Motion during all-night functional magnetic resonance imaging sleep studies

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Introduction

Previous functional magnetic resonance imaging (fMRI) sleep studies have been hampered by the difficulty of obtaining extended amounts of sleep in the sleep-adverse environment of the scanner and often have resorted to manipulations such as sleep depriving subjects before scanning. These manipulations limit the generalizability of the results. Additionally, only eight fMRI rapid eye movement (REM) sleep studies exist to date (Chow et al., 2013; Deuker et al., 2013; Dresler et al., 2011; Hong et al., 2009; Lövblad et al., 1999; Miyauchi et al., 2009; Wehrle et al., 2005; Wu et al., 2012), with an average of 5.6 subjects exhibiting 3-53 min of REM sleep. Total scan time varies widely, ranging from 0.38 hr (Fukunaga et al., 2008) to 2-7 hr (Miyauchi et al., 2009). The current study is a methodological validation of procedures aimed at obtaining all-night fMRI data in sleeping subjects with minimal experimentally induced sleep deprivation. Subjects slept in the scanner on two consecutive nights, allowing the first night to serve as an adaptation night.

Methods

Pre-Inpatient Visit:

- Extensive at-home internet screening using psychometrically validated questionnaires to increase likelihood of sleeping in MRI environment.
  - Assessments measured: risk of airway obstruction and insomnia, claustrophobia, arousing pre-sleep thoughts, susceptibility to noise and likelihood of back discomfort.
- Volunteers maintained ~23:00-07:00 sleep schedule for 14 days prior to visit. Verified by actigraphy (Actiwatch 2, Philips Respironics) and time-stamped voicemail call-ins.

Design:

- Volunteers slept in scanner on two consecutive nights with the first night being an adaptation night.

Study Timeline

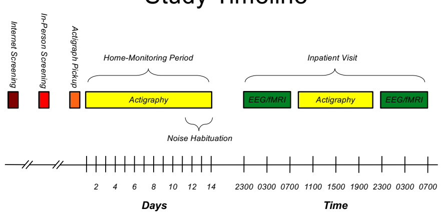

Figure 1: Procedures and the associated timeline.

Methods

MRI Environment and Safety:

- Volunteers slept on a clinical-grade memory foam mattress (TEMPUR-MED, Tempur-Pedic).
- Active noise cancelling headphones (Optoactive, Optoacoustics Ltd.), trained on the MRI acoustic noise were used along with standard hearing protection. This technique results in an approximately 20 dB sound reduction (from ~85 to ~65 dB).
- Amplifiers were placed inside the bore on a sled fastened to the scanner table to minimize gradient artifact and ease subject insertion and removal.
- Assessed hearing safety with baseline and post-MRI audiology examinations.

Scan:

- fMRI sequence: constant slice timing, no jitter, used to reduce gradient artifact in EEG, TR = 3 s, 50 slices, resolution = 2.5 x 2.5 x 2 mm^3 (Figure 2).
- EEG data were artifact-corrected in real-time to allow for live sleep scoring during scans (Figure 3a).
- EEG data were scored offline with optimized artifact correction algorithms (Figure 3b).
- Other peripheral signals such as variations in cardiac and respiratory cycles and eyelid position were measured.

fMRI Images Sample

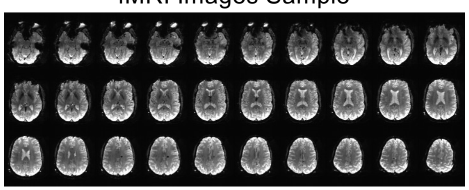

Figure 2: Sample of fMRI images from a single subject.

EEG Samples

a b

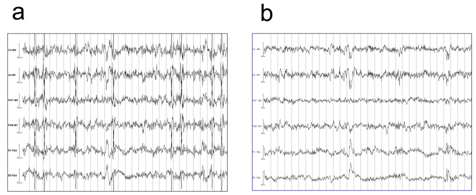

Figure 3: a) Real-time optimized EEG traces. b) Offline artifact-corrected EEG traces.

Results

- Despite sleep-adverse circumstances, nonREM-REM cycling was observed (see Figure 4); the typical overall architecture favoring slow-wave sleep early in the night and REM sleep later in the night can be seen.

Representative Hypnogram

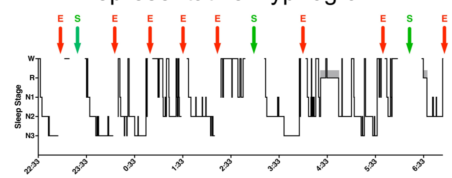

Figure 4: Representative hypnogram for one subject from Night 2. Arrows indicate experimenter (E) or subject (S)-request arousals.

- For most variables, subjects slept significantly worse in the scanner (Table 1); this was expected given the sleep-adverse environment of the scanner and the auditory arousal threshold protocol.

Normative Data Comparison

	Toussaint (1995) (*n* = 32)		Current Study (*n* = 12)			
	M	*SD*	*M*	*SD*	*t*	*d*
N3 (min)	90.5	22.1	52.1	26.5	5.0	1.6
R (min)	99.8	28.5	45.2	27.9	6.8	1.9
N3 (% of TST)	20.7	5.5	19.0	8.1	0.7	0.3
R (% of TST)	22.5	5.2	16.0	9.3	2.4	1.0
Cycles (#)	3.7	1.1	2.1	1.1	5.2	1.5

Table 1: Summary of the statistical comparisons between sleep in the scanner on Night 2 and sleep in a previous normative study (Toussaint, 1995). TST = Total Scan Time.

- Subjects were sleep deprived by the Night 1 procedures. Nightly total sleep time averages were 4.2 hr on Night 1 and 4.6 hr on Night 2 (average total recording time of scanning: 6.1 hr on Night 1, 5.8 hr on Night 2).
- Only one subject complained of back discomfort that was significant enough to warrant withdrawal from the study.
- Unsuccessful studies were the result of prodromal sleep apnea, inability to sleep and a stress reaction to the scanner environment (Table 2).

Volunteer Screening Success Rate

	n	% of prior category
Completed Internet screening	99	N/A
Passed Internet screening	49	49.5
Passed in-person screening	35	71.4
Attempted inpatient visit	16	45.7
Completed inpatient visit	12	75.0

Table 2: Success rate of volunteers at each screening stage.

- Maximal head displacement was M = 2.69 mm (SD = 3.03 mm) (Figure 5).
- Only 7 of the 239 scans had a maximal head displacement greater than 3 SD from this mean.

Max Head Displacement / Scan

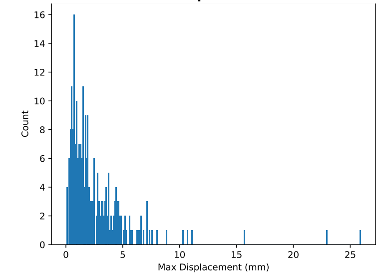

Figure 5: Histogram of maximum head displacement per scan.

Discussion and Conclusion

Effect of Adaptation Night

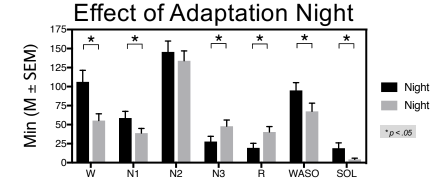

Figure 6: Representative hypnogram for one subject from Night 2. Arrows indicate experimenter (E) or subject (S)-request arousals. WASO = wakefulness after sleep onset; SOL = sleep onset latency.

- Because the two nights of the study were performed consecutively, some sleep deprivation from Night 1 as a cause of the Night 2 results (Figure 6) is likely, so consideration should be given to replicating the current study with a washout period.
- These findings demonstrate that our method was able to successfully promote sleep across an all-night continuous fMRI scan.
- The ability to scan sleeping subjects for an entire night opens up many future directions for studying neural circuits associated with sleep such as sleep state cycling, the mechanisms of the sleep-wake cycle and even the core functions of sleep itself.
- Future directions may involve the use of screen-printed MRI receive coils
- These data show that motion during long sleep scans is comparable to the motion in resting-state scans of shorter duration.