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Failure to Find Executive Function Deficits Following One Night's Total Sleep-Deprivation in University Students under Naturalistic Conditions

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Abstract

Young adult male students participated in a naturalistic, group-design experiment to ascertain the effects of one night's total sleep deprivation (TSD) on performance of diverse executive function tasks presented as an extended, multi-task battery. On the majority of component tasks in this battery, performance has been reported to be impaired following one night's TSD when tasks are administered in isolation. However, subjects sleep deprived 35–39 hours showed few performance deficits among tests in this battery when compared with non sleep-deprived controls. Sleep-deprived subjects showed only poorer recognition memory and overconfidence in incorrect temporal judgments. Behavioral and physiological adaptation to chronically sleep-restricting lifestyles may confer resistance to the cognitive effects of sleep deprivation in high-functioning young adults.

Introduction

Voluntary sleep deprivation and sleep restriction is ubiquitous among students in American colleges and universities. It has been suggested that many students maintain a degree of sleep debt (Hawkins & Shaw, 1992; Lack, 1986; Levine, Roehrs, Zorick, & Roth, 1988) that is compensated by sleep extension on weekends (Hawkins & Shaw, 1992). Moreover, average sleep duration has significantly diminished among university students over the last 30 years (Hicks, Fernandez, & Pellegrini, 2001a). Performance deficits resulting from sleep loss have been documented both in naturalistic (Curcio, Ferrara, & De Gennaro, 2006; Czeisler, 2006) and experimental settings (Durmer & Dinges, 2005).

One night's acute total sleep deprivation (TSD) has been shown to degrade performance on neuropsychological tests of executive function (EF), a cognitive domain that includes complex functions such as such as planning, cognitive flexibility and decision-making (Harrison & Horne, 2000b; Jones & Harrison, 2001; Muzur, Pace-Schott, & Hobson, 2002). Executive functions are believed to be dependent to a large degree on the prefrontal cortex (Fuster, 1997).

The majority of EF assessments that have been used in TSD studies are those traditionally associated with lateral areas of the prefrontal cortex and probe capacities such as verbal fluency (Harrison & Horne, 1997, 1998; Horne, 1988), temporal memory (Harrison & Horne, 2000a; Harrison, Horne, & Rothwell, 2000), logical reasoning (Blagrove, Alexander, & Horne, 1995), working memory (Drummond et al., 1999) and planning (Horne, 1988). More recently, however, investigators have begun to describe the effects of TSD on cognitive capacities traditionally associated with ventral (e.g., orbital, inferior frontal junction) and medial (e.g., ventromedial, dorsomedial) prefrontal cortices (see Derrfuss, Brass, Neumann, & von Cramon, 2005; Northoff et al., 2006; and Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004 for reviews of functional anatomy). For example, sleep loss has been reported to impair performance on tests measuring behavioral inhibition (Chuah, Venkatraman, Dinges, & Chee, 2006; Drummond, Paulus, & Tapert, 2006), decision-making (Killgore, Balkin, & Wesensten, 2006), moral judgment (Killgore et al., 2007), risk taking (Killgore, 2007), and emotional intelligence (Killgore et al., 2008) as well as perceptual skills associated with the orbitofrontal cortex such as olfactory discrimination (Killgore & McBride, 2006).

The importance of sleep to the integrity of the prefrontal cortex is suggested by its marked deactivation during sleep (Braun et al., 1997; Kaufmann et al., 2006; Nofzinger et al., 2002). In addition, frontal regions may show greater need for recovery sleep than more posterior regions (Finelli, Borbely, & Achermann, 2001) and a larger increase in homeostatic sleep pressure following sleep deprivation (Cajochen, Foy, & Dijk, 1999).

TSD is sometimes associated with decreased task-related regional activity in brain regions activated by the same task in waking (Mu et al., 2005; Thomas et al., 2000). However, TSD has also been reported to increase task-related activity and/or recruit additional brain areas -- responses that have been suggested to compensate for the impact of sleep loss (Drummond, Brown, Salamat, & Gillin, 2004; Drummond, Meloy, Yanagi, Orff, & Brown, 2005). For example, in some reports, TSD-induced deterioration in working memory performance has been accompanied by reduced activation of prefrontal areas normally activated by working memory tasks (Mu et al., 2005; Thomas et al., 2000). However, in other reports, performance declines have been associated with deactivation of parietal cortices accompanied by increased prefrontal activity (Chee & Choo, 2004). Similarly, when performing divided attention or logical reasoning tasks, TSD can result both in compensatory increases in prefrontal cortex activity and recruitment of posterior areas not normally activated by such tasks (Drummond & Brown, 2001; Drummond et al., 2004).

Although recent studies associate sleep loss with academic impairment (Curcio et al., 2006; Kelly, Kelly, & Clanton, 2001; Medeiros, Mendes, Lima, & Araujo, 2001; Thacher, 2008;

Wolfson & Carskadon, 2003) and psychopathology (Thacher, 2008), many university students in the United States subject themselves to sleepless nights. It is therefore important to consider why this behavior continues to be viewed, by students, as a benign, normal part of undergraduate life. Notably, EFs are both crucial to academic success in higher education (Higgins, Peterson, Pihl, & Lee, 2007) and selectively impacted by sleep loss (Harrison & Horne, 2000b; Jones & Harrison, 2001)

We employed an extended battery of EF assessments, including tests believed to recruit various regions of the prefrontal cortex, which required several hours to complete. The purpose of this study was three-fold. First, we sought to assess TSD effects on performance of diverse EF tasks that, in isolation, have been reported to be impacted by one night's TSD but have not been studied in a massed, battery format. This was done in order to probe the impact of sleep loss on the prolonged deployment of higher cognitive functions, a demand often encountered in the course of undergraduate academic life. Second we sought to ascertain the effects of sleep loss on several EF tasks for which TSD effects had not been reported at the time of study. Third, we sought to identify EF tasks for which no practice effects occurred upon repeat testing that might be used as within-subject measures in future studies. In keeping with past studies of student populations, our initial hypothesis was that decrements in EF, as measured by one or more component tasks in the battery, would be observed in a group acutely sleep deprived for one night when compared with a similar group allowed normal sleep on the night before testing.

Methods

Participants

Participants were 25 right-handed males with English as their first language, aged 19–25, who were undergraduates, college graduates or graduate students at 4-year liberal arts colleges with competitive admissions. Participants were recruited through daily newspaper classified ads and word of mouth. Participants were free of medical, psychiatric, neurological, substance use or sleep disorders as well as psychotropic medication or sensory deficits*. All subjects signed informed consent forms approved by the Massachusetts Mental Health Center Institutional Review Board and were paid for their participation. Participants were pseudo-randomly assigned, in the order they were enrolled, to groups of 2 to 3 individuals that alternated between the total sleep deprivation (TSD, N= 11) and control (CTL, N=14) conditions.

Following advice from an authority on gender differences in psychiatric disorders, males alone were studied in order to avoid inter-subject variability resulting from interactive effects of gender and phase of menstrual cycle with the cognitive effects of TSD. Gender differences have been reported on a number of tasks utilized in the current study including verbal fluency (Weiss et al., 2006), smell identification (Doty, 1995) and, for both behavior and regional brain activity, the Iowa Gambling Task (Bolla, Eldreth, Matochik, & Cadet,

*One subject disclosed that he was partially color blind after participation and his results from tests that rely upon color discrimination were excluded. Another subject's thick accent precluded clear identification of his audio taped responses and such results for this subject were also excluded.

2004; Reavis & Overman, 2001). Menstrual cycle phase variation has been demonstrated in an extinction-learning task (Milad et al., 2006) that is known to recruit brain regions in proximity to ventromedial prefrontal areas recruited by the Iowa Gambling Task. Menstrual-cycle related variation has also been reported for tests of behavioral inhibition (Roberts, Newell, Simoes-Franklin, & Garavan, 2008), as well as mental rotation, and Stroop color-word tests (Farage, Osborn, & Maclean, 2008).

Procedures

The study protocol extended from Monday (Day 1) to Monday (Day 8), with sleep deprivation occurring on Night 4 (Thursday night) and Day 5 (Friday). Subjects were told to keep their normal sleep schedule but were not additionally prescribed a specific sleep duration or clock hours in bed. Subjects were asked to remain alcohol and drug-free throughout the entire week of the study. TSD subjects (TSDs) were instructed not to nap after arising on Day 4 (mean rising time 7:40 hr, range 6:50–9:30 hr) and they reported to the laboratory at 19:00 hr to complete the remainder of their TSD under supervision. CTL subjects (CTLs) continued to sleep normally on the night of Day 4..

After 19:00 hr on day 4, TSD participants were monitored continuously by research staff and passed the time watching movies, snacking, playing board games, conversing and taking supervised outdoor walks. Participants were permitted to consume caffeinated beverages not exceeding their normal daily intake until 14:00 hr on Day 5 (i.e., 4–5 hours prior to the start of testing). TSDs had access to caffeinated beverages only at meal times. Every hour (on-the-hour) during the entire sleep deprivation period (TSDs) or when awake on Days 4 and 5 (CTLs), participants completed sleepiness and mood scales described below.

Participants were tested from approximately 18:30 to 23:00 hr on Day 5, following approximately 35 to 39 hours of TSD in the experimental group. All but 3 subjects (1 TSD and 2 CTL) returned to the laboratory on Day 8, after three subsequent nights of sleep, and completed a second battery of tasks, largely identical to those completed on Day 5 (see below), again starting at 18:30 hr.

Sleep, sleepiness and mood measures

All nights of home sleep were monitored using the Nightcap ambulatory sleep monitor. The Nightcap is a two-channel recording device that can distinguish wake, REM sleep, and non-REM sleep (Ajilore, Stickgold, Rittenhouse, & Hobson, 1995), distinguish good and poor sleepers (Pace-Schott, Kaji, Stickgold, & Hobson, 1994) and provide reliable estimates of sleep onset (Atienza, Cantero, Stickgold, & Hobson, 2004; Cantero, Atienza, Stickgold, & Hobson, 2002) and sleep quality parameters (Silvestri et al., 2001) including NREM, REM and total sleep times (Ajilore et al., 1995). Relative to simultaneous PSG, in normal subjects, one-minute epochs of Nightcap data analyzed by a computerized algorithm predicted sleep with 87% accuracy (Ajilore et al., 1995). Additionally, time in NREM, REM and wake did not significantly differ between Nightcap and simultaneous PSG (Ajilore et al., 1995).

In addition, each evening and morning, participants completed appropriate sections of a sleep quality questionnaire that queried daytime activities, bed and rising times as well as subjective ratings of sleep quality (Pace-Schott et al., 2005). Sleepiness was assessed using

the Stanford Sleepiness Scale (SSS, Hoddes, Zarcone, Smythe, Phillips, & Dement, 1973), a 7-point, self-assessment scale extending from full alertness to nearly asleep (for psychometric properties see MacLean, Fekken, Saskin, & Knowles, 1992). Mood was assessed using the Bipolar Profile of Mood States (POMS, McNair, Lorr, & Droppleman, 1981), a reliable and validated 72-item self report questionnaire scored on the basis of 7 factor analytically derived dimensions. Its psychometric properties have been extensively reported (see POMS Technical Manual and POMS bibliography, Multi Health Systems, Inc., <http://www.mhs.com/mhs/>).

Test battery and experimental tests

Thirteen EF and working memory (WM) tests as well as a mental rotation test were included in the battery (Table 1). The EF and WM tests were divided into two groups that putatively engage cognitive functions traditionally assigned to one or the other of two major subdivisions of the prefrontal cortex (Table 1)—lateral and ventromedial/orbitofrontal regions (see Fuster, 1997). Mental rotation is believed to recruit more posterior (parietal) cortices (Kosslyn, DiGirolamo, Thompson, & Alpert, 1998). After completing each component test of the battery, participants self-rated “Effort” and “Motivation-to-do-well” on two 100 mm Visual Analog Scales (VAS).

Testing sessions always began with the mental rotation test and the EF and WM tests followed. Across subjects, test order was first counterbalanced according to the two putative anatomic groupings of tests (see Table 1) and then by component tests within each grouping.

Individual tests and their outcome measures are described below. When readily available, published psychometric properties of tests are cited, however, because test-retest correlation is a powerful means of assessing reliability (Parrott, 1991), such values derived from current data of subjects that were tested twice (Days 5 and 8) are also presented. For additional test details, please refer to sources (see Table 1) or (Pace-Schott, 2006).

Verbal Fluency (Controlled Oral Word Association Test)—Subjects spoke as many words beginning with three letters as they are able given 1 minute. The letters F, A, and S were used on Day 5 and B, C, T on Day 8. Various letter combinations of this test have test-retest reliability exceeding $r=0.7$ using alternate letter sets (Lezak, Howieson, & Loring, 2004; Mitrushina, Boone, Razani, & D’Elia, 2005; Spreen & Strauss, 1998) and exceeding $r=0.8$ using only F,A,S (Spreen & Strauss, 1998). In the current study, test-retest correlation (Pearson correlation coefficients) with alternate letter sets was 0.71, 0.68 and 0.76 for total subjects, TSDs and CTLs respectively.

Category Fluency (a.k.a. Animal Naming Test)—Subjects generated as many names of animals (Day 5) or vegetables (Day 8) as they were able given 1 minute. In the current study, test-retest correlation was 0.58, 0.55 and 0.62 for total subjects, TSDs and CTLs respectively.

Baddeley Logical Reasoning—In this pencil and paper test, subjects were presented with three pages containing 90 short sentences describing grammatical rules pertaining to the ordering of two letters, C and M, after each of which the two letters appear. Subjects

must decide whether or not the ordering of the letters fulfills the preceding rule. Subjects were given 5 minutes to complete as many problems as they were able. The identical test was presented to subjects on Days 5 and 8 except that the order of the three test pages was changed. Outcome was the total number of Correct solutions. Test-retest correlation was 0.58, 0.61 and 0.52 for total subjects, TSDs and CTLs respectively.

Tower of London^{DX}(TOL)—The subject was presented with a peg board with three pegs onto which three beads (red, green and blue) are placed. The investigator sat across from the subject facing an identical second board with beads. The subject's task was to move the beads from a standard starting position on his or her board to an end position demonstrated by the investigator on the second board. This was to be done in as few moves as possible and without removing more than one bead at a time from the pegs. After two practice trials, the subject was presented with 10 test trials of increasing difficulty while the investigator counted and timed the subject's moves. The identical test was presented on Days 5 and 8. Outcomes were total number of moves above the theoretical minimum (Total move score), number of trials done in the minimum number of moves (Total correct), mean time over all trials to initiate first move (Initiation time), and mean time over all trials to complete all moves (Execution time).

The Tower of London^{DX}—Technical manual (Culbertson & Zillmer, 2001) reports test-retest correlations in the moderate to high range for a clinical sample of children. In addition, they report significant correlation between TOL^{DX} scores and other executive measures as well as loading of TOL^{DX} scores with other measures of EF in factor analyses. In the current study, test-retest correlation for total subjects, TSDs and CTLs respectively was 0.46, 0.73 and 0.28 for Total move score, 0.50, 0.64 and 0.23 for Total correct, 0.89, 0.79 and 0.90 for Initiation time, and 0.76, 0.71 and 0.79 for Execution time.

Temporal Memory—Stimuli and procedures followed Harrison and Horne's (2000a) adaptation of a verbal stimulus task (Parkin, Walter, & Hunkin, 1995). Stimuli were 4 X 6 photographs of unfamiliar faces with emotionally neutral expressions presented sequentially for one minute each. Two sets of 12 photographs (balanced for gender and approximate age) were presented in the same order across all participants with 5 min between first and second set and between second set and testing. Testing included 48 photographs including the presented sets and 24 novel faces. Subjects were asked "did you see this face previously?", "in which set did it occur?" and "on a scale of 1 to 5, how confident are you of your answers." Outcomes were the d-prime measure of recognition accuracy (Macmillan & Creelman, 1991) and the number of faces correctly assigned to set 1 or 2 (Correct set). Two relative confidence measures were computed. First, each rating was divided by that subject's grand mean rating (Relative confidence). Second, each subjects mean rating for incorrect answers was subtracted from their mean confidence rating of correct answers. The identical test was presented on Days 5 and 8.

Digit Span—Digit Span was presented according to standard rules of the WAIS-R®. Outcomes were the uncombined Digits forward and Digits backward. The identical test was presented on Days 5 and 8. The WAIS-R® Manual (Wechsler, 1981) gives the split-half

reliability coefficient for forward and backward scores combined as 0.89 in the age range closest to participants. In the current study, test-retest correlation for total subjects, TSDs and CTLs respectively was 0.60, 0.57 and 0.65 for Digit Span Forward and 0.50, 0.61 and 0.39 for Digit Span Backward.

2-Back—Five series of 16 letters (series 1 was practice) containing 4 targets apiece were presented with 200 msec inter stimulus interval (ISI). Each series was followed by a 20-sec fixation rest period. Outcome measures were the d-prime measure of target detection accuracy and reaction time (RT) for correct responses. The identical test was presented on Days 5 and 8. Test-retest correlation for total subjects, TSDs and CTLs respectively was 0.39, 0.39 and 0.37 for d-prime and 0.84, 0.87 and 0.87 for RT correct responses.

Modified Iowa Gambling Task—In the Modified Iowa Gambling Task, advantageous and disadvantageous decks followed (Bechara, Damasio, Damasio, & Lee, 1999) with the following modifications designed to allow repeated test presentation: (i) Disguise of the game strategy was accomplished by dividing the 100 draws into 10 ten-card blocks that were randomly sorted before each presentation. (ii) Disadvantageous decks yielded wins of \$.80–1.20 per card and losses of \$1.50–12.50 resulting in a net loss of \$2.50 if chosen for all draws in a 10-card block. (iii) Advantageous decks yielded wins of \$.40–.60 per card and losses of \$.25–\$1.00 resulting in a net gain of \$2.50 if chosen for all draws in a 10-card block. (iv) Motivation of participants was promoted by adding any net winnings to their subject fee. Outcome was number drawn from advantageous decks (Advantageous draws). Automatically randomized test versions were given on both days. Test-retest correlation was 0.47, 0.68 and 0.01 for total subjects, TSDs and CTLs respectively.

Object Alternation—In this computerized test, two cups, one red, the other blue, appeared at each of a maximum 50 trials. The subject was told that a coin was hidden in one of them and their task is to guess which one, red or blue. The side of the screen on which a particular cup color appears changed every 1 or 2 trials. After each correct response, the coin moved to the cup of the other color. When the subject responds correctly on 12 trials, the test learning criterion was considered met and the task ended. The identical test was presented on Days 5 and 8. Test-retest correlation was 0.69, 0.59 and 0.64 for total subjects, TSDs and CTLs respectively.

Haylings Sentence Completion—Subjects were given 20 incomplete sentences and asked to generate a word they “think could fit at the end of the sentence” (“congruent” responses) followed by 20 for which participants were instructed to “respond with a word that makes no sense at all in the context of the sentence” (“incongruent” responses). Incomplete sentences for which 90 to 99 percent of American young adults gave the same word ending were obtained from Bloom and Fischler (1980). Forty sentences were used on Day 5 and a different 40 were used on Day 8. Testing conditions and instructions were identical to those described for the second study in Harrison and Horne (1998).

All responses were recorded, coded for subject, randomly admixed, and three judges who were entirely blind to instruction type (congruent or incongruent) or participant identity gave each sentence an “error score.” Error scores were a modification of Burgess and Shallice’s

(1996) three-level (0, 1 or 3) scoring system that added a fourth level (.5). Maximum error score (3) was given to sentences that were logically completed. Therefore, the first 20 sentences of each list (congruent ending) usually received this rating and were not included in the computation of final error score. Minimum error score (0) was given to responses that successfully made “no sense at all in the context of the sentence” while scores of 1 and .5 reflected a degree of response relatedness to sentence context based upon specific rules. After all sentences were rated, they were re-matched with participants and the mean error score for the three judges was computed for each sentence.

Outcomes were the mean error scores of three judges (Error score), mean reaction time to produce incongruous responses (RT incongruous), and ratio of mean incongruous reaction time to mean congruous reaction time (RT incongruous/congruous). Test-retest correlation of error scores was 0.17, 0.45 and 0.17 for total subjects, TSDs and CTLs respectively.

Stroop Color-Word—In this standard, investigator-administered booklet version of the Stroop test, subjects were presented with three pages each with items in 5 columns. The first had columns with color names in black ink, the second with columns of red, green and blue X’s and the third with color names written in a different color ink. The subject had 45 sec to read as many items as possible on each page. For the Interference score, slowing of color naming on the third page produced by the conflicting, pre-potent tendency to instead read the word name is computed as the difference between an predicted score based on the non-conflict pages and the actual timed score. The Color-word score was the actual number read correctly on the third, conflict page. The identical test was presented on Days 5 and 8. The “Manual for Clinical and Experimental Uses” (Golden, 1978) reports test-retest reliabilities of 0.69 to 0.73 for the Color-word score. In the current study, test-retest correlation for total subjects, TSDs and CTLs respectively was 0.15, 0.01 and 0.33 for the Interference score and 0.57, 0.57 and 0.67 for the Color-word score.

Smell Identification Test™—Consisted of 40 microencapsulated samples of odorous substances, equally divided among 4 booklets that the participant released by scratching. The participant then chose an identity from four written smell names. The identical test was presented on both days. Outcome score was the number correct. The Administration Manual (Doty, 1995) gives average correlation between each 10-item booklet as 0.73–0.78 and between pairs of booklets as 0.81–0.87. Test-retest correlation was 0.63, 0.60 and 0.64 for total subjects, TSDs and CTLs respectively.

Shepard-Metzler Mental Rotation—Participants viewed two objects made of several cubes combined at their faces on a computer screen and, by mentally rotating them, determined whether they were the same or different. Eighty stimuli were presented in two 40-stimulus blocks. The identical test was presented on both days. Outcomes were percent of figures correctly judged (Percent correct rotations) and mean time (milliseconds) for correct responses (RT correct rotations). The identical test was presented on Days 5 and 8. Test-retest correlation for total subjects, TSDs and CTLs respectively was 0.75, 0.78 and 0.74 for Percent correct rotations and 0.78, 0.75 and 0.78 for RT correct rotations.

Statistical Analyses

Differences between CTL and TSD groups' Day-5 performance on each outcome variable were compared using two-tailed, unpaired-t and Mann-Whitney U-tests. Demographic, Nightcap and subjective-report variables were similarly compared between groups.

Because, on Day 5, outcome variables might have systematically varied with factors other than the direct effects of sleep deprivation, TSD and CTL subjects were also compared after adjusting each outcome variable for 8 specific covariates (Table 2) in separate analyses of covariance (ANCOVA). Covariates were post-hoc proxy estimates for uncontrolled factors potentially affecting performance at time of testing and included demographic (e.g., age) and trait (e.g., intelligence), fatigue and mood prior to testing (e.g., SSS, POMS), potential fatigue secondary to testing itself (ordinal position), and estimated objective and subjective sleep parameters during baseline nights. Outcome variable-covariate combinations that showed significant ($p < .05$) group X covariate interaction were not further analyzed due to non-homogeneity of regression coefficients (Wildt & Ahtola, 1978). ANCOVAs in which the group X covariate interaction was not significant were repeated excluding any variance due to interaction. If, and only if, the outcome variable then significantly varied ($p < .05$) with the covariate, the group (TSD vs. CTL) difference was re-examined. When, for a particular outcome variable, correlation with more than one covariate proved significant, ANCOVA was repeated including all possible pairs of such covariates.

Paired t-tests were used to compare Day 5 to Day 8 performance within each group for those tests given in identical form on both days.

Results are presented both without and with Bonferroni correction in order to both maximize sensitivity to potential group differences and adjust for multiple comparisons. Although Kolmogorov-Smirnov tests showed that no distribution of Day 5 outcome scores significantly differed from normality across all subjects, analyses were repeated using log-10 transformed outcome scores as a conservative measure to confirm results using untransformed scores. For similar reasons, unpaired t-test analyses were confirmed using Mann-Whitney U-tests. TABLE 2 HERE

Results

Comparison of TSD and CTL group characteristics

The TSD and CTL groups did not differ in age (TSD mean 21.1 years, SD 1.9; CTL 21.1, SD 1.6), years of undergraduate education (TSD 2.9 years, SD 0.8; CTL 2.8, SD 1.2) or self-reported total SAT score (TSD 1371, SD 143; CTL 1338, SD 153). At their initial telephone screening, TSDs and CTLs self-estimated their habitual sleep time to be an identical mean of 7.4 hours. There were no significant differences between weekdays and weekends or between groups in subjects' estimated habitual duration elapsing between bedtime and rise time [weekdays: TSDs 8.1 hours (SD 0.9), CTLs 8.3 (1.3); weekends TSDs 8.8 (1.2), CTLs 8.3 (0.8)].

Sleepiness, sleep duration, motivation and effort

Hourly SSS scores were significantly greater ($p < 0.01$) in the TSD group at each hour from 10:00 to 18:00 hr on Day 5 (Figure 1a) indicative of greater Day 5 sleepiness in the TSD group. Moreover, for the POMS “Energetic” and “Clear-headed” factors, the difference between afternoon scores (mean of 12:00–18:00 hr) on Day 4 (when neither group was yet sleep deprived) and Day 5 was significantly greater in the TSD group (Energetic factor, TSD=9.5 SD=7.1, CTL=0.1 SD=4.2, $p = 0.002$; Clear-headed factor, TSD=3.2 SD=3.8, CTL=0.5 SD=2.1, $p = 0.02$).

Day-5 questionnaire-measured time from lights out until wake-up and Nightcap-measured total sleep time were significantly greater in the TSD group (Figure 1b,c) indicating greater accumulated sleep pressure in this group. Neither measure differed between TSD and CTL groups on any other night. Moreover, the CTL group’s Day 4 sleep, during which the TSD group was sleep deprived, did not differ from either their own or the TSD group’s Day 1–3 baseline values. Notably, across all subjects, estimated habitual sleep reported at screening (7.4 hours, SD 0.8) was significantly longer than their mean baseline (Days 1–3) Nightcap-measured total sleep time of 6.3 hours (SD 1.4, paired t-test, $p = 0.0003$), and trended longer than their Day 1–3 questionnaire-measured time in bed (6.9, SD 1.2, $p = 0.06$).

Overall mean absolute VAS ratings also did not differ between groups for “effort” (TSD 82.6 mm, SD 13.2; CTL 78.2, SD 18.5) or “motivation” (TSD 81.4 mm, SD 12.7; CTL 72.4, SD 20.3). For TSD subjects, across all tests, average relative* VAS ratings for effort significantly declined from the first to tenth test (simple regression $R = .82$, $p = 0.004$) whereas average relative ratings for motivation did not ($R = .45$, $p < .2$) while for CTL subjects there was a similar trend for effort ($R = .62$, $p = 0.06$) but not motivation ($R = .53$, $p < 0.2$).

Group Comparisons of Day 5 Performance Following TSD versus Normal Sleep (CTL)

Performance measures for Day 5 testing are shown in Table 3, along with effect sizes for TSD versus CTL differences. Among all outcome variables, CTLs performed better than TSDs at the unadjusted $p < 0.05$ level only on the Temporal Memory test’s d-prime measure for correct identification of items previously seen in either set, an effect driven by greater numbers of false (“false alarms”) rather than correct (“hits”) recognitions (Table 3). Notably, groups performed equally well in assigning correctly recognized faces to either the first or second set presented (“Correct set”). However, TSDs were more confident than CTLs in their incorrect set assignments as measured either by their relative confidence ratings or by the difference in mean raw confidence ratings between correct and incorrect set assignments. The results presented in Table 3 are unadjusted for multiple comparisons. Despite this, only Temporal memory showed group differences. Notably, among these Temporal memory measures, performing Bonferroni adjustment for three outcome variables (d-prime, Correct set, Relative confidence), resulting in an alpha level of $p = 0.017$, would eliminate significance for even these variables. It also should be noted in Table 3 that the majority of effect sizes were either uninformative (< 0.2) or small ($.2 < \text{effect size} < .5$, Lipsey and

*Relative VAS was absolute VAS in mm divided by a subject’s grand mean VAS over all tests.

Wilson, 2000). Moderate effect sizes ($.5 < \text{effect size} < .8$) were seen only for Mental Rotation RT correct rotations (TSD group better), Tower of London Initiation time (TSD group better), and Category Fluency Words generated (CTL better). Large effect sizes (>0.8) were observed only in the Temporal memory variables for which unadjusted ($p < 0.05$) significance was achieved,

Almost identical results were obtained when log-10 transformed scores were used in analyses. Similarly, group comparisons of Day 5 testing using the Mann-Whitney U test showed the same group differences at $p < 0.05$ as the above un-paired t-tests.

Only three additional group differences were revealed when ANCOVA was used to control for potentially confounding factors. Without adjustment for multiple comparisons, significantly better performance by the CTL group was seen using log-10 transformed (but not raw) values of the Stroop Interference score controlling for pre-test sleepiness as measured by the SSS [$F(1,22) = 5.5$, $p = 0.03$]. Controlling for sleepiness also revealed an unadjusted trend toward better CTL performance on the Verbal Fluency test for both raw and log-transformed scores [$F(1,21) = 2.9$, $p = 0.1$ and $F(1,21) = 3.5$, $p = 0.08$ respectively]. Similarly, a trend toward better CTL Category Fluency performance (both raw and log-transformed) was seen when participants' mean baseline (Days 1–3) Time-in-bed was controlled [both, $F(1,21) = 4.0$, $p = 0.06$]. However, the fact that multiple ANCOVA comparisons were made among tests measuring abilities with a degree of cognitive overlap (i.e., different EF assessments) precludes confidence that these findings truly represent statistical significance or trends. ANCOVA using pairs of covarying factors revealed no additional group differences.

Changes in performance between Days 5 and 8

Table 4 shows the results of paired t-tests comparing performance on Days 5 and 8 in TSD and CTL groups for only those tests given in identical form on both days and in which one or both groups showed significant improvement. (Verbal and Category Fluency and Haylings tests were excluded because alternate test variants were used on the two days while Temporal Memory was excluded due to complex memory effects expected from multiple exposures to stimuli.) Both groups improved on Logical Reasoning, Tower of London Initiation and Execution times, Object Alternation and Mental Rotation Percent correct rotations. Improvement was seen only in CTLs on the remaining Tower of London and Mental Rotation variables as well as the Stroop Color-word score while improvement was seen in only TSDs on the Digit Span tests. When the two groups were compared on retest Day 8, with few exceptions, unpaired t-tests showed no significant differences between the two groups' performance either on those tests given as alternate versions or on those tests repeated in identical form. Exceptions were Tower of London Total correct (CTLs better, $p = 0.06$) and Object Alternation (TSDs better, $p = 0.05$).

As noted, an ancillary goal of the current study was to identify assessments that showed no practice effects in control subjects and might, therefore, be used as a repeated measure without the need for alternate versions. Tasks fulfilling this criterion included Digits Forward, Digits Backward, 2-Back, Modified Iowa Gambling and Smell Identification tests as well as the Stroop Interference score.

Discussion

Despite subjective evidence of enhanced sleepiness and objective evidence of elevated sleep pressure, young adult male college students sleep deprived for 35–39 hours showed few deficits compared to control subjects on a battery of tests believed to assess executive functions and their component skills such as working memory. Among 23 main outcome measures on 13 EF tests, superior performance reaching an unadjusted $p < 0.05$ level of significance in control subjects was seen only on the Parkin Temporal Memory test using a signal detection analysis of simple recognition memory and in confidence assessments of temporal memory accuracy. The latter finding constitutes replication of a result reported by Harrison et al. (2000). Notably, simple recognition memory is not itself considered an executive function. ANCOVA suggested that co-varying factors such as pre-test sleepiness and habitual time-in-bed may have masked some further impact of TSD on performance of the Stroop, Verbal Fluency and Category Fluency tests. Adjustment for multiple comparisons would, however, eliminate even these modest group differences. At re-test following recovery sleep, the majority of outcome variables showing practice effects displayed lesser benefit from prior test exposure in sleep-deprived versus control subjects. This suggests poorer encoding of performance-relevant information due to TSD at initial exposure. Improvement in sleep-deprived subjects following recovery sleep on Digit Span tests, which lacked practice effects in controls, may have resulted from sleep-deprivation induced deficits at initial testing.

In contrast to current findings of absent or weak TSD effects, impairments in EF following TSD have been extensively reported in previous investigations (reviewed in Harrison & Horne, 2000b; Jones & Harrison, 2001). Possible explanations for these differences are described below with details given in Table 5. It is notable that for each such explanation of the current study's failure to find differences in EF performance between TSD and CTL subjects, other studies exist that have reported EF deficits produced by TSD under similar conditions. In the final section, it is therefore suggested that the naturalistic design of the current study resulted similar performance in both groups due to subjects' being tested under some degree of sleep restriction. This possibility, in turn, holds important implications as to how young adult students perceive adequate sleep and manage sleep loss.

Ceiling effects in healthy, resilient participants—Assessments designed to detect deficits in neurologically impaired subjects (e.g., Smell Identification) may not detect the mild effects of TSD in healthy, intelligent young subjects. Nonetheless, sleep-loss related deficits in healthy young adults have been previously reported on many of these same tasks (Table 5). Ceiling effects might also arise if the EF capacity of the study population was much higher than populations on which tests were normed. Therefore, where available, age-adjusted standardized or percentile scores of were determined for subjects' Day 5 performance (Table 6). Mean standardized scores for subjects show their performance on Digit Span (sum of forward and backward) to be approximately 1 standard deviation (SD) above average, and on Stroop to be less than 1 SD above average relative to respective standardization samples. Percentile scores for Smell Identification were slightly below median, whereas, for Tower of London, 4 of 5 measures in the current sample were well

below the standardization sample median, especially for performance speed. Subjects' mean Verbal and Category Fluency scores were similar to those of demographically similar populations. However, group means for TSD and CTLs fall in the higher range of percentiles reported for a large sample of normal individuals segregated by age and level of education (Sprenn & Strauss, 1998). Therefore, except for some indication of superior working memory and/or attention (Digit Span) and verbal skills (Fluencies), the current subjects' performance resembles or, in some cases may even be poorer than that of age-adjusted norms.

Floor effects—The modified Iowa Gambling Test was too difficult for the majority of participants to report even a strong hunch, when queried, as to what the rule might have been. Such a floor effect was apparent in the only slightly above-chance performance (56 to 58 % advantageous moves) on the Modified Iowa Gambling Task in contrast with normal performance on the standard Iowa Gambling Test (Bechara et al., 1999). Effects of TSD on the standard IGT reported by Killgore et al. (2006), therefore, cannot be compared with the current results.

Duration of TSD—Although a greater degree of experimental TSD has been employed by some investigators, the majority of studies reporting TSD effects on EF have, like the current study, used only one night's TSD (Table 5)

Sex ratio—Unlike most prior studies, this study tested only males. However, a mixed group has also been reported not to have shown TSD effects on EF following 34–36 hours TSD.

Between vs within-subject design—Group comparisons in the current study lacked statistical power to demonstrate TSD effects reported from published within-subject design studies that used counterbalanced alternate versions of tests (Horne, 1988; Harrison & Horne, 1997; Killgore & McBride, 2006). However, other studies have reported such impact of TSD on EF using group designs (Table 5).

One way in which a group, versus within-subject design might fail to detect TSD-induced impairment would be if the TSD group had, fortuitously, a greater baseline EF capacity than the CTL group. In the current study, three observations argue against this possibility. First, when practice effects occurred, greater improvement was seen in controls rather than sleep-deprived subjects, contrary to what might be expected if sleep-deprived subjects' putatively superior performance had both recovered its normal rested capacity and benefited from practice effects. Second, for those measures that did not change at re-test in controls, suggesting little practice effect, the groups continued not to differ at re-test suggesting a baseline similarity between groups. Third, alternate versions of Verbal Fluency, Category Fluency and Haylings tests administered to both groups after recovery sleep failed to show group differences.

Sample size—Although fewer subjects were studied in the current study than in some other one-night TSD group-design studies (e.g., Harrison & Horne, 2000a; Harrison et al., 2000), other studies have reported group differences using comparable sample sizes (Table

5). Additionally, power analysis for two-tailed $\alpha = 0.05$ at 80% power revealed that only two variables would have yielded significance for superior performance in the CTL group with less than 90 subjects (Category Fluency, 2-back d-prime), the same number of variables, in other tasks, that would have yielded superior performance in the TSD group (Tower of London Initiation time, Mental Rotation RT correct rotations).

Test battery versus single assessment—The current study used a longer test battery with a wider variety of tests than most prior studies that were limited to a few tests lasting only 1–2 hours (Table 5). Interestingly, in the one prior study that used an extended battery, a similar lack of TSD effects on EF was reported.

Although it might be hypothesized that “getting into set” could improve performance as the subject progresses through the battery, across-subjects regression analyses of tests’ ordinal positions in the battery against performance gave no indication of improvement. Instead, poorer performance with later presentation on Tower of London was indicative of fatigue effects. Nonetheless, diverse, challenging, enjoyable and relatively brief tests, alternating between different examiners, might have compensated for the deleterious effects of TSD seen in less interesting testing contexts (see Broughton & Ogilvie, 1992; Chee & Choo, 2004).

Circadian influences—Testing occurred in early to mid-evening when an enhanced drive to waking and alertness during the circadian acrophase produces a “forbidden zone” for sleep (Binks et al., 1999; Lavie, 1986). Whereas in some studies testing closer to the morning circadian nadir have revealed one-night’s-TSD-related impairments of EF, early evening testing has also revealed such impairments (Table 5).

Homeostatic influences—Accumulation of homeostatic sleep pressure in CTL subjects during their prior 10–12 hours of waking may have equalized fatigue and EF capacity between TSD and CTL subjects, possibly in synergism with alerting influences of the circadian acrophase. However, again, TSD-related deficits have been revealed by evening testing (Table 5).

Caffeine use—Caffeine use, allowed up to 4 hours prior to testing, might have ameliorated sleepiness in some TSD subjects. However, both groups were allowed this freedom, the majority of TSD subjects did not report even moderate baseline caffeine use and TSD subjects had access to caffeine only at mealtimes. Moreover, evidence exists that caffeine does not alter the effects of TSD on certain EF tests (Table 5).

Habitual sleep-wake behavior of subjects—Because there exist studies that show TSD effects on EF despite each of the above demographic and methodological factors, it is reasonable to consider whether the behavioral characteristics of this population under study may have contributed to negative findings. One such population characteristic is chronic sleep restriction. In a recent meta-analysis of normative values from 65 sleep studies (Ohayon, Carskadon, Guilleminault, & Vitiello, 2004), the regression line for age-related changes in total sleep time passed from slightly above to slightly below 7.5 hours across the 19–25 year age range. In contrast, mean Nightcap-measured sleep on the three baseline

week nights ranged from 3.5 to 10.8 hours (mean 6.3 hours, median 6.2). Additionally, a prior Nightcap study of Boston undergraduates, revealed sleep duration of 6.2 hours in self-described good and poor sleepers alike (Pace-Schott, Kaji, Stickgold, & Hobson, 1994). Notably, participants' estimate at screening of their habitual sleep was over an hour longer than their actual Nightcap-measured baseline (i.e., 7.4 hr versus 6.3 hours).

Chronic sleep restriction (SR) results in chronically enhanced sleep homeostatic drive ("sleep debt"), that, like TSD, degrades sustained attention and vigilance in a cumulative, dose-dependent manner (Jewett, Dijk, Kronauer, & Dinges, 1999). Executive function deficits following SR have also been reported in some (e.g., Herskovitch, Stuss, & Broughton, 1980) but not all studies (Minkel, Banks, McGillinchey, & Dinges, 2005). Several studies have also shown significant amelioration of the negative impact of SR on vigilance when sleep duration is reduced gradually versus rapidly (Drake et al., 2001; Friedmann, Globus, & Huntley, 1977). Therefore adaptation to chronic sleep restriction in this population may have ameliorated the homeostatic impact of TSD on performance.

Conversely, pre-existing sleep debt might have masked the acute effects of TSD because chronic SR-related impairment had eliminated a putatively sleep-sensitive EF reserve in control subjects. Notably, participants in many prior studies were selected for "good sleepers" who normally obtained 7 to 8 hours of sleep per night (Harrison & Horne, 1997; Harrison et al., 2000; Horne, 1988). Moreover, these studies prescribed a normative 7–8 hours of sleep opportunity for baseline days or for the night prior to sleep deprivation (Harrison & Espelid, 2004; Harrison & Horne, 1997; Horne, 1988; Nilsson et al., 2005). Therefore, by prescribing optimal habitual and pre-study sleep duration, earlier studies may have ensured that such a putative sleep-loss sensitive component of EF capacity would be initially present to then deteriorate in the face of experimental TSD. However, in the current naturalistic design, the habitual behavior of subjects might have precluded the presence of such reserves resulting in a full night's TSD having little effect in comparison with similarly sleep-restricted controls.

Implications and areas of future research

The current study suggests one possible reason for the persistence of sleep-restricting behavior and subjective tolerance of sleep debt that recent reports suggest is endemic among American college students (Hawkins & Shaw, 1992; Hicks, Fernandez, & Pellegrini, 2001b; Lack, 1986; Levine et al., 1988; Thacher, 2008). Acclimation to chronic sleep debt and/or chronic, sleep-debt-related deficits in EF reserves, may convince some young adults that acute sleep deprivation minimally impacts valued skills (e.g., academic performance, time management, social judgment). Such perceived evidence for the benign nature of sleep loss might be further strengthened by the resilience of young persons to the subjective effects of sleep deprivation (Banks & Dinges, 2007; Pilcher & Walters, 1997).

A recent study of Harvard University undergraduates suggests a second reason for the persistence of all-nighters. This study showed that, following several night's recovery sleep, long-term retention of complex mixed verbal-nonverbal declarative memory was little affected by one night of post-training TSD (Pace-Schott, Morgan, & Stickgold, 2007). Therefore, highly intelligent students with well-developed study skills possess cognitive

reserves in academic-performance-related domains (e.g., declarative memory) that are not fully expended by a single night of TSD.

Nonetheless, recent studies have indeed reported an association of sleep loss and poorer academic performance at the high school, undergraduate and professional school levels (Curcio et al., 2006; Kelly et al., 2001; Medeiros et al., 2001; Thacher, 2008; Wolfson & Carskadon, 2003). Moreover, both vigilance and performance are increasingly demonstrated to be sensitive to sleep loss throughout adolescence and early adulthood (Czeisler, 2006; Durmer & Dinges, 2005; Wolfson & Carskadon, 2003). In addition, impaired alertness in sleep-deprived young adults is hazardous under many circumstances such as driving (Millman, 2005). Cognitive reserves provided by sufficient sleep, although perceived as temporarily dispensable for adequate performance, may, in fact, represent valuable assets that have become under-appreciated by young adults accustomed to chronic sleep debt.

In future studies, it will be important to investigate the interaction of chronic sleep restriction with acute sleep loss in order to identify educationally relevant aspects of cognitive performance that are most sensitive to TSD under naturalistic conditions. To be ecologically meaningful, such studies must balance the need for realistic levels of physiological stress and cognitive demand with the need for adequate control of experimental conditions. Within-subject experimental designs that systematically vary the degree of pre-TSD sleep restriction, the degree of acute TSD and the difficulty and type of cognitive demand may help reveal key areas of vulnerability to sleep loss in student populations. The two above hypotheses on how sleep debt might equalize performance between acutely sleep-deprived and non-sleep-deprived but equally sleep-restricted individuals, viz. acclimation versus shared loss of reserves, have very different implications for how adequate sleep might be perceived and promoted by students, administrators and health care providers.

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C. Total Sleep Time (Nightcap)

Figure 1.

Stanford Sleepiness Scale ratings and daily objective and subjective sleep duration demonstrating that both sleepiness and sleep pressure on Day 5 (Friday) were greater in subjects with a night's total sleep deprivation between Days 4 (Thursday) and 5. A. Hourly Stanford Sleepiness Scale ratings on Days 4 and 5 showing increasing sleepiness in TSD subjects overnight and significantly greater sleepiness ratings in this group throughout Day 5. B. Questionnaire-response estimates of time-in-bed (from lights out to waking), note significantly longer sleep in the TSD group the night of Day 5 following sleep deprivation. C. Total sleep time scored algorithmically by Nightcap. Note again significantly longer sleep in the TSD group on Day 5. Arrow indicates night TSD subjects sleep deprived. [†] $p < .05$, * $p < .01$, ** $p < .001$.

Table 1

Study 1 test battery, presentation modality, variables and their units of measure, source.

Test	Modality	Variable(s)	Reference or source
Verbal Fluency (L) a	Investigator	Words generated in 1 min (#)	Lezak et al. 2004
Category Fluency (L) a	Investigator	Words generated in 1 min (#)	Lezak et al. 2004
Logical Reasoning (L)	Paper and Pencil	Correct solutions (#)	Baddely, 1968 modified by Blagrove et al., 1995
Tower of London ^{dx} (L)	Investigator	Total move score (#)	Shallice (1982) modified by Culbertson and Zillmer (2001), Mental Health Systems, Inc.
Tower of London (L)		Total correct (#)	
Tower of London	stopwatch	Initiation time (sec.)	
Tower of London	stopwatch	Execution time (sec.)	
Temporal Memory (P)	Investigator	recognition memory, d-prime	Harrison and Horne (2000a) modification of Parkin et al. (1995)
Temporal Memory (L)		Correct set (1 or 2) identified (#)	
Temporal Memory		Confidence (subject scored 1–5)	
Digits Span Forward (L) b	Investigator	Digits forward (#)	Weschler (1981), WAIS-R®, The Psychological Corp
Digits Span Backward (L) b	Investigator	Digits backward (#)	Weschler (1981), WAIS-R®, The Psychological Corp
2-Back (L) b	Computer	signal detection, d-prime	Cohen et al. (1994) modified by Thermeos et al. (2005)
2-Back		RT correct (msec.)	
Modified Iowa Gambling Task (V)	Computer	Advantageous draws (#)	Bechara et al. (1999) modified by C. Hart and R. Foltin
Object Alternation (V)	Computer	Trials to criterion (#)	Freedman (1990) modified by Dinn and Harris (2000)
Haylings Sentence Completion (V)	Audiotape	Error score (judged)	Burgess and Shallice (1996) modified by Harrison and Horne (1998)
Haylings Sentence Completion	stopwatch	RT incongruous (sec)/RT congruous (sec)	
Stroop Color Word Test (V)	Investigator	Interference score	Stroop (1935) modified by Golden (1978), Stoelting Company
Stroop Color Word Test		Color-word score (#)	
Smell Identification Test™ (V)	Investigator	Correct discriminations (#)	Doty (1995), Sensorics, Inc.
Mental Rotation (P)	Computer	Percent correct rotations (%)	Kosslyn et al. (1998)
Mental Rotation (P)		RT correct rotations (msec.)	

L, V or P--Traditionally believed to recruit strongly lateral (L) or ventromedial/orbitofrontal (V) PFC or posterior regions (P), lowercase letters (a, b) indicate tests that were always given together within the each of the counterbalanced test orders.

Covariates used to adjust group comparisons of Day 5 performance following TSD versus normal sleep

Table 2

Estimated factor	Covariate
Age	Exact age within the 19–25 year limits
Academic ability	Self-reported Scholastic Aptitude Test (SAT) Total Score
Fatigue at testing	Mean Day 5 SSS score for 17:00 and 18:00 hours, mean POMS “Energetic” and “Clear-headed” factors for 17:00 and 18:00 hours
Mood State	Mean POMS “Elated” factor for 17:00 and 18:00 hours
Effort at testing	Mean VAS (as % of S’s overall mean VAS) rating (in mm) for “Effort” & “Motivation”
Test order	Ordinal position in the specific counterbalancing in which the test was presented
Baseline sleep quantity	Time-in-bed, average for Days 1–3 computed from sleep questionnaire
Baseline sleep quantity	Total-sleep-time, average of Days 1–3 computed from Nightcap data.

Mean scores for test variables on Day 5 showing TSD and CTL group means and standard deviations (in parentheses) as well as effect size of difference between TSD and CTL

Table 3

Test	Variable(s)	TSD *	CTL *	ES **
Verbal Fluency	Words generated	47.8 (12.1)	48.9 (12.0)	0.08
Category Fluency	Words generated	23.2 (4.1)	26.6 (6.2)	0.65
Logical Reasoning	Correct solutions	43.7 (13.1)	46.3 (18.2)	0.16
Tower of London	Total move score	18.3 (14.0)	22.3 (14.9)	0.28
Tower of London	Total correct	5.7 (2.8)	5.9 (2.2)	0.06
Tower of London	Initiation time	7.5 (4.7)	12.9 (12.0)	0.60
Tower of London	Execution time	23.7 (8.9)	28.0 (11.8)	0.42
Temporal Memory	d-prime	2.73 (0.67)	3.28 (0.50)	0.93 [‡]
Temporal Memory	hits	22.50 (1.78)	22.86 (1.10)	0.24
Temporal Memory	false alarms	5.10 (3.60)	2.36 (1.69)	-0.97 [‡]
Temporal Memory	Correct set	17.7 (2.2)	18.3 (2.7)	0.24
Temporal Memory	Relative confidence (wrong)	1.03 (0.21)	0.86 (0.15)	-0.93 [‡]
Temporal Memory	Confidence (right-wrong)	0.37 (0.67)	0.87 (0.52)	0.83 [‡]
Digits Span Forward	Digits forward	10.8 (1.6)	11.4 (1.9)	0.31
Digits Span Backward	Digits backward	9.3 (2.5)	9.4 (2.4)	0.06
2-Back	d-prime	2.73 (0.92)	3.14 (0.78)	0.48
2-Back	RT correct	725 (179)	671 (151)	-0.33
Modified Iowa Gambling Task (mIGT)	Advantageous draws	58.2 (16.8)	56.1 (14.1)	-0.14
Object Alternation	Trials to criterion	24.1 (15.1)	29.3 (18.7)	0.31
Haylings Sentence Completion (Haylings)	Error score	3.21 (1.66)	3.43 (1.55)	0.14
Haylings	RT incongruous/congruous	2.8 (1.4)	2.4 (1.2)	-0.25
Stroop Color Word Test (Stroop)	Interference score	4.4 (10.6)	5.7 (6.4)	0.15
Stroop	Color-word score	51.5 (13.4)	52.6 (9.3)	0.10
Smell Identification Test™	Correct discriminations	35.7 (2.5)	35.9 (2.2)	0.08
Mental Rotation	Percent correct rotations	81.3 (13.5)	83.4 (10.4)	0.17
Mental Rotation	RT correct rotations	5638 (1724)	8135 (4349)	0.76

* Entries consist of mean (standard deviation), $n = 10 - 11$ for TSDs, 12 - 14 for CTLs.

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$$Effect\ Size\ (Cohen's\ d) = \frac{(mean\ CTL - mean\ TSD)}{[(SD\ CTL^2 + SD\ TSD^2)/2]}^{1/2}$$

*
*
† Differed significantly between groups (p < .05 on t-and Mann Whitney U-tests).

Change between Days 5 and 8 in sleep deprived (TSD) and control (CTL) groups compared with paired t-tests for tests on which one or both groups significantly improved.

Table 4

test	Mean (SD) TSD *	Mean (SD) CTL *
LOGIC		
Correct solutions		
Day 5	43.2 (13.7)	40.5 (11.2)
Day 8	54.8 (13.8)	51.8 (10.8)
p	0.02	0.004
TOWER OF LONDON		
Total move score		
Day 5	18.3 (14.0)	20.4 (14.8)
Day 8	17.0 (12.0)	11.1 (11.1)
p	NS	0.08
Total correct		
Day 5	5.7 (2.8)	6.4 (1.8)
Day 8	6.5 (2.2)	8.2 (1.7)
p	NS	0.02
Initiation time		
Day 5	7.5 (4.7)	13.3 (12.5)
Day 8	4.0 (3.5)	7.8 (6.5)
p	0.004	0.03
Execution time		
Day 5	23.7 (8.9)	29.4 (13.1)
Day 8	15.5 (5.8)	18.9 (6.7)
p	0.003	0.001
DIGIT SPAN		
Digits Forward		
Day 5	10.7 (1.8)	10.9 (1.8)
Day 8	11.5 (1.6)	11.3 (1.7)
p	0.03	NS

test	Mean (SD) TSD *	Mean (SD) CTL *
Digits Backward		
Day 5	9.6 (2.4)	9.0 (2.5)
Day 8	10.8 (2.3)	9.6 (2.6)
p	0.1	NS
Digits Backward		
Day 5	9.6 (2.4)	9.0 (2.5)
Day 8	10.8 (2.3)	9.6 (2.6)
p	0.1	NS
OBJECT ALTERNATION		
Trials to criterion		
Day 5	23.3 (15.7)	31.7 (19.4)
Day 8	5.6 (9.3)	18.7 (17.6)
p	0.0005	0.02
STROOP		
Color-word score		
Day 5	52.4 (13.8)	50.6 (6.6)
Day 8	52.7 (12.1)	55.3 (8.2)
p	NS	0.03
ROTATION		
Percent correct rotations		
Day 5	80.3 (14.0)	77.4 (20.1)
Day 8	86.7 (9.6)	84.8 (13.7)
p	.07	.08
RT correct rotations		
Day 5	5614 (1827)	9533 (5346)
Day 8	4796 (1893)	6310 (3052)
p	NS	.009

* Means computed only for subjects with both Day 5 and Day 8 testing, n = 9–10 for TSDs and 11–12 for CTLs.

Additional details on published findings showing significant impact of TSD on EF using populations, experimental designs, sample sizes, timing of tests and other factors similar to the current study in which such an impact was not observed.

Table 5

Issue(s)	Question	Relevant tests	Relevant Studies	Comment
Ceiling effects	Are tests sufficiently sensitive in normal young adults?	Smell Identification Verbal fluency	Killgore & McBride 2006 Harrison & Horne 1997; Horne, 1988	Sleep-loss related EF deficits have been demonstrated in healthy young adults. (See also Table 6.)
Resilience of youth	Does cognitive reserve obscure effects?	Tower of London Temporal Memory Logical reasoning	Horne 1988 Harrison & Horne 2000a; Harrison et al. 2000 Blagrove & Akehurst 2000	
Duration of TSD	Is 36–39 hours sufficient to reveal effects of TSD on EF?	Iowa Gambling Test Logical Reasoning Verbal Fluency Temporal memory Haylings sent. compl. Smell Identification	Blagrove & Akehurst, 2000; Killgore et al., 2006) Harrison & Horne 1997 Harrison & Horne 1998, 2000a. Harrison et al., 2000 Killgore & McBride, 2006	Studies with TSD greater than 36–39 hours have reported EF deficits. However, EF deficits have also been reported following 36–39 or less hours TSD.
Sex ratio	Does entirely male cohort obscure TSD effects?	Verbal fluency Stroop	Binks et al. 1999	A mixed gender study also failed to find deficits following an equivalent duration TSD.
Between vs within-subject design	Is there insufficient power to demonstrate TSD effects in a group design	Haylings sent. compl. Temporal Memory	Harrison & Horne, 1998; Harrison et al., 2000) Harrison & Horne 2000a; Harrison et al. 2000	Between-subjects as well as within-subject designs have demonstrated one-night's TSD performance effects on EF tests.
Sample size	Were insufficient subjects studied to reveal significant differences?	Haylings sent. compl. 6-Elements Test	Harrison & Horne, 1998; Nilsson et al., 2005	One-night's TSD effects on EF have been reported using sample sizes similar to the current study.
Duration of testing sessions	Does an extended test battery obscure effects of TSD?	Verbal Fluency Temporal memory Haylings sent. compl. Other EF tests Verbal fluency Stroop	Harrison and Horne, 1997; 1998; 2000a; Harrison et al., 2000; Nilsson et al., 2005 Harrison and Espelid, 2004 Binks et al. 1999	Most studies reporting EF deficits had test durations of less than 2 hours. The one other extended (2- to 2.5-hour) battery also failed to reveal EF deficits following TSD

Issue(s)	Question	Relevant tests	Relevant Studies	Comment
Circadian Factors	Does testing during the circadian acrophase mask TSD deficits?	<p>Small Identification Iowa Gambling 6-Elements Test</p> <p>Verbal Fluency, Tower of London, Temporal Memory, Haylings sent. compl.</p> <p>Temporal Memory, Haylings sent. compl</p>	<p>Killgore & McBride, 2006 Killgore et al., 2006 Nilsson et al., 2005</p> <p>Harrison & Horne, 1998, 2000a; Harrison et al., 2000; Horne, 1988)</p> <p>Harrison et al. (2000)</p>	<p>Studies testing nearer in time to the circadian nadir have reported TSD-related EF deficits.</p> <p>However, studies testing nearer to the circadian acrophase, as in the current study, have also shown one-night's-TSD-related EF impairments.</p> <p>No circadian effects on performance of Temporal memory and Haylings were seen in older adults.</p>
Homeostatic factors	Does testing when CTL subjects have had maximal time awake mask TSD deficits?	Verbal Fluency, Tower of London, Temporal Memory, Haylings sent. compl	Harrison & Horne, 1998, 2000a; Harrison et al., 2000; Horne, 1988)	Studies that tested in the evening, following almost the entire normal waking duration of controls, have also shown EF impairments in experimental groups resulting from the previous night's TSD.
Caffeine availability	Did allowance of caffeine within 4 hours of testing mask TSD deficits?	<p>Temporal memory</p> <p>Haylings sent. compl Verbal Fluency</p>	<p>Harrison & Horne, 2000a</p> <p>Harrison, Horne, & Rothwell, 1997</p>	Acute caffeine has been shown not to eliminate one-night's-TSD-related EF impairments.

Table 6

Day 5 performance of TSD and CTL participants compared to published standardization samples by conversion to standardized scores or by comparison to demographically similar samples.

Test	reference	standard/comparison	variable	comparison	TSD mean (SD)	CTL (SD)
Digit Span	Weschler 1981	* scaled score	Digits Forward+Backward		13.1 (2.2)	13.5 (2.3)
Stroop	Golden (1978)	* T-score	Interference score		53.5 (9.1)	55.4 (5.4)
			Color-word score		56.4 (13.3)	57.5 (9.1)
Tower of London	Culbertson & Zillmer (2001)	* Percentile	Total move score		31.7 (25.4)	38.8 (28.0)
			Total correct		64.7 (28.9)	68.7 (25.2)
			Initiation time		29.9 (19.3)	24.0 (24.0)
			Execution time		28.7 (15.7)	18.7 (19.1)
			Total time		25.5 (17.2)	19.4 (23.3)
Snell identification	Doty (1995)	* Percentile	Correct discriminations		44.2 (28.1)	43.7 (26.9)
Verbal fluency	Mitrushina et al. 2005	[†] 7 samples of Ss' matched by gender and appx.age	# words (FAS): range	40.3 – 53.2		
			mean (SD)	43.9 (11.1)	47.8 (12.1)	48.9 (12.0)
			FAS matched by age & level of education		50–60	50–60
Category fluency	Ruff et al. 1996	* Percentile of mean	The letter C: mean (SD)	14.1 (4.15)	16.6 (4.8)	16.7 (4.4)
	Mitrushina et al. 2005	[†] 6 samples of Ss' matched by gender and appx.age	# words (animals): range	19 – 26.3		
			mean, (SD)	22.3 (4.8)	23.2 (4.1)	26.6 (6.2)
			animals age/edu. match		50–75	75–90

* TSD/CTL scores converted: scaled scores (mean=10, SD=3), T-scores (mean=50, SD=10), Percentile score (median=50);

[†]Unconverted mean TSD/CTL and comparator population values