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An fMRI Study of Abrupt-Awake Episodes during Behavioral Microsleeps

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Abstract—**This paper reports the brain activation patterns of five subjects who were abruptly awakened from microsleeps in a simulated automotive driving experiment. By comparing the BOLD signals between behavioral microsleep (BM), abrupt awakening (AA) and post-abrupt awakening (post-AA) stages, we observed that *visual area*, *frontal cortex*, *limbic lobe* manifested more intense activation during the AA stage while *frontal cortex*, *temporal cortex*, *primary motor area* and *insula* were more activated during the post-AA stage. These results suggested that the subjects were likely in mental states differ from those associated with decision making processes as they went through and emerged from the abrupt awakening episodes.**

I. Introduction

MICROSLEEPS are involuntary episodes of sleep that lasted merely seconds [1]. When they occur, subjects experience time lapses without conscious of fallen asleep. Microsleeps can be caused by mental fatigue rather than sleep deprivation. Specifically, *behavioral microsleeps* [2] can be induced by the automatic behaviors of subjects engaging in monotonous tasks. Behavioral microsleeps are known to have plagued car drivers, flight pilots and air traffic controllers and caused disasters such as the Waterfall train accident [3].

Like previous experiments [4,5,6], we studied the response of subjects as they endured episodes of behavioral microsleeps (BMs). However, in our simulated automotive driving experiments, we paid specific attention to drivers' *brain activation* as they were abruptly awakened by the sharp deviations from their driving courses. Once out of their BMs, the drivers would try instinctively to re-orientate themselves, take back the control of their cars and concentrate once again on driving. We compared the fMRI scans of our subjects during and after their episodes of *abrupt awakening (AA)* against the scans of those who engage in cognitive decision making processes. Our comparisons revealed notable differences in brain activation patterns, which in turn suggested that the subjects might be in distinct mental states as they went through and then emerged from AA episodes.

Although driving is a routine activity for many people, it is nonetheless one that taxes a wide range of cognitive functions including perception, attention, working memory, decision making and motor control [7]. Hence, Callan et al. made comparisons between driving and gambling, a decision making process, the neural substrates of which have been thoroughly studied [8]. While gambling can be regarded as a *reward-weighted decision making process* because subjects may profit from their participation, driving was regarded as a *cost-weighted decision making process* because risk avoidance likely overrides reward anticipation and becomes dominant activity in driving. Studies showed that anterior cingulate cortex, insula, lateral prefrontal cortex, ventromedial prefrontal cortex, orbital frontal cortex, parietal cortex and dopaminergic mid-brain regions are activated in the reward-weighted decision making process [9,10,11]. In contrast, amygdale and anterior cingulated cortex play an active role in cost-weighted decision making [8].

We attempted to study subjects' brain activation during automotive driving from a different perspective. Instead of focusing on the BM stage, we paid attention to brain activation patterns in the AA and post-AA stages [Figure 2]. While gambling and normal driving involve high-level cognitive functions—for example, deciding when to step on the gas paddle—we believe that subjects' responses during AA episodes are largely reflexive. We intended to identify the neural signatures of these low-level activities by examining the increases of blood-oxygen-level-dependence (BOLD) signals during the AA and post-AA stages in comparison with those of the BM stage.

The rest of this paper is organized as follow. Section II describes the setup of our experiments and the analysis techniques we employed. The experiment results were described in Section III. We then discuss our findings in Section IV before concluding the paper with a summary of our contributions and future work items in Section V.

II. Methods

A. Related Work

Visuomotor tracking has long been used as the standard task to study BM behaviors. Several continuous visuomotor experiments took a multi-modal approach to observe brain activations during BMs with the use of functional magnetic resonance imaging (fMRI), eye video acquisition and vertical electrooculography (VEOG) [4,5]. These studies found that BOLD of motor cortex, superior parietal cortex, middle temporal cortex, parahippocampal gyrus, thalamus, ganglia and cingulate cortex all intensified during BMs. These studies focused their attention on the neural signatures of BM stage. They overlooked the post-BM brain activation patterns such as those appeared in AA and post-AA stages.

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Several recent studies used electroencephalography (EEG) aided with independent component analysis (ICA) to gauge subjects' driving performance under the influence of BMs [12,13]. Although the use of EEG in these studies provided high temporal resolution records of brain activities during BMs, they did not reveal the intricate interactions among cerebral cortices throughout the BM/AA/post-AA cycles. Our experiments were designed to complement these studies.

B. Experiment Design

In our experiment, the subjects were asked to perform simulated driving while they underwent continuous MRI acquisition using a 1.5-T Siemens Symphony scanner. The driving simulation software has been developed and used in previous EEG based studies [14].

To induce behavioral microsleeps, the tested subjects were asked to perform the monotonic task of driving a simulated vehicle in constant speed (approx. 100km/hour) along a straight four-lane freeway. During this exercise, uniformly random bi-directional deviations from the nominal driving course were introduced by the simulation software. The subjects should try to return the vehicle to its nominal course (along the third lane) as quickly as possible. The elapsed time and the magnitude of course offsets were recorded and used as the evidence of BM occurrences.

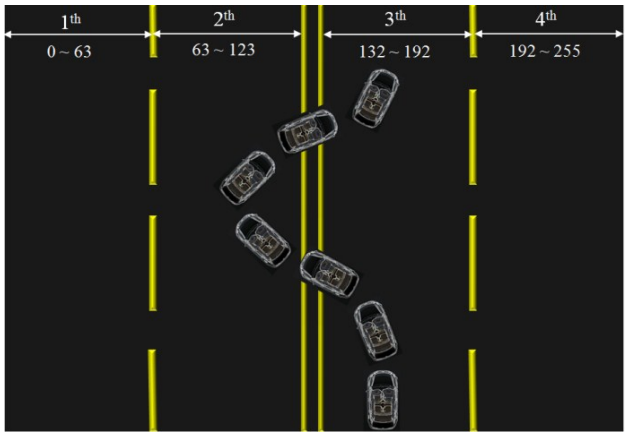


Figure 1: An illustration of the simulated freeway driving task. The position of the simulated vehicle may vary between 0 and 255, and its nominal course was set along the third lane.

C. Subject Preparation

Five healthy right-handed volunteers (three males and two females between 22 and 35 years of age) with no history of head injury, neurological, psychiatric, or sleep disorder have participated in this experiment. All of them consented that they understood the nature of this experiment and willingly participate in it without any coercion.

The driving tests were conducted between 2pm and 4pm while the subjects felt a little sleepy after having their lunch. The subjects were asked to refrain from taking any substance with stimulating or sedative effects such as caffeine, nicotine or alcohol within four hours before the tests.

Before starting the MRI acquisition, each subject was given a five-minute warm-up period, in which he/she could practice the simulated driving. After the practice, a 30-minute driving section with MRI acquisition would commence. Throughout the experiment, the test subjects wore headphones to block off audible noise produced by the scanner and used cushions to reduce potential head movements.

D. MRI Acquisition

MRI scans were performed on a 1.5-T Siemens Symphony scanner equipped with Numaris 4 (MRease) system. Functional images were acquired using gradient echo-planar imaging sequences with repetition time (TR) = 2000 ms, time to echo (TE) = 35 ms, field of view (FOV) = 240 mm, flip angle = 90°, matrix size = 64×64, slice thickness = 5 mm. Each time series consisted of 900 scans with 25 transversal slices per scan. Thus, a total of 22,500 images were acquired from each subject. Following functional measurements, high-resolution anatomical a 3D sequence of T1-weighted images consisting of 128 axial slices (each has 256×256 voxels with slice thickness = 1.5 mm, TR = 1700 ms, TE = 3.96 ms, FOV = 240 mm, flip angle = 15°) were acquired as the reference matrix for functional imaging.

E. fMRI Data Extraction

We used the 3σ offsets from nominal driving course as the evidence of BM occurrences. In order to estimate the *mean position* μ and *standard deviation* σ of the subject's driving course, we used the first three minutes of his/her driving record as the *baseline*. As shown in Figure 2, we decided that the subject had experienced a BM episode if an offset larger than three times of the standard deviation σ was found on his/her driving record. The subject was considered being in the BM stage (1) during the initial deviation and then entered the AA stage (2) when he/she tried to return to the nominal course. The subject was regarded in the post-AA stage (3) when he/she stayed roughly on course during the quiescent period immediately following a BM episode.

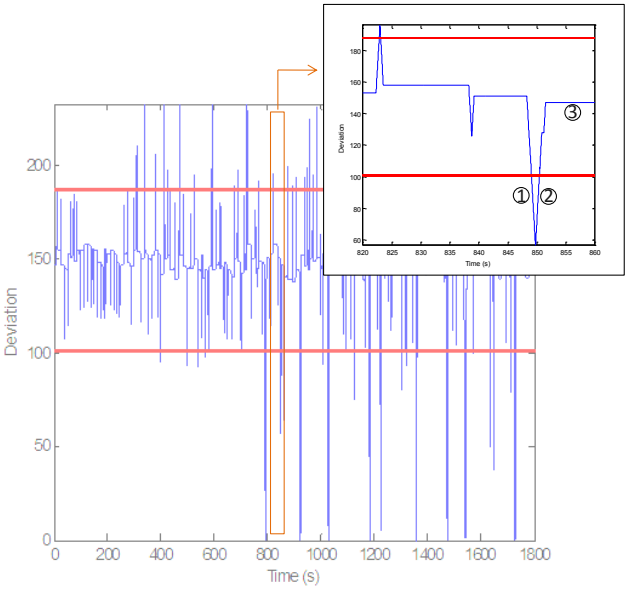
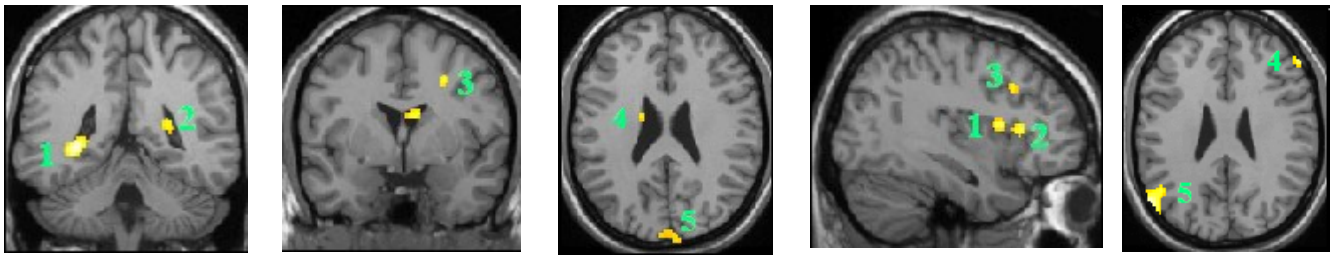


Figure 2: Driving record of a subject revealing (1) BM, (2) AA and (3) Post-AA stages. The two red lines delimit the $\mathbf{3\sigma}$ deviation from the nominal driving course. The insert shows a few BM episodes and the three stages in detail.



(a) Y = −44 (b) Y = 0 (c) Z = 24

Figure 3: Statistical brain maps of BOLD contrasts between AA and BM stages. The maps showed BOLD signal increases in parahippocampal gyrus (1), lateral ventricle (2), middle frontal gyrus (3), cingulate gyrus (4) and cuneus (5) in the AA stage.

(a) X = 38 (b) Z = 26

Figure 4: Statistical brain maps of BOLD contrasts between post-AA and BM stages. The maps showed BOLD signal increases in insula (1), inferior frontal gyrus (2), precentral gyrus (3), middle frontal gyrus (4) and middle/superior temporal gyrus (5) in the post-AA stage.

Successive fMRI images were acquired in two second fixed intervals. Among them, those acquired before and after the abrupt turns as well as those after the return to the right course were extracted for event related analysis. From the five subjects, we managed to record approximately *sixty* BM/AA/post-AA episodes with 10 – 15 episodes from each subject.

F. fMRI Data Processing

The SPM2 program (Wellcome Department of Imaging Neuroscience, London, UK) was used for processing the fMRI data. Following pre-processing was applied to each subject's data: (1) image realignment for correcting motion artifacts; (2) image normalization based on the standard EPI template in stereotactic space (MNI) with a resampled voxel size of 3 × 3 × 3 mm; (3) spatial smoothing using a Gaussian FWHN filter of 8 mm. After the preprocessing, statistical analyses were performed using general linear models. Task related neural activitions were modeled as a series of BM, AA, and post-AA events convolved with a canonical hemodynamic response function. As a preliminary investigation, we performed merely fixed effect (FFX) group analysis onto our data. Activations were reported if the results met the criteria of $p < 0.01$ (uncorrected) with the extents over 20 voxels.

III. Results

In our experiment, parahippocampal gyrus, lateral ventricle, superior frontal gyrus, middle frontal gyrus, cingulate gyrus and cuneus showed significant BOLD activations during the AA stage in contrast with the BM stage [Figure 3, Table 1].

On the other hand, insula, frontal cortex, primary motor area, and temporal cortex showed significant BOLD activations during the post-AA stage in contrast with the BM stage [Figure 4, Table 1].

Table 1: Brain Activation Regions in (a) AA and (b) Post-AA Stages

Brain Regions	Voxel Coordinates		
	X	Y	Z
(a) AA Stage			
Parahippocampal Gyrus	−34	−44	−4
Lateral Ventricle	26	−48	12
Middle Frontal Gyrus	26	0	43
Cingulate Gyrus	−16	−10	26
Cuneus	3	−98	9
(b) Post-AA Stage			
Insula	44	12	10
Inferior Frontal Gyrus	38	22	8
Middle Frontal Gyrus	54	34	30
Precentral Gyrus	40	18	34
Superior Temporal Gyrus	−50	−60	28
Middle Temporal Gyrus	−56	−70	24

IV. Discussions

Our experiment results showed that the BOLD signals in *visual area*, *middle frontal gyrus* and *limbic lobe* (both *parahippocampal* and *cingulate*) increased during the AA stage when compared with those of the BM stage. In other driving experiments, Spires et al. reported *middle frontal activations* when drivers tried to decide whether to make a left or right turn [7]. Epstein et al. suggested that *parahippocampal activations* may be related to subjects' perception of spatial layout [15] while Duzel et al. correlated similar activations to subjects' use of spatial memory [16]. Based on these results, we inferred that our subjects may have gone through a rapid sequence of activities when they were abruptly awakened from their microsleeps: (1) they tried to reacquire their vision; (2) they tried to recognize the positions of their vehicles (that we surmised was the cause of parahippocampal activations); (3) they decided whether they need to turn left or right in order to get back on course (that in turn caused middle frontal activations). These reflexive driving behaviors differ notably from those of normal driving. Specifically, the parahippocampal activations suggest that the subjects need to recover from their spatial disorientation caused by microsleeps before they can make their turn decisions. Since we performed our experiments onto oriental subjects but used the standard

Caucasian brain templates in our analysis, a few activations appeared close to or within the CSF space as a result.

We also noticed BOLD signal increases in lateral ventricles. These increases were probably related to changes of subjects' heart rates. In vigilance experiments [17], BOLD signals in lateral ventricles were shown to decrease while the subjects entered into sleep stages I and II [18].Thus, we surmised the increase of lateral ventricular BOLD signals might be caused by palpitations experienced by the subjects as they were suddenly awakened from their sleep.

In comparison with BM stage, the post-AA stage showed BOLD signal increases mainly in *inferior/middle frontal gyrus*, *superior/middle temporal gyrus*, *motor area* and *insula*. Activations in frontal cortex usually correlated with increases or shifts of subjects' attention. Their appearance in our experiment may imply that the subjects were trying to recollect themselves and focus again on driving. Insular activations were known to be related to visual attention and limb movements [19]. Their appearance in the post-AA stage may hint at drivers' attempt either to focus on the simulation display or to touch the controls using their fingers. Several subjects salso mentioned that they felt "shocked" when they were woken from microsleeps.

V. CONCLUSIONS

We designed a visuomotor experiment for studying subjects' neural activation patterns during the AA and post-AA stages of behavioral microsleeps. To our knowledge, our experiment was the first attempt to study these unusual stages of semi-alertness. From the BOLD contrasts, we observed notable activations of visual area, frontal cortex, limbic lobe in the AA stage. We postulated that these activations were caused by a rapid sequence of quasi-reflexive responses taken by the subjects to re-orientated themselves and re-gain the control of their vehicles. We also observed activations in frontal cortex, temporal cortex, primary motor area and insula during the post-AA stage. These activations were postulated to be associated with increases in subjects' visual attention, limb movements and their "shocked" feelings.

Further investigation will be needed to confirm and enrich our findings. First, we shall perform the experiment on more subjects in order to improve the statistical significance of our results. We shall also calibrate the parameter settings of our SPM analysis and perform second level analyses. Then, we shall employ EVOG and ECG to help us to identify the AA and post-AA stages more accurately. Finally, we hope to correlate our findings with those of EEG brain mapping experiments. Currently, no such EEG brain mapping has been performed on AA and post-AA stages.

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