Wearable Modular Device for Facilitation of Napping and Optimization of Post-nap Performance*

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Abstract. Sleep deprivation-induced deficiencies in performance can be associated with high financial and human costs. Napping is an effective countermeasure, but the effects depend on previously accumulated sleep debt and timing, duration and sleep architecture of the naps. Long-term assessment of sleep architecture of nap/sleep episodes could yield an estimate of the accumulated sleep debt and help optimize the napping schedule. Moreover, sensory stimulation coupled with real-time assessment of sleep states could optimize sleep architecture and duration of each nap. With these goals in mind we designed a wearable device, dubbed Nap Cap, which integrates real-time EEG analysis with audio, visual and thermal stimulation. The prototype was evaluated on seven subjects (fully rested vs. sleep-deprived). While the prototype provided high quality EEG and comfort, sensory stimulation did not significantly influence sleep architecture. Evaluation of more paradigms of sensory stimulation on larger samples is warranted before final conclusions can be made.

Keywords: Nap, Sleep Deprivation, Performance Optimization, Wearable Devices.

1 Introduction

Sleep restriction has a profound impact on human behavior, performance and physical health. Even small amounts of sleep loss accumulate over time resulting in a "sleep debt", and manifest in impairments of alertness, memory and other cognitive functions [1]. Deficient performance can be associated with significant social, financial and human costs. Impaired vigilance is the leading cause of transportation and industrial accidents in the US [2, 3], while recent National Aeronautics and Space Administration (NASA) reports revealed that pilots often experience brief episodes of sleep while flying [4]. Due to the large number of shift workers or workers with irregular schedule sleep restriction is considered a serious public health and safety concern [5].

While temporary amelioration of the effects of sleep restriction on motor and cognitive performance can be achieved by natural or pharmacological stimulants (e.g. caffeine) or overt stimulation of the senses, brief naps taken at appropriate times throughout the day are the only intervention without long-term adverse effects that

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efficiently counter chronic sleep restriction. Unfortunately, attempts at designing optimal napping schedules [6] have been unsuccessful. The main reason for failure was the narrow focus on duration and timing of naps, whereas the influence of other factors such as sleep architecture, sleep debt accumulated prior to a nap and the subject's susceptibility to sleep deprivation, was neglected. However, adequate amounts of stable NREM Stage 2 sleep in each nap [7] and long-term balance among NREM, REM and slow-wave sleep [1, 6] have been identified as key determinants of post-nap performance. These findings suggested that manipulating the proportions of the key sleep stages during napping could substantially reduce the number and/or duration of naps necessary to optimize motor and cognitive performance.

Our group has recently developed a modular device for optimization of napping in operational environments. Dubbed the "Nap Cap", the device is designed to assess sleep architecture of each nap in real-time by measuring brain electrical activity (EEG), maintain a record of all naps taken, provide protection from environmental disturbances, deliver sensory stimulation to influence the sleep architecture in the desired way and awaken the subject at an appropriate time to avoid sleep inertia (Fig.1A). This article presents the results of a pilot evaluation of a prototype device.
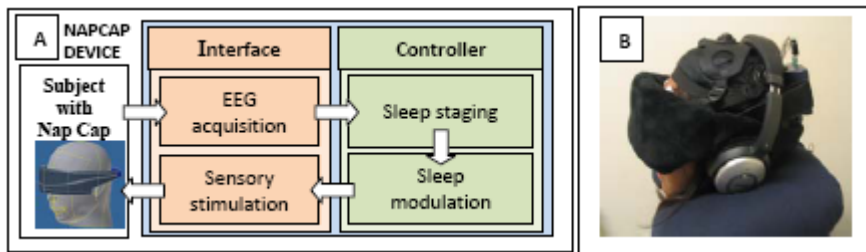

Fig. 1. A. Architecture of the Nap Cap device consisting of four main modules. B. Prototype device assembled of off-the-shelf component.

2   Methods

2.1   Prototype Nap Cap Device

The prototype Nap Cap device (Fig.1B) was assembled with off-the-shelf components. EEG was recorded with a wireless wearable 9-channel headset (Advanced Brain Monitoring Inc., Carlsbad, CA). Recorded channels included C3-A2, C4-A1, Fp-Fp2, Fz-PO, Cz-PO, vertical and horizontal electrooculogram and submental EMG. Bose® noise cancelling headphones and an eye cover provided protection from environmental noise and light respectively. The headphones also delivered auditory stimulation, whereas two blue LED arrays built into the foam of the eye cover provided visual stimulation. Blue light was chosen because of its reported beneficial effect on duration and severity of post-nap sleep inertia [8]. An inflatable neck pillow with a battery powered heating element ensured increased comfort, and provided thermal stimulation of the neck which was expected to produce effects similar to the well known 'hot bath effect' [9].

2.2   Study Design

Seven healthy subjects (three females, age range: 22-25 yrs) participated in the study. The subjects reported no significant previous or existing health problems, including substance abuse, and specifically, had no sleep-related complaints.

The subjects took a 1-hour midday nap wearing the Nap Cap on two separate occasions: fully rested, and after sleep deprivation. The rested and sleep-deprived sessions were between one and seven days apart. The subjects completed sleep logs and wore actigraphs for three days prior to either session so that their sleep schedule could be assessed. Subjects were required to abstain from caffeinated beverages on the days the experimental sessions were conducted.

On the night before their second session the subjects were allowed only 2 hours of sleep. Compliance with the instructions was enforced by requiring that the subjects leave phone messages and send emails every 30 minutes between 12AM and 6AM except for the 2 hours they were allowed to sleep. The compliance was further confirmed by a visual inspection of the actigraphic data for all seven subjects.

2.3   Experimental Sessions

Both experimental sessions consisted of four main parts (Fig.2). The subjects were evaluated with the proprietary battery of psycho-physiological tests called Attention and Memory Profiler (AMP) before and after the nap during each session. Upon completion of the pre-nap AMP, the subjects were given lunch and then took a 60-minute nap wearing the Nap Cap prototype. The subjects completed a brief questionnaire about comfort of the Nap Cap immediately after the nap, and then started the post-nap AMP evaluation.
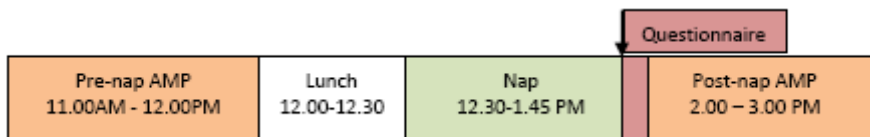

Fig. 2. Experimental protocol on both experimental sessions

AMP evaluation: The AMP evaluation included three tests of vigilance and memory. The 3-Choice Vigilance Test (3C-VT) required the subjects to discriminate primary (70%) from two secondary geometric shapes and respond as quickly as possible over a 20-minute test period. The memory tests, each 7 minutes long, were variants of the Image Recognition Test (IR) where the subject had to memorize 20 images and identify the 20 training images among 80 previously unseen testing images. In Numbers Paired Associate Learning Test, (N-PAL), a number was assigned to each image and subjects had to identify the correct image-number pairs. Five-minute breaks were given to the subjects in between the tests, thus the total duration of the AMP evaluation was little less than an hour.

Napping: The subjects napped in a room at the temperature of 24-25°C, lying supine in a comfortable chair with the back tilted so that the angle to the ground was
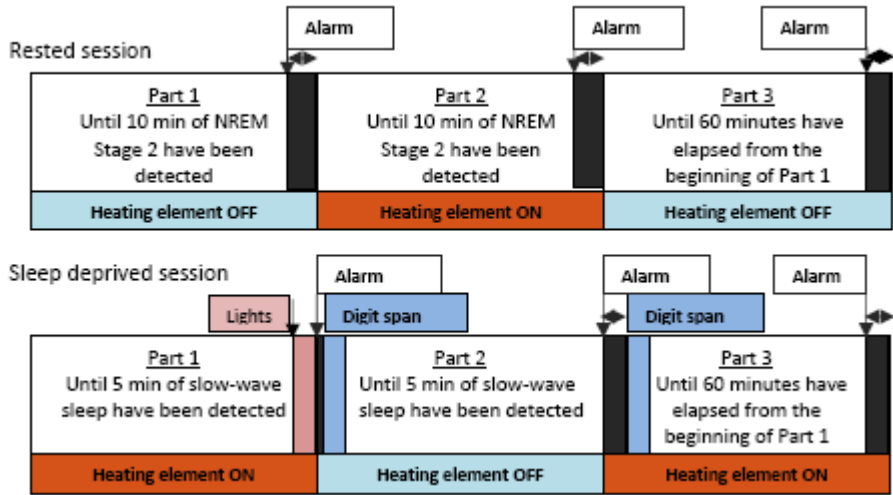
Fig. 3. Experimental manipulations during rested (above) and sleep-deprived session (below)

approximately 30°. The lights in the room were turned on in order to test the efficacy of the eye cover in blocking the environmental light. The subjects were constantly monitored through a camera mounted next to the chair, and the recorded EEG was transmitted in real-time to the computer in front of the experimenter.

On both sessions napping consisted of three parts during which the heating element was alternately turned on and off (Fig.3). Such design aimed at separating effects of increasing the local skin temperature on sleep variables (see below) from the expected effects of sleep deprivation and sleep propensity. The emphasis during the rested session was on interventions facilitating transitions from wakefulness to solid sleep. Therefore, the subjects were not allowed to progress beyond NREM Stage 2, and were awakened with a 2-minute long alarm after they had spent 10 minutes in stable sleep. In contrast, during the sleep deprived session the emphasis was on procedures facilitating a smooth transition from deep sleep to wakefulness with minimal post-nap sleep inertia. Consequently, the nap was interrupted after 5 minutes of slow-wave sleep with either light from the LED arrays, or the alarm sound delivered through the headphones. If slow-wave sleep had not occurred, the nap was interrupted after 30 minutes while the subject was in deep Stage 2 sleep. The LEDs were activated for 90 seconds only during the first interruption. In case the subjects did not wake up during this manipulation, the alarm sound was played briefly (30 seconds) to awaken them. On subsequent interruptions only a 2-minute alarm sound was used to awaken the subjects. Upon each interruption the subjects were asked to complete an auditory digit span test (2 sequences of 7 random digits that the subjects were supposed to reproduce immediately after hearing them). Failure to correctly reproduce the digits was interpreted as a presence of sleep inertia.

2.4 Outcome Measures

Sleep staging and sleep variables: The EEG records of the naps were scored by a board-certified sleep specialist in 30 second epochs according to the AASM standard rules [10]. Recorded EEG contained very few artifacts. Generated hypnograms were then used to calculate total sleep time (TST), sleep efficiency (SE), number of spontaneous awakenings after sleep onset (WASO), % time spent in each sleep stage, sleep onset latency (SOL), latencies to NREM stage 2 and SWS (Table 1 and 2, and Figure 4). Sleep onset latency (SOL) was defined as time from the beginning of each part of a nap till the first occurrence of 3 or more consecutive epochs of Stage 1 or 1 epoch of any deeper stage of sleep. Latencies to stage 2 and SWS were defined as the time from the sleep onset till the first epoch of stage 2 or slow-wave sleep respectively.

Performance measures: included reaction times and percentages of correct responses on AMP tests as well as the digit span test. Any error during reproduction of digits was interpreted as a presence of sleep inertia.

Questionnaire: Comfort of the Nap Cap prototype was evaluated with a questionnaire which the subjects filled after the nap on both their rested and sleep-deprived session. The subjects graded perceived comfort for each component (EEG Headset, pillow, eye cover, headphones) and the device as a whole on a nominal scale with 5 categories that were later converted into ranks for the purposes of analysis (1-very uncomfortable, 2-uncomfortable, 3-neutral, 4-comfortable, 5-very comfortable).

Statistical analyses: The effects of experimental conditions on the sleep variables were tested by a 3-way ANOVA, with session (rested, sleep-deprived), time (Part 1 or 2) and heat (off, on) as the factors. Factor Time essentially modeled sleep propensity – it was expected that latencies to all stages will be shorter and % time spent in deeper sleep stages (Stage 2 and SWS) bigger in Part 2 than Part 1. Only main effects were tested because of the small sample size which created numerical problems in a model with interactions. Part 3 was excluded from the analysis because its duration was very variable (from 5 to 15 minutes) during the rested session, while most subjects did not complete it at all on the sleep-deprived session. The results of the questionnaire were analyzed only descriptively.

AMP performance measures were analyzed with a 2-factor RMANOVA with Session (rested, sleep-deprived) and Condition (pre- and post-nap) as the factors.

3   Results

3.1 Effects of Sleep Deprivation, Sleep Propensity and Thermal Stimulation on Sleep Variables

Consistent with our expectations, latency to Stage 2 ($F_{(3,18)}$=3.8, p=0.05) and % time spent in Wake ($F_{(3,18)}$=6.05, p=0.023), and Stage 1 ($F_{(3,18)}$=7.57, p=0.013) decreased while TST ($F_{(3,18)}$=6.01, p=0.027), SE ($F_{(3,18)}$=6.45, p=0.017) and % time spent in SWS ($F_{(3,18)}$=4.22, p=0.054) increased after sleep deprivation. SOL was significantly

shorter in Part 2 in both sessions ($F_{(3,18)}$ =4.85, p=0.041). The magnitudes of all the significant effects can be inferred from Figure 4 and Tables 2 and 3.

Contrary to our expectations, the heating did not seem to have had any effect on the sleep architecture. The only variable that was (marginally) affected by heat was the number of awakenings after sleep onset (3.8±2.2 without vs. 2.3±1.7 with heat, p=0.08).
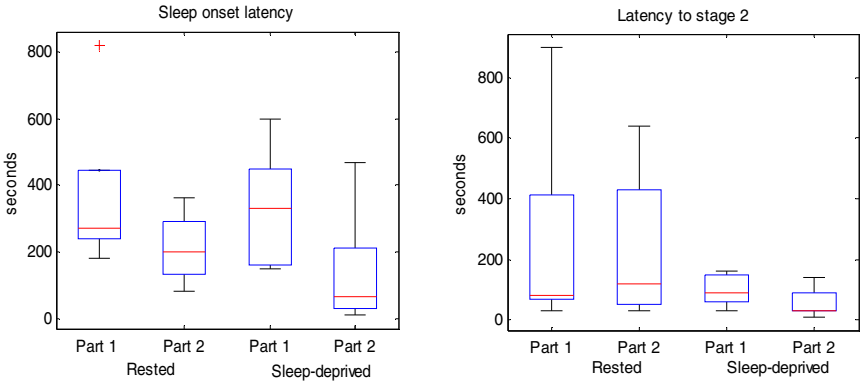

Fig. 4. Sleep onset latency and latency to Stage 2 (both in seconds) across various parts of the experiment. Red lines – medians; blue boxes - lower and upper quartile; black whiskers - full range.

Table 1. Sleep architecture of naps with subjects fully rested (SE in %, all other variables in minutes)

Subject	TST	SE	Wake	S1	S2	SWS
1626	52.8	84.4	14.1	18.6	65.8	0.0
1627	41.6	70.4	28.5	13.5	55.5	1.4
1628	31.8	64.9	33.7	17.4	47.6	0.0
1629	42.3	71.9	26.9	23.8	48.2	0.0
1630	39.8	65.5	33.4	46.0	19.5	0.0
1631	38.3	61.3	37.6	25.9	35.5	0.0
mean±sd	41.8±8.2	69.7±8.1	29.0±8.3	24.2±11.6	45.3±16.1	0.2±0.6

Performance measures: Reaction times and percentages of correct responses showed the expected pattern of performance deterioration following sleep deprivation, and its restoration after a nap (Fig.5). However, none of the visually apparent differences was statistically significant, probably due to the small sample size and high within-subject variability. No subject failed the digit span test.

Comfort: The subjects found the Nap Cap comfortable (grade: 3.3±0.7) with the EEG headset being the least comfortable component (grade: 2.7±0.6). The most frequent complaint/suggestion about the prototype as a whole was that it contained too much

Table 2. Sleep architecture of naps following sleep deprivation (SE in %, all other variables in minutes)

Subject	TST	SE	Wake	S1	S2	SWS
1626	45.3	76.0	24.0	15.0	50.8	10.0
1627	48.7	84.8	12.2	02.2	52.9	32.7
1628	47.5	78.7	21.0	13.8	64.9	00.0
1629	44.8	72.7	27.3	15.1	57.6	00.0
1630	47.0	82.0	18.0	12.2	36.6	33.4
1631	45.8	82.8	17.2	07.8	43.4	31.6
1632	51.5	85.6	14.4	21.8	63.7	00.0
mean±sd	47.2±2.3	80.4±4.8	19.2±5.3	12.6±6.2	52.8±10.4	15.4±16.4

stuff and should be lighter and less obtrusive. Grades were consistently (although insignificantly) higher on all items on the sleep deprived session, which may reflect a change in perceptual threshold due to sleep deprivation, or an adaptation to wearing the Nap Cap. The two subjects who gave the lowest grade for comfort had the lowest sleep efficiencies and highest % of stage 1. Their complaints had however little to do with the Nap Cap: one was uncomfortable about sleeping under surveillance and another complained of not being able to sleep well in the supine position.

4 Discussion and Conclusions

Contrary to common reports of low signal quality in unattended sleep recording with ambulatory polysomnographs the Nap Cap prototype delivered high quality EEG with very few artifacts, demonstrating that careful mechanical and electrical design can result in a robust yet easy to use wearable EEG acquisition system. Algorithms for real-time sleep staging have been developed and successfully tested on a larger data set [11]. However, the EEG headset used in the Nap Cap prototype acquires many more channels that it is needed for accurate sleep staging, and utilizes modified 'wet' Ag/AgCl electrodes with a small amount of conductive paste, which is a clear disadvantage for in-field use. The next generation of Nap Cap will be designed to use forehead and peri-orbital dry electrodes, possibly similar to those used in the ARES[TM] Unicorder. Forehead EEG in combination with head actigraphy suffices for accurate automated distinction among wakefulness, REM, light NREM and slow-wave sleep [12].

  While the sleep monitoring in real time was successfully accomplished, sleep modulation by means of sensory stimulation achieved very little effect on the transition from wakefulness to sleep. Thermal stimulation of the neck that we hoped would have replicated the 'hot bath' effect bore no objective impact on sleep architecture of the naps, and some subjects even found it distracting. The heating was however not excessive since the skin temperature increased in all subjects for less than 4°C during
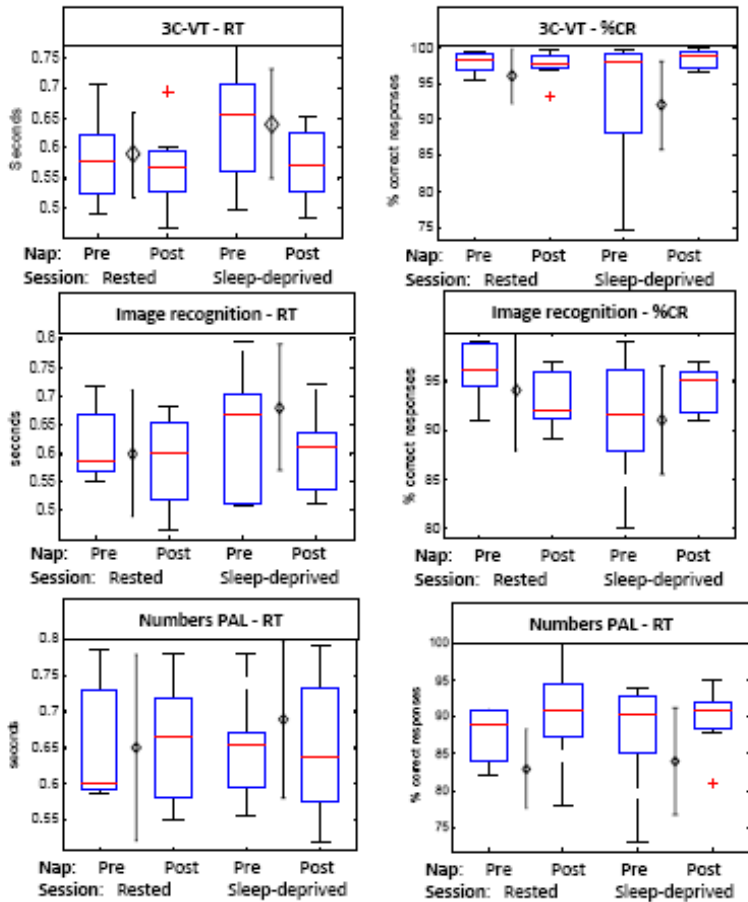
Fig. 5. Mean reaction times (RT) and percentages of correct responses (%CR) on AMP tests. Black error bars between the box plots represent the mean and standard deviation of the same variables from a reference database of over 1,000 rested and sleep-deprived subjects.

the parts of the experiment when the heating element was switched on (rested session: $2.18\pm1.01^{\circ}C$, sleep deprived session: $2.81\pm0.52^{\circ}C$, in both cases measured after 20 minutes). The measured increase in skin temperature is comparable to that in recent reports of the successful use of thermal suits to increase the depth and quality of sleep [9]. The failure of thermal stimulation in our experiment could perhaps be explained by the substantially smaller area of the skin that was heated with the Nap Cap. Efficient heating of larger areas of the skin would be difficult to achieve with a battery powered system without compromising the lifetime of usage before the batteries need to be replaced or recharged. We plan to conduct more studies of the effects of thermal stimulation on sleep architecture, and build eventual positive findings into an improved version of the Nap Cap.

Fig. 6. Two potential form factors: a soft ski-mask design (left) and a more rigid visor design (right). In both cases the electronics and batteries will be housed in the appropriately designed eye cover.

Awakened by the applied auditory stimulation the subjects showed no gross signs of residual sleep inertia on the digit span test. The applied visual stimulation on the other hand did not awaken most of the subjects, and there was no evidence that it added anything to the subsequent brief auditory stimulation in terms of mitigating the post-nap sleep inertia. It is however unclear whether subtle deficits in motor or cognitive performance would have been noted, and differences between the visual plus auditory vs. auditory stimulation alone detected if a more sensitive (but still brief) test had been applied upon each awakening. Furthermore, it would be premature to draw general conclusions on the basis of few fixed stimulation patterns that have been tested so far. Our future research will focus on designing a variety of the stimulation patterns, exploring more sensitive metrics for quick detection of residual sleep inertia, and improving the experimental design of the future validation studies. Comfort of the Nap Cap also needs to be further improved as it is crucial for success of a device that aims at optimizing sleep. This will be achieved by reduction in the number of sensors and weight of electronic circuitry, custom design of the earphones, and integration of all components into one-piece easy-to-apply device (figure 6).

In conclusion, the results of the pilot validation confirmed the viability of the concept of using an EEG-based wearable device to monitor and optimize sleep, but more psycho-physiological research and further technical improvements are warranted before it becomes ready for field use.

Acknowledgements

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