements in elementary cognitive abilities such as vigilance and sustained attention (Doran et al., 2001; Wesensten et al., 2004), as well as impairments in complex, higher-order cognitive processes such as verbal fluency, logical thought, decision making, and creativity (Harrison & Horne, 1997, 1999, 2000). In occupational settings such as aviation, air traffic control, and sustained military operations where constant vigilance is a necessity, extended periods of sleep loss have been associated with catastrophic accidents (Mitler et al., 1988) and may have been a factor in some friendly fire incidents (Belenky et al., 1994). Studies of sleep-deprived individuals show that errors attention begin to emerge by 19 h of continuous wakefulness (Russo et al., 2004) and cognitive performance declines at a rate of approximately 25% for each 24-h period of wakefulness (Belenky et al., 1994).

Sleep deprivation produces global decreases in cerebral metabolism and blood flow, with the greatest declines evident in those regions critical for higher order cognitive processes (Thomas et al., 2000). These regions, the heteromodal association cortices, are associated with attention, vigilance, and complex cognitive processing, and reductions in activity within these regions are associated with decrements in these higher-order cognitive process (Mesulam, 1999). As a global blood flow and metabolic activity decline during prolonged periods without sleep, the brain appears to compensate by recruiting cognitive resources from nearby brain regions within the prefrontal and parietal cortices in order to maintain cognitive performance at acceptable levels (Drummond et al., 2001). Some evidence suggests that these compensatory activities may be particularly prominent within the right cerebral hemisphere (Drummond et al., 2001). Consistent with these reports, other studies suggest that cognitive processes mediated by the right hemisphere are more adversely affected by sleep deprivation than those mediated by the left (Johnsen et al., 2004; Pallesen et al., 2004).

Neuropsychological evidence suggests that the right cerebral hemisphere is dominant for attentional processes (Heilman & Van Den Abell, 1980; Mapstone et al., 2003). Much of the evidence supporting the dominance of the right hemisphere in attention comes from studies of patients with unilateral brain damage (Heilman & Van Den Abell, 1980; Weintraub & Mesulam, 1987). Lesions to the right cerebral hemisphere are more likely to produce contralateral hemispatial neglect than similar lesions to the left hemisphere (Behrmann et al., 2004; Mapstone et al., 2003, Mesulam, 1999). Further evidence supporting the prominent role of the right hemisphere in attentional processing comes from several functional neuroimaging studies that reveal greater right hemisphere activity in response to tasks requiring allocation of spatial attention (Fink et al., 2001; Macaluso et al., 2001). The accumulating evidence suggests that the left cerebral hemisphere allocates its attentional processing predominantly toward the contralateral (i.e., right) hemispace, whereas the right hemisphere appears to distribute attentional processing more equally between both hemispaces, and is therefore considered dominant for attention (Mesulam, 1999). Consequently, the phenomenon of contralesional neglect occurs nearly exclusively following lesions to the right hemisphere.

Given the apparently greater role of the right hemisphere in attentional processing and the preliminary evidence that the cognitive processes mediated by the right hemisphere may be more sensitive to the detrimental effects of sleep deprivation, it was hypothesized that prolonged sleep loss results in greater impairment of right hemisphere visual attention mechanisms oriented toward the contralateral (i.e., left) perceptual hemispace. Participants were assessed several times each day while remaining awake for 40 h. During each 15-min testing session, participants monitored a 150° arc of lateral visual space for periodic occurrences of brief flashes of light while simultaneously performing a continuous serial addition task.

METHOD

Subjects

Twenty-one active duty military personnel (9 females; 12 males; M age $= 28.2$, SD $= 5.5$) participated in the study. Volunteers were recruited through word of mouth and flyers posted at the Walter Reed Army Institute of Research. Visual acuity was assessed prior to entry with a standard Snellen Chart. Screening criteria required distant acuity of 20/20 and near acuity of 20/25 without refractive correction or from +1.00 D.S. to −3.00 D.S. with correction to 20/20. All participants were in good physical health, had no evidence of a current sleep disorder, and were free of any history of neurologic, psychiatric, or serious medical condition, as determined by the study physician. All potential volunteers consented to a urine drug screen and were excluded if there was any evidence of use of illegal substances or stimulants. Volunteers were also excluded if they regularly consumed more than 300 mg of caffeine per day. Financial compensation was provided for participation in the study and all procedures were conducted in accordance with the requirements of the Human Use Committee at Walter Reed Army Institute of Research and the Surgeon General's Human Subjects Research Review Board.

Apparatus

In order to assess divided attention capacities, participants were required to engage in two demanding attentional tasks simultaneously. Attention to visual stimuli within the lateral visual field was assessed with the Choice Visual Perception Task (CVPT). The CVPT consists of a horizontal U-shaped bar fitted with 11 light-emitting diodes (LEDs) located at 15° increments around the arc (see Figure 1). The arc was placed at eye level and the center diode was located 18 inches from the bridge of the nose of the participant. Remaining LEDs were located in the left and right visual fields at 15° intervals (i.e., L75, L60, L45, L30, L15, C, R15, R30, R45, R60, and R75). The task was performed against a black backdrop and ambient room light was maintained at approximately 5 foot candles to ensure uniform visibility of the stimuli. A chin rest was used to stabilize head movement and volunteers were instructed to maintain visual fixation on a focal point presented on a laptop computer. Each stimulus appeared for 250 ms, with an interstimulus interval varying from 3.50 to 15.25 s for each trial. Fifteen variations of visual stimuli were presented randomly 10 times for a total of 150 stimulus presentations for each trial. Each administration of the CVPT lasted 15 min. For single LED presentations, responses were made via a keypad with buttons for "left," "center," and "right," corresponding to the location of the stimulus.

Double simultaneous stimuli were also presented on 40 trials. These presentations always included the center stimulus (C) and an additional stimulus located within the left or right peripheral field (i.e., C+L75, C+L60, C+R60, and C+R75). During presentations of double simultaneous stimuli, responses

Figure 1. An example of a participant engaged in the Choice Visual Perception Task (CVPT) and Serial Addition Test (SAT). The SAT was presented on a laptop computer placed in front of the participant. The CVPT apparatus includes a laterally placed U-shaped bar with light emitting diodes placed at 15-degree intervals around a 150 degree arc of the visual field. Participants completed the SAT continuously while monitoring the CVPT for intermittent light flashes.

were made by pressing the two corresponding buttons simultaneously (e.g., “center” and “right” keys). All volunteers were instructed to use their right-hand for the keypad response, regardless of reported handedness. Hits, misses, and response omissions were recorded for each stimulus presentation.

In conjunction with continuous monitoring of the light locations of the CVPT, participants were required to sustain continuous performance on a Serial Addition Task (SAT). During the SAT, participants were required mentally to add sequences of single digit numbers that were presented on the screen and then vocally report the answers for each trial. During each sequence, a number from 0 to 9 would appear on the screen for 750 ms, which would be immediately replaced by a “plus-sign” (+) for 750 ms, then a second number, followed by an equal sign (=). At the presentation of the equal sign, the participant would vocally report the sum of the preceding two digits. The

SAT stimuli were presented three inches below the center LED on a 15-inch (diagonal) computer screen placed immediately below the CVPT. The target stimuli were presented in 72-point bolded Tahoma font at a screen resolution of 1024 × 768 pixels. Participants were required to continuously engage in the SAT while simultaneously monitoring the CVPT for periodic stimulus occurrences.

Design and Procedure

Each study run was conducted over two consecutive weeks. On the first day (Monday) of the baseline phase, volunteers reported to the sleep laboratory at approximately 0945. Each volunteer was fitted with an actigraph watch, given a sleep log to record their daily sleep habits, and reminded to abstain from caffeine, alcohol, and tobacco products. On that same day, the volunteers were trained on a battery of neuropsychological tests and the CVPT-SAT. Baseline testing concluded at approximately 1130. The residential phase began the following week.

Volunteers arrived at the sleep laboratory at 0800 to begin the residential phase. The residential phase involved a second baseline testing session, 40 h of sleep deprivation, 9 h of recovery sleep, and a postrecovery sleep testing session. On day 1 (Monday), subjects completed CVPT-SAT at 2-h intervals to provide a second rested baseline measure. Starting at 24:00 (midnight) volunteers received 8 h time in bed. The 40 h sleep deprivation period began when participants awakened at 0800 on day 2 (Tuesday). Volunteers remained awake until 2400 (midnight) on Day 3 (Wednesday). Throughout the course of the sleep deprivation period, the CVPT-SAT was administered at 2-h intervals. After the 40 h sleep deprivation period was concluded, each volunteer received 9 h of time in bed to obtain recovery sleep. On Thurs (day 4) volunteers were awakened at 0900, were retested twice on the CVPT-SAT, debriefed, and released from the study at 18:00. Each CVPT-SAT administration lasted for 15 min.

Data Analysis

To control for the effects of circadian influences, data were averaged and compared across blocks of time encompassing the same time periods each day (i.e., 1500, 1700, and 1900). For each trial, the number of single and double stimulus response omissions was calculated and averaged across trials for each session. Similarly, the percentage correct for each trial of the serial addition task was calculated and averaged across trials for each session. Data were analyzed using repeated measures analysis of variance, with Greenhouse-Geisser corrections for lack of sphericity. Stimulus location within the visual field (11 locations) and testing session (4 sessions) were entered as repeated measures variables. The criterion for significance was set at $\alpha = .05$. Because a greater number of errors were hypothesized within the leftmost peripheral field as a consequence of sleep deprivation, the authors conducted planned comparisons between the number of errors at the leftmost peripheral location (L75) versus the central (C) and rightmost peripheral (R75) sites, with $\alpha = .05$, uncorrected. Post hoc comparisons were conducted using a Bonferroni correction to $\alpha = .05$ for experiment-wise error rate.

RESULTS AND DISCUSSION

Accumulating evidence suggests that sleep deprivation affects lateralized processing of stimuli (Iskra-Golec, 2001), and may be particularly disruptive to cognitive and perceptual processes that involve the right hemisphere (Johnsen et al., 2002; Pallesen et al., 2004). It was predicted, therefore, that sleep deprivation is associated with a general decline in alertness and attention to visual stimuli and that these deficits would be most evident within the left peripheral visual field. There was a significant main effect of session, ($F_{3,60} = 45.18, p < .001$), indicating that the number of response omissions differed across the four test sessions (see Figure 2). Post hoc comparisons revealed that participants made significantly more errors of omission, regardless of visual field, when tested on the sleep deprived day than on either of the baseline days or following a night of post recovery sleep (all p's $< .001$). These data are consistent with a large body of research suggesting that sleep deprivation is associated with increased lapses in attention or "microsleeps" (Doran et al., 2001; Ferrara et al., 1999; Priest et al., 2001; Summala et al., 1999), and confirms that the manipulation of 40 h of sleep deprivation resulted in a general decline in visual attention.

The location of the visual stimulus was also important. When the data were collapsed across the four sessions a significant main effect for location of the stimulus within the visual field was found ($F_{10,200} = 7.72, p < .002$). Planned comparisons among the two most peripheral locations (i.e., L75, R75) and the central location (C) demonstrated significantly more errors at L75 than either C ($p = .005$) or R75 ($p = .008$), but only a nonsignificant trend toward fewer errors at C than R75 ($p = .084$; see Figure 3). These data are consistent with a growing body of research that suggests that the right hemisphere is dominant

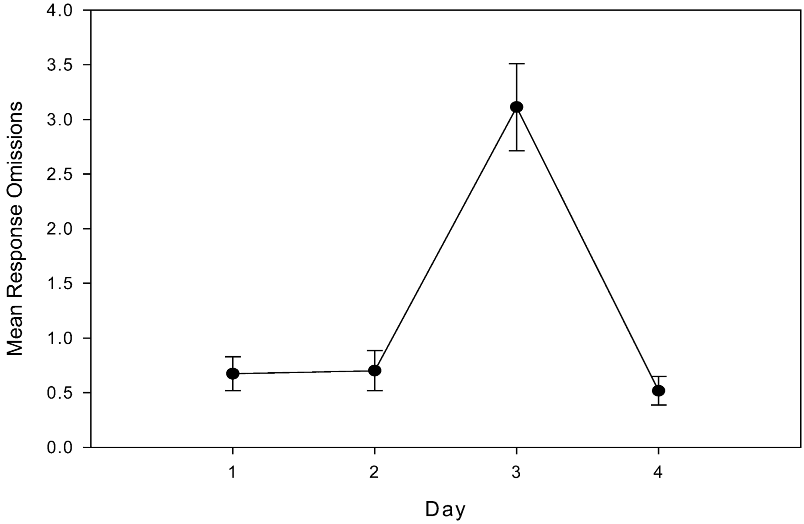

Figure 2. Mean response omissions across the four testing sessions. Response omissions were significantly higher during sleep deprivation (day 3) relative to baseline (days 1 and 2) and following recovery sleep (day 4).

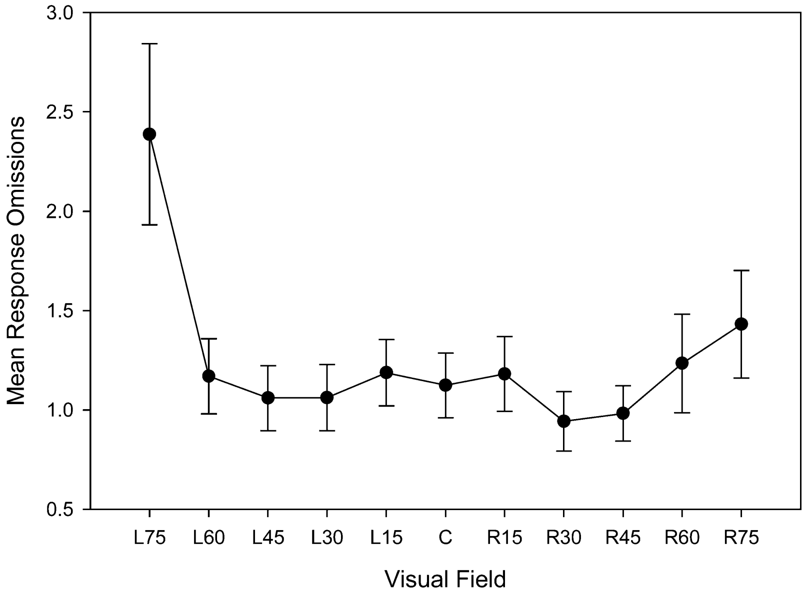

Figure 3. Mean response omissions across the four sessions for each location. Total omissions were significantly higher in the L75 location relative to the Center and R75 locations.

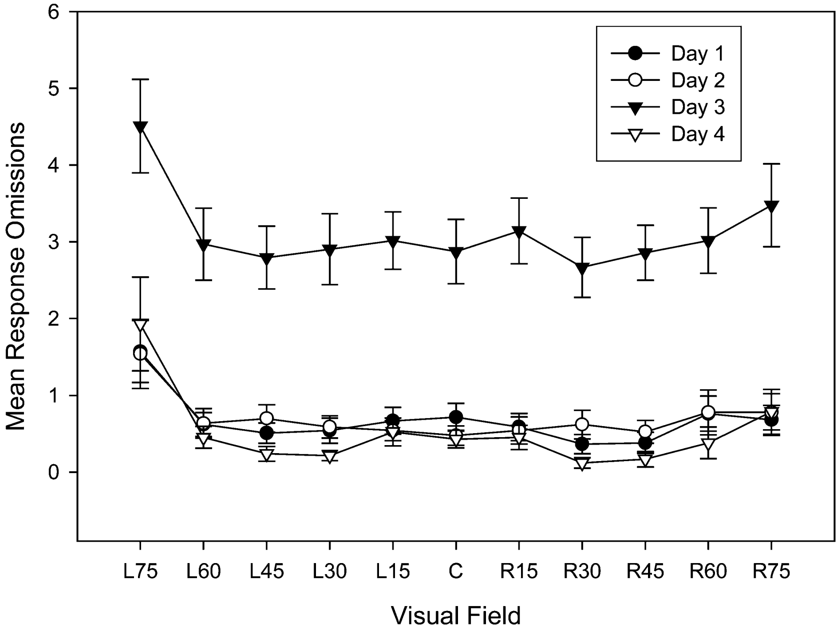

Figure 4. The mean frequency of response omissions across the 11 visual field locations is presented separately for each day. Sleep deprivation (day 3) was associated with significantly higher rates of response omissions than the baseline (days 1 and 2) and post-recovery days (day 4), regardless of location within the visual field.

for attentional processing (Heilman et al., 1986; Heilman & Van Den Abell, 1980; Muri et al., 2002).

Because recent evidence suggests that the attentional mechanisms of the right hemisphere may be disrupted by sleep loss (Johnsen et al., 2002; Pallesen et al., 2004), it was predicted that sleep deprivation is associated with more frequent errors in the left visual field. This hypothesis was not supported. Specifically, despite a trend in the expected direction, the hypothesized interaction between session and visual field location failed to reach statistical significance ($F_{30,600} = 1.45, p = .06$) (Figure 4). Planned comparisons between the L75 and R75 during each session revealed that the left peripheral visual field consistently showed more omission errors than the right for the first ($t_{20} = 3.02$, $p = .007$) and second ($t_{20} = 2.78$, $p = .012$) baseline days, as well as during the sleep deprived day ($t_{20} = 2.18, p = .041$). Although there was a trend in the same direction on the post-recovery day, the difference between the peripheral fields only reached a marginal level of significance ($t_{20} = 3.04$, $p = .055$).

Overall, these findings suggest that there were significantly more errors within the leftmost peripheral visual field, but that this trend was not significantly exacerbated by sleep loss. Interestingly, the data were not consistent with the findings of Russo and colleagues (Russo et al., 2004), who used the same task (i.e., CVPT), but found that omission errors during sleep loss were greatest within the right visual field (i.e., R45 and R75). The data reported by Russo and colleagues were derived from a significantly smaller sample and consisted entirely of U.S. Air Force pilots, which may account for some of the differences in the findings between the two studies.

The present study also examined the effects of sleep loss on attention to double simultaneous stimuli. Data from the simultaneous presentations of the center stimulus with either the stimulus located at 60 or 75° in the periphery were entered into a repeated measures analysis of variance for the four sessions. There was a main effect for session ($F_{3,60} = 43.07, p < .001$), but no evidence of any effect for stimulus location or interaction between session and stimulus location. Post-hoc analyses with Bonferroni correction revealed that total omission errors during simultaneous double stimuli were more frequent during the sleep deprivation session compared to the baseline and post-recovery sleep sessions (all ps $< .001$). To test the hypothesis that sleep deprivation leads to more frequent errors within the left relative to the right peripheral visual field, the authors conducted planned comparisons between the mean number of omission errors during simultaneous C + L75 and C + R75 for each of the four sessions. None of these comparisons were significant. Together, these findings are consistent with the results found for the single stimuli, suggesting that sleep deprivation was associated with increased errors in general, but not with any significant lateralized pattern across the visual fields.

Recent functional neuroimaging studies suggest that sleep-deprived individuals are often able to maintain relatively stable cognitive performance during divided attention tasks by recruiting additional cortical regions to compensate for the detrimental effects of prolonged wakefulness (Drummond et al., 2001; Drummond & Brown, 2001). It was hypothesized that participants would be able to maintain continuous performance on the SAT during sleep deprivation, but that this would require additional recruitment of attentional resources, and therefore come at the cost of increased omission errors on the CVPT. Data from the SAT were compared across the four days. This hypothesis was also not supported, as a repeated measures analysis of variance with the percentage of correct responses as the dependent variable suggested a significant difference in performance across sessions ($F_{3,60} = 51.62$, $p <$ .001). Bonferroni-corrected post hoc comparisons indicated that arithmetic

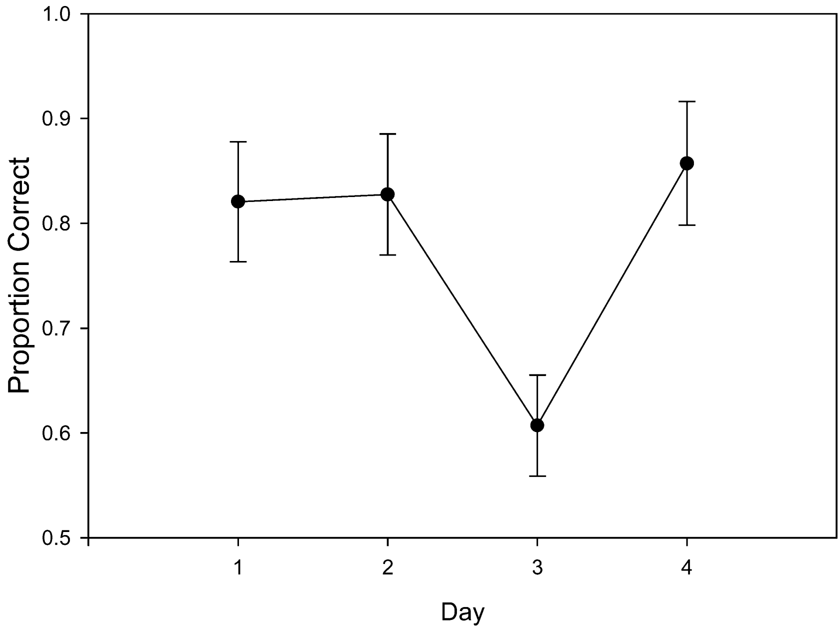

Figure 5. The mean proportion of correct arithmetic problems differed across the 4 days. Relative to the baseline (days 1 and 2) and post-recovery sessions (day 4), performance during the sleep deprived session (day 3) was significantly impaired.

performance during the sleep deprived session was significantly worse than either of the two baseline days and the post recovery days (all ps $< .001$; see Figure 5). Arithmetic performance returned to baseline levels following a night of recovery sleep. These findings are consistent with previous work that shows that sleep deprivation significantly impairs cognitive processing (Newhouse et al., 1989). Furthermore, performance on the SAT was not significantly correlated with mean errors on the CVPT for either the first ($r = .24$, *ns*) or second baseline days ($r = .17$, *ns*), the sleep deprived day ($r = .09$, *ns*), or the post recovery day ($r = .23$, *ns*). These data suggest that sleep deprivation was associated with significant variability in attention, which yielded a hapazard and uncorrelated pattern of performance on the two tasks. This explanation is consistent with the notion of increased wake-state instability during sleep deprivation. Wake-state instability occurs when the sleep-deprived individual begins to rely more heavily on compensatory mechanisms and cognitive performance becomes progressively more variable the longer the individual remains awake (Doran et al., 2001; Durmer & Dinges, 2005).

In conclusion, this study found that 31–35 h of sleep deprivation was associated with a global decline in sustained visual attention and continuous cognitive performance. Although global performance deteriorated on both tasks and performance decrements were consistently observed in the leftmost peripheral visual field across all conditions, there was no evidence that sleep deprivation resulted in any change in the lateralization of attention errors. These findings suggest that sleep deprivation has the effect of increasing the variability of attentional allocation and cognitive processing globally across the entire lateral visual field, rather than affecting specific locations or lateralized sectors of the visual hemi-space.

REFERENCES

Behrmann, M., Ebert, P., & Black, S. E. (2004). Hemispatial neglect and visual search: A large scale analysis. *Cortex*, *40*(2), 247–263.

Belenky, G., Penetar, D., Thorne, D., Popp, K., Leu, J., Thomas, M., et al. (1994). The effects of sleep deprivation on performance during continuous combat operations. In B. M. Marriot (Ed.), *Food components to enhance performance*. (pp. 127–135). Washington, D.C.: National Academy Press.

Doran, S. M., Van Dongen, H. P., & Dinges, D. F. (2001). Sustained attention performance during sleep deprivation: Evidence of state instability. *Arch. Ital. Biol.*, *139*(3), 253–267.

Drummond, S. P., & Brown, G. G. (2001). The effects of total sleep deprivation on cerebral responses to cognitive performance. *Neuropsychopharmacology*, *25*(5 Suppl), S68–73.

Drummond, S. P., Gillin, J. C., & Brown, G. G. (2001). Increased cerebral response during a divided attention task following sleep deprivation. *J. Sleep. Res.*, *10*(2), 85–92.

Durmer, J. S., & Dinges, D. F. (2005). Neurocognitive consequences of sleep deprivation. *Semin Neurol*, *25*(1), 117–129.

Ferrara, M., De Gennaro, L., & Bertini, M. (1999). The effects of slow-wave sleep (SWS) deprivation and time of night on behavioral performance upon awakening. *Physiol. Behav.*, *68*(1–2), 55–61.

Fink, G. R., Marshall, J. C., Weiss, P. H., & Zilles, K. (2001). The neural basis of vertical and horizontal line bisection judgments: An fMRI study of normal volunteers. *Neuroimage*, *14*(1 Pt 2), S59–67.

Harrison, Y., & Horne, J. A. (1997). Sleep deprivation affects speech. *Sleep*, *20*(10), 871–877.

Harrison, Y., & Horne, J. A. (1999). One night of sleep loss impairs innovative thinking and flexible decision making. *Organ Behav. Hum. Decis. Process*, *78*(2), 128–145.

Harrison, Y., & Horne, J. A. (2000). The impact of sleep deprivation on decision making: A review. *J. Exp. Psychol. Appl.*, *6*(3), 236–249.

Heilman, K. M., Bowers, D., Valenstein, E., & Watson, R. T. (1986). The right hemisphere: Neuropsychological functions. *J. Neurosurg.*, *64*(5), 693–704.

Heilman, K. M., & Van Den Abell, T. (1980). Right hemisphere dominance for attention: The mechanism underlying hemispheric asymmetries of inattention (neglect). *Neurology*, *30*(3), 327–330.

Himashree, G., Banerjee, P. K., & Selvamurthy, W. (2002). Sleep and performance—recent trends. *Indian J. Physiol. Pharmacol.*, *46*(1), 6–24.

Iskra-Golec, I. (2001). Ultradian rhythms in processing speed of laterally exposed words and pictures. *J. Hum. Ergol. (Tokyo)*, *30*(1–2), 241–244.

Johnsen, B. H., Laberg, J. C., Eid, J., & Hugdahl, K. (2002). Dichotic listening and sleep deprivation: Vigilance effects. *Scand. J. Psychol.*, *43*(5), 413–417.

Macaluso, E., Frith, C. D., & Driver, J. (2001). Multimodal mechanisms of attention related to rates of spatial shifting in vision and touch. *Exp. Brain Res.*, *137*(3–4), 445–454.

Mapstone, M., Weintraub, S., Nowinski, C., Kaptanoglu, G., Gitelman, D. R., & Mesulam, M. M. (2003). Cerebral hemispheric specialization for spatial attention: Spatial distribution of search-related eye fixations in the absence of neglect. *Neuropsychologia*, *41*(10), 1396–1409.

Mesulam, M. M. (1999). Spatial attention and neglect: Parietal, frontal and cingulate contributions to the mental representation and attentional targeting of salient extrapersonal events. *Philos. Trans. R. Soc. Lond. B. Biol. Sci.*, *354*(1387), 1325–1346.

Mitler, M. M., Carskadon, M. A., Czeisler, C. A., Dement, W. C., Dinges, D. F., & Graeber, R. C. (1988). Catastrophes, sleep, and public policy: Consensus report. *Sleep*, *11*(1), 100–109.

Muri, R. M., Buhler, R., Heinemann, D., Mosimann, U. P., Felblinger, J., Schlaepfer, T. E., et al. (2002). Hemispheric asymmetry in visuospatial attention assessed with transcranial magnetic stimulation. *Exp. Brain Res.*, *143*(4), 426–430.

Newhouse, P. A., Belenky, G., Thomas, M., Thorne, D., Sing, H. C., & Fertig, J. (1989). The effects of d-amphetamine on arousal, cognition, and mood after prolonged total sleep deprivation. *Neuropsychopharmacology*, *2*(2), 153–164.

Pallesen, S., Johnsen, B. H., Hansen, A., Eid, J., Thayer, J. F., Olsen, T., et al. (2004). Sleep deprivation and hemispheric asymmetry for facial recognition reaction time and accuracy. *Percept. Mot. Skills.*, *98*(3 Pt 2), 1305–1314.

Penetar, D., McCann, U., Thorne, D., Kamimori, G., Galinski, C., Sing, H., et al. (1993). Caffeine reversal of sleep deprivation effects on alertness and mood. *Psychopharmacology (Berl)*, *112*(2–3), 359–365.

Priest, B., Brichard, C., Aubert, G., Liistro, G., & Rodenstein, D. O. (2001). Microsleep during a simplified maintenance of wakefulness test. A validation study of the OSLER test. *Am. J. Respir. Crit. Care Med.*, *163*(7), 1619–1625.

Russo, M. B., Sing, H., Santiago, S., Kendall, A. P., Johnson, D., Thorne, D., et al. (2004). Visual neglect: Occurrence and patterns in pilots in a simulated overnight flight. *Aviat. Space Environ. Med.*, *75*(4), 323–332.

Summala, H., Hakkanen, H., Mikkola, T., & Sinkkonen, J. (1999). Task effects on fatigue symptoms in overnight driving. *Ergonomics*, *42*(6), 798–806.

Thomas, M., Sing, H., Belenky, G., Holcomb, H., Mayberg, H., Dannals, R., et al. (2000). Neural basis of alertness and cognitive performance impairments during sleepiness. I. Effects of 24 h of sleep deprivation on waking human regional brain activity. *J. Sleep Res.*, *9*(4), 335–352.

Thomas, M., Sing, H. S., Belenky, G., Holcomb, H. H., Mayberg, H. S., Dannals, R. F., et al. (2003). Neural basis of alertness and cognitive performance impairments during sleepiness II. Effects of 48 and 72 h of sleep deprivation on waking human regional brain activity. *Thalamus & Related Systems*, *2*, 199–229.

Weintraub, S., & Mesulam, M. M. (1987). Right cerebral dominance in spatial attention. Further evidence based on ipsilateral neglect. *Arch. Neurol.*, *44*(6), 621–625.

Wesensten, N. J., Belenky, G., Thorne, D. R., Kautz, M. A., & Balkin, T. J. (2004). Modafinil vs. caffeine: Effects on fatigue during sleep deprivation. *Aviat. Space Environ. Med.*, *75*(6), 520–525.