

Effects of sleep inertia following daytime naps vary with executive load and vary time of day.

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ABSTRACT

The effects of executive load on working memory performance during sleep inertia following morning or afternoon naps were assessed using a mixed design with nap /wake as a between-subject factor and morning/afternoon condition as a within-subject factor. Thirty-two healthy adults (mean 22.5 ± 3.0 years) attended two laboratory sessions following a night of restricted sleep (6 hrs), and at first visit, were randomly assigned to the Nap or Wake group. Working memory (n-back) and subjective workload were assessed approximately 5 and 25 minutes after 90 minute morning and afternoon nap opportunities and at the corresponding times in the Wake condition. Actigraphically-assessed nocturnal sleep duration, subjective sleepiness and psychomotor vigilance performance prior to daytime assessments did not vary across conditions. Afternoon naps showed shorter EEG assessed sleep latencies, longer sleep duration, and more Slow Wave Sleep than morning naps. Working memory performance deteriorated, and subjective mental workload increased at higher executive loadings. After afternoon naps, participants performed less well on more executive-function intensive working memory tasks (i.e. 3-back), but waking and napping participants performed equally well on simpler tasks. After some 30 minutes of cognitive activity, there were no longer performance differences between the waking and napping groups. Subjective Task Difficulty and Mental Effort requirements were less affected by sleep inertia and dissociated from objective measures when participants had napped in the afternoon. We conclude that executive functions take longer to return to asymptotic performance following sleep than does performance of simpler tasks which are less reliant on executive functions.

Keywords:

Executive function, Sleep Inertia, Daytime naps, Sleep Restriction, Sleep structure

Introduction

Sleep inertia is that post-sleep state in which people experience reduced alertness and during which they gradually regain levels of performance characteristic of their rested waking levels of functioning (Lubin, Hord, Tracy & Johnson, 1976).

The effects of sleep inertia are strongest immediately after sleep and dissipate systematically, as a function of time awake, with residual detectable impairment for as long as 2-3 hours after awakening (Jewett et al., 1999). Effects of sleep inertia are greater following sleep deprivation and restriction (Balkin & Badia, 1988; Dinges, Orne & Orne, 1985; Rosa & Bonnet, 1985;) and some have postulated that inertia is associated with the stage from which sleepers awaken, and with the extent of slow wave (SWS) or non-REM sleep (Åkerstedt, Hume, Minors & Waterhouse, 1997; Bruck & Pisani, 1999; Ferrara, Gennaro, Casagrande & Bertini, 2000; Lavie & Weler, 1989; Rosa & Bonnet, 1985; Silva & Duffy, 2008). These findings suggest that sleep structure is associated with sleep inertia, but evidence, using a forced de-synchrony protocol (in which sleep and wakefulness are distributed across all phases of the circadian cycle (Dijk & Czeisler, 1995)), suggest that circadian phase also influences sleep inertia, independent of sleep stage. With 9 h 20 min sleep opportunities within a 28 hour sleep/wake cycle, effects of sleep inertia following awakening from stage 2 are greatest during the biological night (circa 2300-0300), decline systematically until 1500-1900 and increase thereafter (Scheer, Shea, Hilton & Shea, 2008). Best performance on waking, following 6 h 40 min sleep opportunities within a 20 hour sleep/wake cycle, is also seen in what would be early afternoon under entrained conditions, and worst performance when waking at times corresponding to an entrained night (i.e at core body temperature nadir; Silva & Duffy, 2008). Effects of sleep

inertia on waking from an extended sleep opportunity and daytime napping are believed to be similar (Achermann, Werth, Dijk & Borbély, 1995; Dinges, Orne, Evans & Orne, 1981).

Sleep inertia has been shown to influence performance on a broad range of tasks, including simple and choice reaction time, sustained attention tasks (e.g. letter cancellation and digit-symbol), mental arithmetic, logical reasoning and memory (Dinges, Orne & Orne, 1985). However, there is some suggestion that the reduction in impairment occurs more slowly, or the initial impairment is greater, when people are required to perform more complex tasks such as serial addition than tasks which simply require subjective reports on alertness (Jewett et al., 1999). A $H_2^{15}O$ PET study of regional Cerebral Blood Flow (rCBF) over the 20 minutes following waking from Stage 2 sleep identified a possible neurological substrate which would account for the differential recovery rate for tasks which vary in complexity (Balkin et al., 2002). $H_2^{15}O$ was injected intravenously before sleep; again 5 minutes later and 15 minutes after participants had been woken from Stage 2 sleep, after approximately 5 hours of sleep. Rate of blood flow increased substantially from Stage 2 sleep (39.8 ± 2.9 ml/100 mg/min) to waking (45.58 ± 2.5 ml/100 mg/min) after 5 minutes and stabilised thereafter. However, critical to the interpretation Balkin and colleagues offered, the estimated brain blood volume remained unchanged. Initial post-awakening increases in rCBF occurred primarily in the basal ganglia, thalamus and brainstem. In contrast, by 20 minutes post-waking increased rCBF was evident in the orbital and dorsolateral prefrontal cortices, frontal opercular cortex, middle temporal gyrus and superior temporal sulcus. That is, activity in brain regions traditionally associated with arousal, such as the reticular formation (Moruzzi & Magoun, 1949), is established very quickly after waking, but brain regions traditionally associated with executive functioning, such as the

prefrontal cortex (Braver et al., 1997; Collette, Hogge, Salmon & van der Linden, 2006; Groeger et al., 2008; Miyake et al., 2000; Vandewalle et al., 2009), only show increased activity some 20 minutes after waking.

To further investigate whether executive function in particular is affected by sleep inertia we designed a study in which executive load was varied by using 1-, 2- and 3-back verbal working memory tasks. While the physical demands of the three levels of n-back are identical, the more demanding n-backs have become paradigmatic exemplars of executive function tasks (Collette, Hogge, Salmon & van der Linden, 2006; Groeger et al., 2008; Miyake et al., 2000), and performance of the n-backs is associated with a parametric increase in rCBF in the prefrontal cortex (Braver et al., 1997). Previous studies have shown that subjective ratings of workload reflect the objective demands of tasks (Reid & Nygren, 1981), and correlate with other subjective workload measures as well as electrophysiological indices such as heart-rate variability, skin conductance responses and eye-blink frequency (Verwey & Veltman, 1996). However, less is known about whether workload assessments are sensitive to sleep inertia, and because of this we took advantage of the parametrically increasing difficulty of the n-back tasks to assess subjective workload after each task. Although exploratory, and of secondary importance to this paper, we expected that perceived task difficulty would increase systematically with n-back load, as would the perceived requirement for mental effort. The physical demand of the three levels of n-back are identical. However we anticipated a smaller increase in the perceived physical effort required, simply because when the rate at which stimuli are encountered is constant, the increased difficulty of higher levels of n-back might increase participants' subjective evaluations of the amount to be done in a short period of time.

The rating of energy available was expected to be constant across n-back tasks, although potentially sensitive to time of day.

The primary hypothesis tested was that sleep inertia would be greater for task(s) with a greater reliance on executive functions. If functioning reliant on the prefrontal cortex is regained more slowly as would be expected on the basis of the PET study of Balkin and colleagues (Balkin et al., 2002), and to a lesser extent the mathematical modelling of the time course of sleep inertia by Jewett and colleagues (Jewett et al., 1999), 3-back, and perhaps 2-back accuracy will be worse immediately after waking. To investigate to what extent these effects depend on time of day and/or sleep structure, we compared sleep inertia following morning naps, which are expected to contain little slow wave sleep (SWS), to afternoon naps, expected to contain more SWS.

Method

The study protocol was approved by the University of Surrey Ethics Committee, and was conducted in accordance with the principles of the Declaration of Helsinki.

Participants

All participants provided written informed consent after having received a detailed explanation of the study procedures, and received financial compensation for participating in each phase of the study. Thirty-two individuals (9 males), with a mean age of 22.5 years (SD = 2.98) participated. Based upon their responses to the British Sleep Survey (Groeger, Zijlstra & Dijk, 2004), all reported habitual bedtimes between 22:30 and 01:00 and wake times between

06:30 and 08:30. None reported persistent sleep difficulties. All scored ≤ 5 on the Pittsburgh Sleep Quality Inventory (Buysse, Reynolds, Monk, Berman & Kupfer, 1989). None reported excessive daytime sleepiness (i.e. Epworth Sleepiness Scores (Johns, 1991) ≤ 10). None reported being on medication other than oral contraceptives, and voluntarily abstained from caffeine and alcohol from 20:00 the night before each laboratory session. All were required to wear an actiwatch (Cambridge Neurotechnology), and not to sleep before 01:00 and for no more than 6 hours on the night before laboratory sessions.

Design

The study employed a mixed design with nap / wake as a between-subject factor and morning /afternoon condition as a within-subject factor. Each participant attended two laboratory sessions and, on the first occasion, was randomly assigned to the nap or wake group. Within the nap group, the Morning (10:00) or Afternoon (15:00) nap opportunities were counterbalanced across visits.

Procedure

In the week before each laboratory session participants were asked to maintain their typical bed and wake times. On the night before laboratory sessions all participants were required not to sleep before 01:00 and to sleep for no more than 6 hours. Their compliance with these requirements was monitored using actigraphy.

On the mornings of laboratory sessions, all participants arrived at the laboratory at approximately 08:30. At approximately 09:15 all participants attempted to learn 80 word pairs

(during which three recall attempts were made), rated their current sleepiness (using the Karolinska Sleepiness Scale, KSS, see below), performed a 10 minute computerised version of the Psychomotor Vigilance Task (PVT, see below), and again attempted to recall the word pairs. Morning nap opportunities began at 10:00, Afternoon nap opportunities began at 15:00. Morning wake group participants, and those scheduled to Afternoon naps, were free to read, watch movies, and play computer games until their napping confederate awoke, not more than 90 minutes later. At 11:30 (or 16:30 for the Afternoon group) n-back testing began, with 1-, 2-, 3- n-backs each followed by four subjective assessments of workload using a Visual Analogue Scale. These were underway within 5 minutes of waking for participants who napped, and at the same point for their waking controls (i.e. approximately 11:35, 16:35). Participants engaged in other cognitively demanding activity (working memory assessments of colour and spatial information, in which successive presentations of colours and/or locations of onscreen stimuli were compared). Some 25 minutes after waking, participants repeated the block of verbal 1-, 2- and 3- back tasks and subjective workload assessments (i.e. approximately 11:55, 16:55).

Materials and performance task configurations

Sleep Recordings. Naps were taken in a dark, sound-proofed booth within the testing area.

Sleep EEG was recorded with a Vitaport 3 recorder (TEMEC[®]) and a ten-channel montage consisting of six EEG (F3-A2, F4-A1, C3-A2, C4-A1, O2-A1, O1-A2), two electro-oculography (EOG), and two electro-myography (EMG) channels. Each 30-second epoch was scored using Rechtschaffen and Kales criteria (Rechtschaffen & Kales, 1968).

Paired-associate task. In each laboratory session, participants learned a different set of 80 randomly ordered word pairs, 40 of which were close semantic associates, each pair of which was sequentially presented on a PC-controlled CRT screen. Participants performed two immediate cued recall tests with feedback in the learning session. A final, delayed, cued recall followed the 10 minute PVT task. The paired-associate task is included here as a measure of morning cognitive functioning; further details of the effects of napping on retention of this learning will be reported elsewhere. The dependent variables of interest here are number of pairs correctly recalled in each cued-recall task.

N-back tasks. Based on previous studies (Groeger et al., 2008; Owens et al., 2005; Walsh et al., 2008), verbal 1-, 2- and 3-back tests each required 32 successive matches with one of nine single consonants presented on a black background for 500 ms, with inter-item delays of 1,500 ms. Number of correct responses was used to characterise performance on this task.

N-back tasks were always administered in order of ascending difficulty. This was partly done in order to equate the interval between the first and subsequent test administration at each difficulty level, and especially in order to avoid the potential additional executive loading consequence of asymmetric switching between tasks of different difficulty levels (e.g. hard to easy vs easy to hard, see Allport, Hsieh, 1994; Mayr & Keele, 2000). Placing the most executive demanding task last in the sequence obviously allows greater time for the reduction of any inertia effects, thus running counter to the direction predicted in our primary hypotheses.

Each n-back task lasted for approximately 2 minutes (Mean (SD) task durations: 1-back: 121s (SD= 10); 2-back: 122s (SD= 11); 3-back: 118s (SD= 12), the variation in task time resulted

from a subject actuated continuation of each task following 8 practice trials which precede the test trials on which the analyses reported below were based).

Psychomotor Vigilance Task (PVT; Dinges & Powell, 1985). A PC-based version of the PVT was developed such that on-screen digits beginning with zero incremented every millisecond until the participant indicated that a digit was present. Trials began at random intervals between 1 and 10 seconds, continuing until 10 minutes had elapsed. PVT performance was assessed in terms of the mean and median response time, the mean of 10% fastest and 10% slowest responses, and number of lapses (i.e. reaction times > 500ms).

Karolinska Sleepiness Scale (KSS; Åkerstedt & Gillberg, 1990). A nine-point scale was presented on-screen (1- very alert; 9- very sleepy); the response selected was taken to indicate the current level of sleepiness.

Visual Analogue Scales (VAS; Monk, 1989). Four 1000-pixel anchored Visual Analogue Scales appeared successively after each n-back task, requiring participants to indicate their evaluation of the preceding n-back task in terms of DEMAND/Difficulty of task, MENTAL Effort Required by Task, PHYSICAL Effort Required by Task, Amount of ENERGY available for task (Low Demand-High Demand; Low Mental Effort-High Mental Effort; Low Physical Effort-High Physical Effort; Had much Energy-Had no Energy). The pixel marked between 1 and 1000 was taken to indicate the participant's assessment of the n-back task. The VAS task following each n-back task were completed in approximately 30 seconds (Mean (SD) task durations: following 1-back: 26s (11); following 2-back: 27s (11s); following 3-back 30s (12)). Paired-associate, N-back, VAS, KSS and PVT tasks were all presented on a PC-controlled CRT screen running the Cognitive Performance Test Battery (CPTB), with all but the paired-associate tasks requiring mouse-based responses

from participants (see Groeger et al., 2008 for further description of CPTB) .

Task sequences and timing: All testing began within 5 minutes of the end of the nap opportunity, and at precisely the same time for the matched participant who remained awake. At that point all participants encountered V1-back and thereafter, VAS1 (+120s), V2-back (+150s), VAS2 (+270s), V3-back (+300s), a 25 minute period of colour and location working memory testing, followed by V1-back and thereafter, VAS1 (+120s), V2-back (+150s), VAS2 (+270s), V3-back (+300s).

Data treatment & statistical analysis. No participants failed to complete the protocol and all 32 subjects were included in the full analysis. For all of the analyses reported here, data were analysed with a correlated errors model using SPSS MIXED (SPSS, version 16.0.1, Nov 2007; Chicago, Illinois). Tests of goodness of fit revealed that an unstructured covariance structure offered the optimal solution for evaluating group differences. As appropriate to the analyses carried out, recall test (Paired-associate task), task difficulty level (1-, 2-, 3-back) and assessment session timing (morning/afternoon), and time point (initial or subsequent N-back/VAS test administration) were treated as fixed-factor repeated measures. Participants were randomly allocated to Wake or Nap groups, with this grouping also treated as a fixed-factor.

For all analyses two-sided significance tests were used with alpha equal to 0.05. Comparisons were made within groups across time and difficulty levels, and between groups at each time/task difficulty level, using Bonferroni-corrected post-hoc contrasts. When statistical comparisons are being described the values reported in the text are least square means

generated by the models for the full analysis set (unless noted otherwise). Error estimates indicated by SEM refers to the standard error for least square means. In Tables 1 and 2, and Figures 1 to 3, unadjusted (observed) means and standard errors are presented for the reader's convenience.

Results

Sleep parameters and initial performance: Actigraphy-monitored baseline sleep durations of approximately 7.8 hours (SEM= 0.21) preceded both laboratory sessions ($F(1,30)= 0.63$, n.s.). Participants in the Nap (Mean (M)= 7.95 hrs; SEM= 0.21) and Wake (M= 7.63 hrs; SEM= 0.21) groups slept for similar durations during the monitoring period before the study ($F(1,30)= 1.21$, n.s.), and did not differ in sleep durations on the sleep restriction nights ($F<1$). Other sleep parameters for the sleep restriction night immediately preceding each laboratory session were also analysed and showed that Nap and Wake groups were comparable in their bedtime, the time sleep started and ended, wake time, sleep duration, sleep latency, but differed somewhat in terms of time in bed and sleep efficiency (see Table 1). Those who were later randomly allocated to the "nap" group had marginally lower sleep efficiency on the nights preceding laboratory sessions (i.e. 86.4% vs 88.9%), and total times in bed differed inconsistently across conditions by approximately 10 minutes.

INSERT TABLE 1 HERE

When assessed soon after arriving at the laboratory (09:00), KSS self-reported sleepiness did not differ between laboratory visits (First visit: 3.50 (SEM= 1.11), Second visit: 4.09 (SEM=

1.21); $F < 1$), or between participants who napped and those who remained awake (Wake: 3.53 (SEM= 0.99), Nap: 4.06 (SEM= 1.33); $F(1,30) = 1.65$, n.s.). Cued recall of the eighty word pairs increased steadily with practice from an initial level of 32.9% (SEM= 1.85) to 49.3% (SEM=2.73) and reached a level of 63.1% (SEM= 2.83) pairs by the end of the learning session ($F(2,30) = 190.45$, $p < .001$). Nap and Wake group participants did not differ in terms of their initial cued-recall accuracy ($F < 1$) or in the rate at which they learned subsequently ($F < 1$). Cued-recall accuracy did not differ between those participants whose n-back performance was assessed in the morning or afternoon ($F < 1$) nor were there interactions involving wake/nap group and morning-afternoon working memory testing ($F < 1$), or between these factors and rate of learning ($F(6,30) = 1.01$, n.s.). Those who napped and those who remained awake remembered similar numbers of word pairs after the ten minute interval during which the PVT was performed (Mean= 63.32%, SEM= 4.35; $F < 1$), irrespective of whether they subsequently napped or remained awake ($F < 1$). Waking and napping groups did not differ in terms of their performance on the PVT, which was carried out during the ten minute interval between learning word pairs and the delayed recall test. Overall mean (344ms, SEM= 20) and median (311ms, SEM= 9) reaction times did not differ between those whose n-back performance was later assessed in the morning or afternoon (both $F < 1$), or between the waking and nap groups ($F(1,30) = 1.74$, 0.85; both n.s.). Participants in the nap and wake group made a similar number of lapses (i.e. reaction times > 500ms; Mean= 4.61, SEM= 1.36), irrespective of whether n-back testing occurred in the morning or afternoon (all F s < 1). Analyses of the fastest and slowest 10% of individual responses also failed to distinguish between groups or morning-afternoon sessions (all $F < 1.5$). In summary, irrespective of whether they napped or remained awake, participants

complied with the required sleep restriction regimen, and were very similar in terms of cognitive performance and subjective sleepiness in the first hours they spent on each occasion in the sleep laboratory.

INSERT TABLE 2 HERE

All participants in the napping conditions slept during the ninety minute morning and afternoon sleep opportunities. As presented in Table 2, analyses of nap sleep parameters showed that time asleep was longer, sleep latency was shorter, and sleep efficiency was greater for afternoon naps. During afternoon naps, more minutes were spent in SWS, and SWS as a percentage of total sleep time was also higher. REM sleep duration and REM sleep as a percentage of total sleep time, as well as Stage 1 sleep duration and Stage 1 sleep as a percentage of total sleep time, were similar for morning and afternoon naps. In the Morning nap condition, three participants were already awake when the 90 minute nap opportunity had elapsed, and all participants but one were woken from sleep in the afternoon condition. In no case were these participants awake for more than 5 minutes before the 90 nap opportunity had elapsed. When data from these participants were excluded statistical analyses of performance data were not materially different to those for the full data set reported in full below, in which these participants were included. Sleeping participants were largely woken from REM (Morning: 6; Afternoon: 8) or Stage 2 sleep (Morning and Afternoon: 4). The remaining participants were woken from Stage 3 (Morning: 2) or Stage 4 sleep (Morning: 1; Afternoon: 3).

Working Memory: Accuracy declined steadily as the difficulty of n-back increased (1-back: $M=30.00$, $SEM=.56$; 2-back: 27.35 , $SEM=.70$; 3-back: 24.35 , $SEM=.73$; $F(2,60)=52.03$, $p<0.001$). Overall, wake and nap groups did not differ on n-back accuracy ($F=1.1$, n.s.), although accuracy was lower in the afternoon ($M= 26.43$, $SEM= 0.53$) than in the morning ($M= 28.04$, $SEM= 0.58$; $F(1,30)= 12.55$, $p<0.001$) and accuracy was lower on the first block of n-backs (wake+5) undertaken within the testing session than on the second block of n-backs (wake +25) ($M= 26.64$, $SEM= 0.74$; 27.82 , $SEM= 0.53$; $F(1,30)= 20.89$, $p<0.001$). The interaction of the four main effects, WAKE/NAP, Morning/Afternoon, n-back level and n-back timing, was statistically reliable ($F(18, 40.85)= 2.19$, $p<.05$, see Figure 1), that is, the size of the discrepancy between the wake+5 and wake+25 n-back tests differed between morning and afternoon testing for some of the n-back difficulty levels, and this differed in the nap and wake groups. Subsequent analyses decomposed this interaction by separately analysing accuracy at each level of n-back difficulty.

INSERT FIGURE 1 HERE

There were no statistically reliable main effects when 1-back performance was considered, although 1-back accuracy was lower on the first post-sleep test (wake+5) in the nap group while accuracy in the wake +5 and wake +25 test were virtually identical in the wake group ($F(1,30)= 2.46$; $p<0.07$). Accuracy on 2-back was higher in the morning ($M= 28.39$, $SEM= 0.62$) than in the afternoon ($M= 26.31$, $SEM= 0.92$; $F(1,30)= 7.82$; $p<0.01$), and better on the wake+25 test ($M= 28.16$, $SEM= 0.57$) than on the wake+5 test ($M= 26.55$, $SEM= 0.88$; $F(1,30)= 14.21$; $p<0.001$).

Both of these effects were influenced by whether participants napped or remained awake. Accuracy on 2-back was lower for afternoon tests than for morning tests, but only in the napping group ($F(1,30) = 4.93$, $p < 0.005$), in which accuracy on the wake+5 test was lower than on the wake+25 test ($F(4, 31.58) = 4.93$, $p < 0.005$). These same main effects were apparent in 3-back performance. Participants were more accurate in the morning ($M = 25.39$, $SEM = 1.04$) than in the afternoon ($M = 23.31$, $SEM = 0.85$; $F(1,30) = 14.73$; $p < 0.001$), and were better on the wake+25 test ($M = 24.95$, $SEM = 0.70$) than on the wake+5 test ($M = 23.75$, $SEM = 0.70$; $F(1,30) = 14.70$; $p < 0.001$). With 3-back performance there were no statistically reliable interactions, although post-hoc Bonferroni-corrected comparisons revealed that among those who napped, 3-back performance in the afternoon was particularly impaired on the test taken at wake+5. In short, more difficult n-back tests were performed less accurately soon after waking from an afternoon nap.

INSERT TABLE 3 HERE

Analyses of N-back accuracy on waking, or following a period of 30 minutes of waking post nap, revealed no statistically reliable correlations between performance or proportional change in initial performance, and sleep parameters (see Table 3).

INSERT TABLE 4 HERE

Workload assessments: Participants rated the workload imposed by each n-back test immediately after completing it in terms of Task Difficulty, Mental Effort, Physical Effort and Energy Available. As might be expected, average workload ratings from each participant correlated highly, but it is also clear that participants were not simply giving the same rating irrespective of which scale they responded to (Table 4). While Task Difficulty and Mental Effort shared in excess of 90% their variance, the variance shared by Task Difficulty and Effort Available was just 17%. An overall mixed analysis contrasting the effects of napping, workload dimension and n-back load revealed that average ratings increased with n-back load, but this depended on which aspect of workload was being rated ($F(6, 233.22) = 6.24, p < 0.001$, see Figure 2). Task Difficulty and Mental Effort showed strongly linear increases with n-back load, but, as might be expected, Energy Available remained constant across n-back loads.

INSERT FIGURE 2 HERE

The effects on each workload dimension of napping, morning/afternoon testing, n-back loads and initial-subsequent exposure to n-back loads were addressed in separate analyses. Perceived Task Difficulty increased systematically with Working Memory load ($F(2,30) = 34.32, p < 0.001$), but the rate of increase differed depending on when and whether participants had napped ($F(4,30) = 3.12; p < 0.05$, see Figure 3). Post-hoc comparisons revealed that those who napped in the afternoon considered that the 3-back was less difficult than those who remained awake ($p < 0.05$).

INSERT FIGURE 3 HERE

Mental Effort required also revealed strong working memory executive load effects ($F(2,30)=36.98$; $p<0.001$), but this interacted with nap/wake, morning/afternoon and whether the n-back rated was the first (wake+5) or second (wake+25) in the testing session ($F(8,30)=2.81$; $p<0.05$). Post-hoc contrasts revealed no statistically reliable differences between the same working memory loadings tested early or late in the testing session. Otherwise the contrast revealed a pattern similar to that observed with Task Difficulty; participants who napped in the afternoon understated the Mental Effort required for the 3-back compared with those who did not nap in the afternoon. Physical Effort required also demonstrated a memory load effect ($F(3,30)=13.89$, $p<0.001$), with 1-back requiring less physical effort than both 2- and 3-back, but no other main effects or interactions. Energy Available was considered to be higher when the second block of n-back tests were performed ($F(1, 100.66)=8.74$; $p<0.005$). There was some evidence that this main effect on energy available interacted with memory load, napping and time of day ($F(8, 69.60)=2.11$; $p<0.05$), but no post-hoc comparisons yielded statistically reliable differences.

Discussion

The results reported above show that sleep inertia upon awakening from daytime naps is more severe for tasks which rely heavily on executive functions (e.g. 3-back) than for tasks which are similar in their perceptual and motor response requirements, but which impose less of an executive loading (e.g. 1-back). These effects of executive load were only evident when

naps had been taken in the afternoon. By this time of the day similarly sleep-restricted participants who remained awake would have been operating under a higher degree of homeostatic sleep pressure, partly because of the time since waking, and perhaps also because of the slight sleep restriction imposed by the protocol. Dinges, Orne & Orne (1985) demonstrated that post nap performance during a 54 hour sleep deprivation, and the circadian phase at which naps were taken, affected performance-decrements on waking. Consistent with this suggestion, the naps which participants took at this point were longer in duration, had a higher percentage of SWS, and sleep was initiated more quickly. However, it is also possible that sleep structure, as reflected by duration, SWS and readiness to sleep, rather than sleep pressure before the nap begins, results in the executive deficit upon waking observed here. Similarly, there is some evidence that SWS during brief afternoon naps is associated with sleep inertia (e.g. Brooks & Lack, 2006, Tietzel & Lack, 2001;), although studies have not considered whether the effects observed differ for tasks which are more demanding of executive functions, nor whether the extent of SWS is related to the level of inertia observed.

Some of the participants who napped in this study woke a few minutes before the nap opportunity ended. Their data are included in the analyses reported above since the time awake was brief, and their inclusion was conservative with respect to the hypothesis tested. Because the numbers involved were small when waking from morning or afternoon napping was considered, no formal analysis was carried out on whether the inertia effects observed varied with the sleep stage from which participants were woken. As noted above, greater inertia has been observed when participants wake from Slow Wave Sleep (e.g. Dinges et al., op.cit.).

Two aspects of the present study run counter to the suggestion that sleep structure exacerbates sleep inertia. Firstly, perhaps because of the relatively small number of naps, we found no statistically reliable correlations between the extent of the inertia observed and these sleep parameters. Secondly, it might also be argued that our attempt to manipulate sleep pressure through time of day, because it confounds sleep pressure and circadian phase, leaves open the possibility that circadian phase, rather than sleep structure, underlies the difference observed between the effects of morning and afternoon naps. While circadian phase and sleep structure related to sleep homeostasis are certainly confounded in the present protocol, neither the amount of REM, nor the percentage of sleep duration spent in REM sleep differed reliably between morning and afternoon naps (although the differences are considerable and go in the expected direction). Nor were any REM-related sleep parameters correlated with the extent of sleep inertia. Given the relationship between REM and circadian phase (Bes, Jobert, Müller & Schulz, 1996; Dijk & Czeisler, 1995; Hume & Mills, 1977), such differences and correlations might have been expected. In addition, although we are doubtful that the data necessarily supports only the conclusion drawn, recent findings by Scheer and colleagues (Scheer, Shea, Hilton & Shea, 2008), in which the effects of sleep inertia were assessed across the whole circadian phase, appear to show that circadian effects on sleep inertia were weakest in the mid-afternoon.

The study reported above does not allow us to choose between these alternative explanations (sleep pressure, sleep structure or circadian influence), but the data do show, and we believe for the first time, that executive loading in tasks exacerbates sleep inertia. The data also suggest that the impairment which results from sleep inertia may extend beyond the

particular requirements of a given 'cognitive' task, to the individual's ability to reflect on their ability to perform that task (i.e. 'metacognition'). Indeed, the executive impairment may actually be understated by the current design, since the most demanding executive function tasks were carried out several minutes after, rather than initially on waking, and after participants had had the opportunity to perform less demanding versions of the task.

Participants' assessments of the workload requirements of the n-back tasks were found to be strongly influenced by the objective demand(s) of the tasks, and also whether they slept before encountering them. Mental effort required revealed that Post-nap subjects gave lower estimates of the difficulty posed by, and mental effort required by, the more onerous tasks than participants who remained awake. This was only evident when participants napped in the afternoon. Analyses revealed no differences between subjective assessments made early and later in the testing session, and thus would appear not to implicate post-nap sleep inertia. However, it is possible that the meta-cognitive skills required to make such assessments are still slower to recover after waking. That aside, the VAS technique adopted here to assess subjective workload showed encouraging sensitivity to task load, time of day and sleep and is worthy of further exploration.

Throughout this discussion of the results reported above we have emphasised the susceptibility of 'executive functions' to sleep manipulations. We do so because the 2- and 3-back versions of n-back which reveal these effects are more dependent upon the planning, monitoring, switching and inhibitory operations which characterise "executive functions" (Stuss, 2007). In contrast, simpler versions of n-back, which depend on more basic aspects of working memory appear less sensitive to sleep manipulations (e.g. Chuah, Venkatraman, Dinges

& Chee, 2006; Groeger et al., 2008). An alternative account of these and other findings is that “more difficult” tasks are compromised by sleep manipulations. Duncan and Owen (2000), exploring the effect of increases in task difficulty across a wide range of tasks, show that a highly specific frontal-lobe network is consistently recruited when quite diverse cognitive tasks become more difficult. At first sight this might suggest that that a task-difficulty and executive-depletion account may not be that easily distinguished, empirically or neurologically. However, the data reported here reveal no effects of inertia on the simplest n-back task, and equivalent decrements for similarly executively demanding, but differentially difficult, versions of n-back. To us this suggests that the more intuitively appealing, but rather vague, notion of generic task difficulty is a less promising account than is the possibility that specific executive functions or resources may be differentially depleted by different sleep manipulations.

The suggestion that more complex cognitive functions are more affected by sleep inertia is consistent with the neurological evidence available from imaging studies of rCBF during awakening (Balkin et al., 2002). Balkin’s account of the transition between sleep and wakefulness shows that the brain systems which modulate arousal are first to recover, and that only subsequently do higher cortical areas, particularly in the frontal cortex, see a similar increase in the rate of cerebral blood flow. The data we report here follow short naps rather than extended sleep, but nevertheless provide an indication of the functional consequences of these patterned increases in rCBF. The data also suggest that the particular susceptibility to sleep deprivation of those human activities which are particularly reliant on the frontal cortex (Chuah, Venkatraman, Dinges & Chee, 2006; Groeger et al., 2008; Harrison, Horne & Rothwell, 2000; Horne, 1993; Vandewalle et al., 2009) may also be mirrored by functional capacity as

people regain wakefulness. It is ironic that sleep itself, the most natural means of counteracting the sleep-loss induced fallibility of executive functions, leaves those same functions particularly vulnerable.

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References

- Achermann, P., Werth, E., Dijk, D.J., & Borbély, A.A. (1995). Time course of sleep inertia after night time and daytime sleep episodes. *Archives of Italian Biology*, 134, 109-119.
- Åkerstedt, T. & Gillberg, M. (1990). Subjective and objective sleepiness in the active individual. *International Journal of Neuroscience*, 52, 29-37.
- Åkerstedt, T., Hume, K., Minors, D. & Waterhouse, J. (1997). Good sleep—its timing and physiological sleep characteristics. *Journal of Sleep Research*, 6, 221–229.
- Allport, A., Styles, E.A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV* (pp. 421–452). Cambridge, MA: MIT Press.
- Balkin, T.J. & Badia, P. (1988). Relationship between sleep inertia and sleepiness: Cumulative effects of four nights of sleep disruption/restriction on performance following abrupt nocturnal awakenings. *Biological Psychology*, 27, 245–258.
- Balkin, T.J., Braun, A.R., Wesensten, N.J., Jeffries, K., Varga, M., Baldwin, P., Belenky, G., & Herscovitch, P. (2002). The process of awakening: A PET study of regional brain activity patterns mediating the re-establishment of alertness and consciousness. *Brain*, 125, 2308-2319.
- Bes, F.W., Jobert, M., Müller, C., & Schulz, H. (1996). The diurnal distribution of sleep propensity: experimental data about the interaction of the propensities for slow-wave sleep and REM sleep. *Journal of Sleep Research*, 5, 90-98.

Braver, T.S., Cohen, J.D., Nystrom, L.E., Jonides, J., Smith E.E. & Noll, D.C. (1997). A parametric study of prefrontal cortex involvement in human working memory. *Neuroimage*, 5, 49-62.

Brooks, A. & Lack L. (2006). A brief afternoon nap following nocturnal sleep restriction: which nap duration is most recuperative? *Sleep*, 29, 831-40.

Bruck, D. & Pisani, D.L. (1999). The effects of sleep inertia on decision-making performance. *Journal of Sleep Research*, 8, 95–103.

Buysse, D.J., Reynolds III, C.F., Monk, T.H., Berman, S.R. & Kupfer D.J. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Journal of Psychiatric Research*, 28, 193-213.

Chuah, Y.M.L., Venkatraman, V., Dinges, D.F. & Chee M.W. (2006). The neural basis of interindividual variability in inhibitory efficiency after sleep deprivation. *Journal of Neuroscience*, 2, 7156-7162.

Collette, F., Hogge, M., Salmon E. & van der Linden, M. (2006). Exploration of the neural substrates of executive functioning by functional neuroimaging. *Neuroscience*, 139, 209-221.

Dijk, D.J. & Czeisler, C.A. (1995). Contribution of the circadian pacemaker and the sleep homeostat to sleep propensity, sleep structure, electroencephalographic slow waves, and sleep spindle activity in humans. *Journal of Neuroscience*, 15, 3526-3538.

Dinges, D.F., Orne, E.C., Evans, F.J. & Orne M.T. (1981). Performance after naps in sleep-conducive and alerting environments. In Johnson, L.C., Tepas, D.I., Colquhoun, W.P., Colligan, M.J. (Eds.), *Biological rhythms, sleep and shift work* (pp. 539–552). New York: Spectrum.

Dinges, D. & Powell, J. (1985). Microcomputer analysis of performance on a portable, simple visual RT task during sustained operations. *Behavioural Research Methods in Instrumental Computing*, 17, 652-655.

Dinges, D.F., Orne, M.T. & Orne, E.C. (1985). Assessing performance upon abrupt awakening from naps during quasi-continuous operations. *Behavioural Research Methods in Instrumental Computing*, 17, 37-45.

Ferrara, M., De Gennaro, L., Casagrande, M. & Bertini, M. (2000). Selective slow-wave sleep deprivation and time-of-night effects on cognitive performance upon awakening. *Psychophysiology*, 37, 440-446.

Groeger, J.A., Zijlstra, F.R. & Dijk, D.J. (2004). Sleep quantity, sleep difficulties and their perceived consequences in a representative sample of some 2000 British adults. *Journal of Sleep Research*, 13, 359-371.

Groeger, J.A., Viola, A.U., Lo, J.C., von Schantz, M., Archer, S.N. & Dijk D.J. (2008). Early morning executive functioning during sleep deprivation is compromised by a PERIOD3 polymorphism. *Sleep*, 31, 1159-1167.

Harrison, Y., Horne, J.A. & Rothwell, A. (2000). Prefrontal neuropsychological effects of sleep deprivation in young adults - a model of healthy aging? *Sleep*, 23, 1067-1073.

Horne, J.A. (1993). Human sleep, sleep loss and behaviour. Implications for the prefrontal cortex and psychiatric disorder. *British Journal of Psychiatry*, 162, 413-419.

Hume, K.I. & Mills, J.N. (1977). Rhythms of REM and slow-wave sleep in subjects living on abnormal time schedules. *Waking and Sleeping*, 1, 291-296.

Jewett, M.E., Wyatt, J.K., Ritz-De Cecco, A., Khalsa, S.B., Dijk, D.J. & Czeisler C.A. (1999). Time course of sleep inertia dissipation in human performance and alertness. *Journal of Sleep Research*, 8, 1–8.

Johns, M.W. (1991). A new method for measuring daytime sleepiness: the Epworth sleepiness scale. *Sleep*, 14, 540–545.

Lavie, P. & Weler, B. (1989). Timing of naps: Effects on post-nap sleepiness levels. *Electroencephalography and Clinical Neurophysiology*, 72, 218–224.

Lubin, A., Hord, D., Tracy, M.L. & Johnson, L.C. (1976). Effects of exercise, bedrest and napping on performance decrement during 40 hours. *Psychophysiology*, 13, 334–339.

Mayr, U., & Keele, S.W. (2000). Changing internal constraints on action: The role of backward inhibition. *Journal of Experimental Psychology: General*, 129, 4–26.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A. & Wager, T.D. (2000). The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cognitive Psychology*, 41, 49-100.

Monk, T.H. (1989). A visual analogue scale technique to measure global vigor and affect. *Psychiatry Research*, 27, 89–99.

Moruzzi, G. & Magoun, H.W. (1949). Brain stem and reticular formation and activation of the EEG. *Electroencephalography and Clinical Neurophysiology*, 1, 455-473.

Owen, A.M., McMillan, K.M., Laird, A.R. & Bullmore, E. (2005). N-back working memory paradigm: a meta-analysis of normative functional neuroimaging studies. *Human Brain Mapping*, 25, 46-59.

Rechtschaffen, A. & Kales, A. (1968). *A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects*. NIH Publication No. 204. Washington, DC: US Government Printing Office.

Reid, G.B. & Nygren, T. E. (1981). *The Subjective Workload Assessment Technique: A scaling procedure for measuring mental workload*. In: Hancock, P.A. & Meshkati, N. (Eds.), *Human Mental Workload* (pp. 185-218). Amsterdam: Elsevier Science Publishers.

Rosa, R.R. & Bonnet M.H. (1985). Sleep stages, auditory arousal threshold, and body temperature as predictors of behavior upon awakening. *International Journal of Neuroscience*, 27, 73–83.

Scheer, F.A., Shea, T.J., Hilton, M.F. & Shea, S.A. (2008). An endogenous circadian rhythm in sleep inertia results in greatest cognitive impairment upon awakening during the biological night. *Journal of Biological Rhythms*, 23, 353-361.

Silva, E.J. & Duffy, J.F. (2008). Sleep inertia varies with circadian phase and sleep stage in older adults. *Behavioural Neuroscience*, 122, 928-935.

Tietzel, A.J. & Lack L.C. (2001). The short-term benefits of brief and long naps following nocturnal sleep restriction. *Sleep*, 24, 293-300.

Vandewalle, G., Archer, S.N., Wuillaume, C., Balteau, E., Degueldre, C., Luxen, A., Maquet, P. & Dijk D.J. (2009). Functional magnetic resonance imaging-assessed brain responses during an executive task depend on interaction of sleep homeostasis, circadian phase, and PER3 genotype. *Journal of Neuroscience*, 29, 7948-7956.

Verwey, W.B. & Veltman, J.A. (1996). Detecting short periods of elevated workload. A comparison of nine common workload assessment techniques. *Journal of Experimental Psychology: Applied*, 2, 270–285.

Walsh, J.K., Snyder, E., Hall, J., Randazzo, A.C., Griffin, K., Groeger, J., Eisenstein, R., Feren, S.D., Dickey, P. & Schweitzer, P.K. (2008). Slow wave sleep enhancement with gaboxadol reduces daytime sleepiness during sleep restriction. *Sleep*, 31, 659-672.

Table 1. Average (SEM) Sleep parameters of Baseline and Sleep Restriction nights

	Nap-AM	Nap-PM	Wake-AM	Wake-PM	AM vs PM F(1,30)=	Nap vs Wake F(1,30)=	AM/PM X Nap/Wake F(1,30)=
Baseline Sleep nights							
Bedtime (HH:MM)	23:56(00:15)	23:59(00:14)	00:10(00:15)	23:58(00:14)	0.30	0.13	0.65
Sleep start (HH:MM)	00:08(00:17)	00:08(00:13)	00:21(00:17)	00:07(00:13)	0.48	0.10	0.53
Sleep end (HH:MM)	08:13(00:13)	07:54(00:10)	08:03(00:13)	07:41(00:10)	3.95	0.73	0.02
Get up time (HH:MM)	08:17(00:13)	08:04(00:11)	08:06(00:13)	07:44(00:11)	2.73	1.33	0.16
Time in bed (Hrs)	8.35(0.29)	8.09(0.25)	7.93(0.29)	7.76(0.25)	0.75	1.64	0.04
Sleep Duration (Hrs)	8.09(0.31)	7.83(0.23)	7.70(0.31)	7.56(0.23)	0.63	1.21	0.07
Sleep efficiency (%)	85.32(1.01)	86.79(1.06)	87.24(1.01)	88.10(1.06)	1.77	1.88	0.12
Sleep latency (min)	11.38(2.93)	9.31(2.84)	10.50(2.93)	9.00(2.84)	0.41	0.04	0.01
Sleep Restriction nights							
Bedtime (HH:MM)	00:59(00:02)	00:59(00:04)	01:06(00:02)	00:56(00:04)	2.57	0.27	2.06
Sleep start (HH:MM)	01:08(00:03)	01:06(00:05)	01:12(00:03)	01:05(00:05)	1.48	0.19	0.45
Sleep end (HH:MM)	06:59(00:01)	06:58(00:02)	07:02(00:01)	06:59(00:02)	1.39	0.89	0.35
Get up time (HH:MM)	07:03(00:01)	07:03(00:02)	07:04(00:01)	07:01(00:02)	2.40	0.23	1.86
Time in bed (Hrs)	6.06(0.04)	6.00(0.06)	5.96(0.04)	6.08(0.06)	0.76	0.02	5.97*
Sleep Duration (Hrs)	5.86(0.06)	5.79(0.07)	5.84(0.06)	5.90(0.07)	0.02	0.28	1.68
Sleep efficiency (%)	86.33(1.05)	86.52(1.06)	89.61(1.05)	88.31(1.06)	0.36	4.68*	0.65
Sleep latency (min)	8.13(2.06)	6.69(2.10)	6.06(2.06)	9.06(2.10)	0.34	0.00	2.72

*p<0.05

Table 2. Average (SEM) Sleep parameters of Morning and Afternoon Naps

	<i>Morning</i>	<i>Afternoon</i>	<i>t(1,15)=</i>	<i>P</i>
Total sleep time (min)	64.47(4.48)	77.13(1.50)	-3.50	0.003
Sleep latency (min)	17.81(2.85)	10.91(1.24)	2.84	0.012
Sleep efficiency (%)	71.50(4.96)	85.58(1.67)	-3.54	0.003
Stage 1 (% of TST)	4.44(1.50)	2.59 (0.58)	0.66	0.517
Stage 2 (% of TST)	51.64(3.74)	32.85(3.34)	6.61	<.001
REM (% of TST)	22.69(4.38)	17.47(1.89)	1.09	0.292
SWS (% of TST)	12.10(3.38)	31.19(3.70)	-6.56	<.001
Stage 1 (min)	3.00(0.83)	2.59(0.58)	0.40	0.692
Stage 2 (min)	37.06(3.02)	25.81(2.58)	4.45	<.001
REM duration(min)	17.19(3.27)	22.06(2.33)	-1.22	0.241
SWS duration (min)	9.09(2.71)	39.24(4.49)	-9.48	<.001

Table 3. Correlations between Morning and Afternoon nap sleep parameters and post nap performance (Wake + 5 min), and proportional change in initial performance

Morning Nap	Performance Wake +5min			Wake +5 (as proportion Wake +30)		
	1-back	2-back	3-back	1-back	2-back	3-back
Total sleep time (min)	-0.08	-0.10	-0.13	-0.09	-0.22	-0.21
Sleep latency (min)	-0.07	0.11	0.19	-0.06	0.02	0.17
Sleep efficiency (%)	-0.08	-0.10	-0.13	-0.09	-0.22	-0.21
Stage 1 (% of TST)	-0.01	-0.18	-0.26	-0.03	-0.06	0.09
Stage 2 (% of TST)	-0.46	-0.45	-0.43	-0.47	-0.25	-0.37
REM (% of TST)	0.18	0.34	0.08	0.16	0.12	-0.29
SWS (% of TST)	0.14	0.05	0.28	0.16	-0.03	0.37
Stage 1 (min)	-0.04	-0.26	-0.38	-0.07	-0.03	0.09
Stage 2 (min)	-0.36	-0.46	-0.49	-0.37	-0.24	-0.45
REM duration(min)	0.20	0.31	0.08	0.18	0.09	-0.29
SWS duration (min)	0.13	0.06	0.26	0.15	-0.03	0.33
Afternoon Nap						
Total sleep time (min)	0.13	-0.18	-0.11	0.15	-0.24	-0.22
Sleep latency (min)	0.11	0.32	0.23	0.09	0.37	0.36
Sleep efficiency (%)	0.14	-0.18	-0.11	0.15	-0.24	-0.22
Stage 1 (% of TST)	-0.33	-0.03	-0.29	-0.39	-0.07	-0.44
Stage 2 (% of TST)	-0.27	-0.14	-0.19	-0.07	-0.07	0.08
REM (% of TST)	0.21	-0.12	-0.21	-0.08	-0.10	-0.31
SWS (% of TST)	0.24	0.20	0.32	0.27	0.14	0.21
Stage 1 (min)	-0.37	-0.09	-0.35	-0.35	-0.13	-0.50
Stage 2 (min)	-0.30	-0.20	-0.23	-0.09	-0.14	0.05
REM duration(min)	0.18	-0.17	-0.25	-0.10	-0.16	-0.37
SWS duration (min)	0.22	0.16	0.29	0.26	0.10	0.15

*p<0.05

Table 4 Correlation between workload measures (N=32)

	Mental Effort	Physical Effort	Energy Available
Task Demand	.96***	.73***	.41*
Mental Effort		.74***	.40*
Physical Effort			.51**
	*p<0.05,	** p<.01	*** p<.001

Figure 1 Mean (SE) Morning (top panel) and Afternoon (bottom panel) working memory performance as a function of memory load and testing occasion. (* indicates $p < 0.05$)

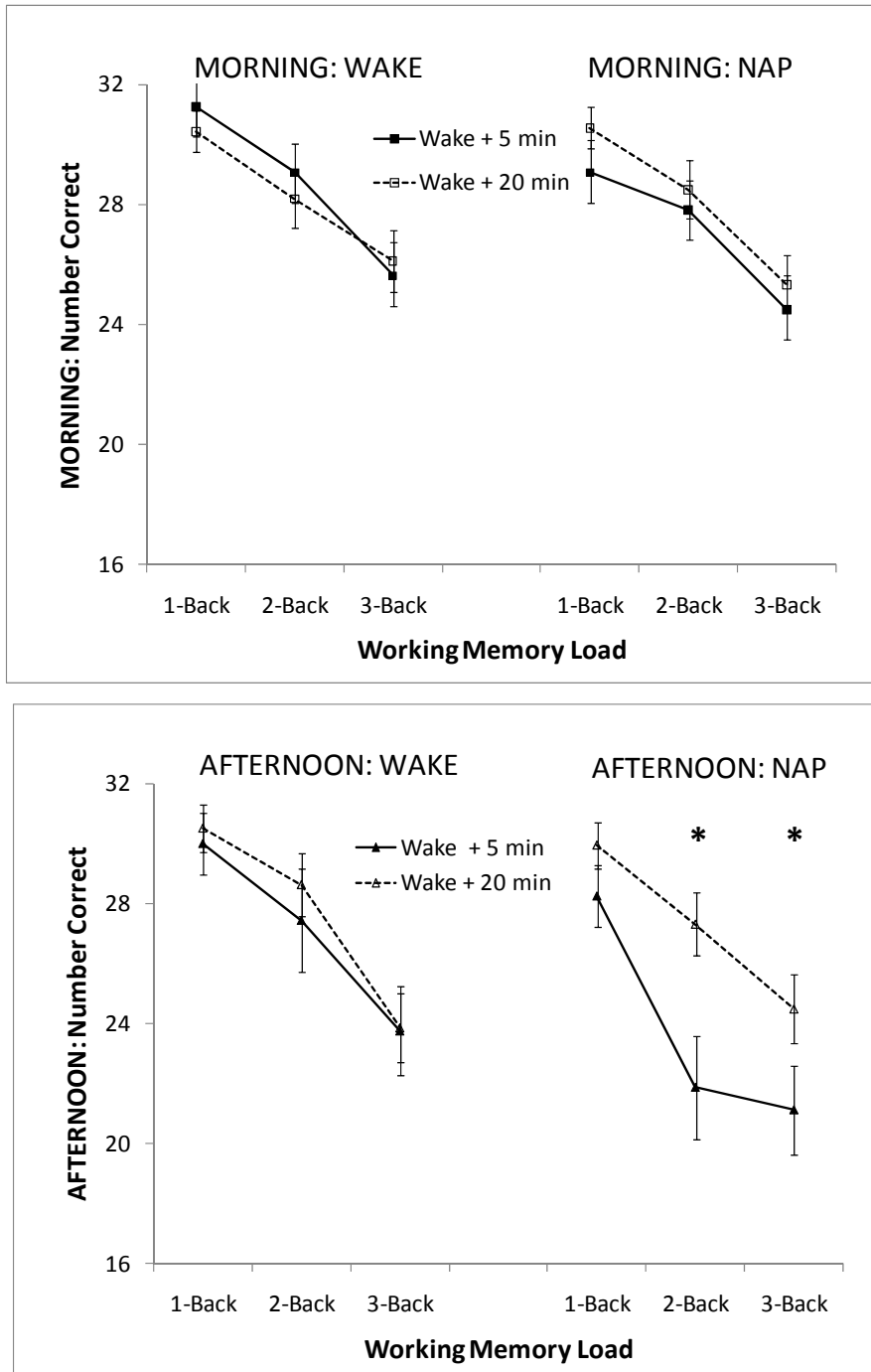


Figure 2 Dimensions of Subjective Workload: Effects of task difficulty on mean (SE) perceived energy available, task difficulty, physical and mental effort (asterisks indicate differences where $p < 0.05$).

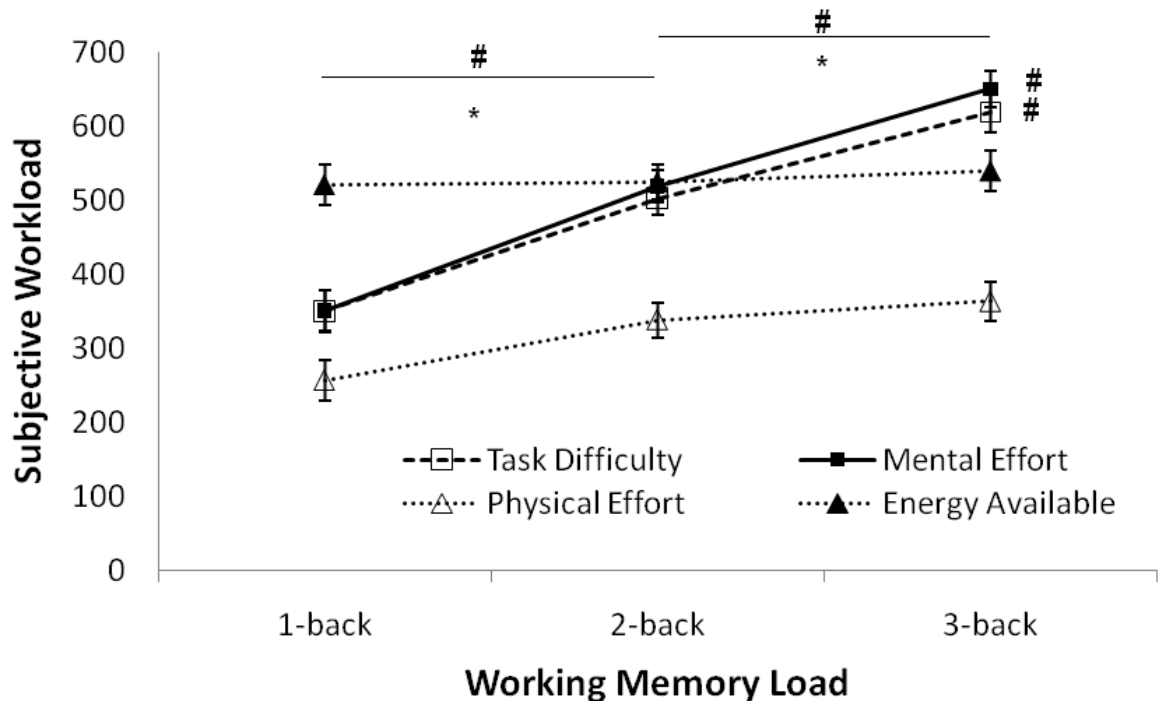


Figure 3 Subjective workload, averaged across workload dimensions (SE), as a function of working memory load in participants who napped or remained awake in the Morning or Afternoon (asterisks indicate differences where $p < 0.05$).

