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A passenger reduces sleepy driver's activation in the right prefrontal cortex: A laboratory study using near-infrared spectroscopy

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ABSTRACT

The present study aimed to examine how a passenger affects the sleepiness effect (awake vs. sleepy) on an individual's prefrontal activation during a simulated driving-game task using a wireless portable near-infrared spectroscopy (NIRS) device. Participants drove from start to goal along default routes either solely (no-passenger group) or with a friend sitting beside him/her as a passenger (with-passenger group). Sleepiness level was assessed by a five-item scale questionnaire. In the no-passenger group, there were no performance and activation differences between the sleepy and awake participants. In the with-passenger group, by contrast, the sleepy participants showed more errors and lower activations in their right prefrontal cortex than the awake participants. These results suggest that a passenger has little effect on awake participants, but may weaken the sleepy participants' vigilance and/or their cognitive abilities of action control. Practically, the present study demonstrates that NIRS may provide us a new possibility to monitor and examine the driver's mental states in the brain.

1. Introduction

Fatigue, defined as a gradual and cumulative process ranging from being weary, drowsy to being hardly awake, lightly asleep or even deep slumber (Grandjean, 1979), is a critical factor endangers driving safety (Philip et al., 2005; Wheaton et al., 2014; Wu et al., 2007). It has been well acknowledged that fatigue (including sleep-related fatigue and task-related fatigue) could lead to loss of effort, reduction of alertness and impairment of cognitive functions, and thus is a critical contributing factor in thousands of industrial and traffic accidents (Lal and Craig, 2001; May and Baldwin, 2009; Philip et al., 2005). For instance, up to 35–45% of yearly road fatalities are ascribed to fatigue (Khushaba et al., 2011). With the development of economics in China, the automotive ownership quantity grows rapidly (Traffic Management Bureau of The Public Security Ministry, 2015). Accordingly, the issue of driving safety is attracting increasing attention (2013 China Road Safety Forum, Beijing). The primary technologies for detecting the driver's mental states such as fatigue are pattern recognition (Wu et al., 2007) and psychophysical measures (Mao et al., 2005). However, to fully understand the cognitive mechanisms of driving, and in turn to detect the driver's fatigue state timely and effectively, it is necessary to measure an individual's brain activity with different levels of fatigue in driving.

Near-infrared spectroscopy (NIRS) is a relatively new, non-invasive brain imaging technique for studying functional activation by measuring changes in the hemodynamic properties of the brain. NIRS is portable, has few physical constraints on participants, and is tolerant to motion artifact and electromagnetic noise (for review on NIRS technique, see Scholkmann et al., 2014; for review on driving research using NIRS, see Liu et al., in press). Therefore, NIRS is potentially appropriate for monitoring brain activity in natural environments such as real driving.

Previous cognitive neuroscience studies have consistently reported that prefrontal cortex (PFC) is sensitive to fatigue (Drummond et al., 2001; Li et al., 2009; Liu, 2014; Miyata et al., 2010; Muzur et al., 2002). For instance, Drummond et al. (2001) have revealed increased prefrontal activation in sleepiness during divided attention task using fMRI. Similarly, Liu et al. (2003) and Van Duinen et al. (2007) have also reported an increase in participants' prefrontal activations during sustained and intermittent submaximal motor fatigue. In a recent NIRS study, Liu (2014) has measured single participant's prefrontal activations in a driving-game task. Participant's task was to drive on a monitor either without speed limit (speed-free group) or with a speed limit of 30–40 km/h (speed-control group). The NIRS data demonstrated

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a positive correlation between participants' sleepiness levels and their prefrontal activations in the speed-control task, but not in the speed-free task. These results suggest that individuals in fatigue may show increased activation in the PFC as additional attention and/or compensatory efforts to maintain the desired level of performance in tasks that require deliberate control of behaviors.

In contrast, Li et al. (2009) have measured participants' prefrontal activation before and after 3-h simulated driving using a one-channel NIRS device. The results revealed that the cerebral oxygen saturation in the participants' left PFC decreased significantly after the long-time driving (i.e., in fatigue), compared with a control group in which the participants rested for 3 h. Another NIRS study (Miyata et al., 2010) has also revealed lower prefrontal activation in the insufficient-sleep participants than in the sufficient-sleep participants during a word fluency task. They concluded that the decline of prefrontal activation may indicate a reduction of cognitive functions, leading to impairments of daily performance (for more information about the role of PFC in driving and the driver fatigue, see Liu et al., in press; May and Baldwin, 2009).

Despite the efforts made by these studies, previous cognitive neuroscience research on fatigue, especially in driving, has mainly examined single individuals' brain activity (Li et al., 2009; Liu, 2014; Liu et al., in press; Miyata et al., 2010; Muzur et al., 2002). Driving with a passenger is a quite common phenomenon in our daily life, however, little is known about how a passenger affects a fatigue driver's mind and behaviors. Since fatigue consists of multi-processes, the present study primarily focused on one important stage—sleepiness, that is a desire or inclination to sleep, and aimed to compare participants' prefrontal activations at different sleepiness levels in either a single driving situation (no-passenger group) or a paired driving situation with a passenger sitting beside (with-passenger group).

On the basis of the findings revealed by previous studies on fatigue in driving (Li et al., 2009; Liu, 2014), we hypothesized that the sleepy participants would show comparable prefrontal activations to the awake participants in the no-passenger group due to the relatively simple, solitary driving-game task. In the with-passenger group, by contrary, the sleepy participants would show lower prefrontal activation than the awake participants due to a relaxation of vigilance induced by the friend-passenger, or show higher prefrontal activation due to increased arousal (or compensatory efforts) in the presence of a passenger.

2. Methods

2.1. Participants

Forty undergraduate students (35 males, 5 females; age: 20.6 ± 2.5 years) participated for course credit. They were randomly assigned to two groups: *no-passenger* group (N = 18) and *with-passenger* group (N = 22). Participants in the with-passenger group were asked to attend the experiment together with their same-gender friend who took a role of passenger. The durations of the 'driver-passenger' pairs' friendship were 1.81 ± 1.36 years as assessed by a self-report questionnaire. All participants were right-handed as assessed by the Edinburgh Handedness Inventory (1971), and had normal or corrected-to-normal vision. They were informed about the purpose and safety of the experiment, and written informed consent was obtained prior to participation. This study was approved by the local ethics committee.

2.2. Experimental task and procedure

Because driving in fatigue or in other dangerous situations cannot be studied using real cars, simulated driving is thus needed for exploration of issues regarding driving safety. Although a high-end driving simulator could provide more realistic driving environments and manipulations, which are necessary for investigation of the neural mechanisms of driving behaviors (Calhoun et al., 2002; Jäncke et al., 2008; Shimizu et al., 2009), the driving game inherently requires various cognitive functions such as visuospatial attention, vigilance and action control that are critical for driving safety. Therefore, in the present study, at the initial stage, we adopted a commercially available driving video-game (The Taxi 2, D3 Publisher, Japan) to present participants a simulated driving task.

The participant's task was to drive from start to goal using default route-maps either solely in a no-passenger group or with a passenger sitting beside him/her (without communication) in a with-passenger group. During the experiment, participant sat in front of a 32-inch monitor. The driving game was displayed on monitor without sound, and the participant controlled the game using a Sony game pad (DualShock 2; Sony Corp., Japan). The distance from the participant to the monitor was 120 cm.

Prior to the experiment, the participant was instructed to obey traffic rules and drive the game from a start to a goal using default paper route-maps. Then the participant practiced operating the game pad for 180 s, and drove two training trials followed by four experimental trials with distinct routes during the experiment. A single trial consisted of three periods, i.e., a pre-task period (20 s), a driving-task period (self-paced with time limit of 5 min), and a post-task period (20 s). In the pre- and post-task periods, a black monitor screen was displayed, and the participant was asked to relax and sit comfortably without movements. The whole experiment lasted about 15 min. To avoid the influence of verbal communication in the with-passenger group, the participant and the passenger were inhibited from communicating throughout the whole experiment. Performance of the participant was videotaped. After the experiment, the participant was instructed to rate his/her sleepiness level (i.e., the subjective feeling of sleep) on a 5-point scale (1 = not at all, and 5 = very much).

2.3. Apparatus

A wireless two-channel NIRS unit (PocketNIRS, DynaSense Inc., Japan) was used to measure the participant's concentration changes of oxygenated hemoglobin (Coxy-Hb), deoxygenated hemoglobin and total hemoglobin. Two probes were attached to the forehead using double-sided adhesive sheets and were centered on Fp1 and Fp2 positions, respectively (according to the international 10–20 system). Each probe consisted of one emitter optode and one detector optode located 3 cm apart. Based on the 3-dimensional probabilistic anatomical cranio-cerebral correlation (Okamoto et al., 2004), Fp1 and Fp2 were projected onto the bilateral prefrontal regions. In addition, NIRS detects hemodynamic changes in the brain with a depth of about 3 cm. Therefore, the PocketNIRS measured prefrontal activations in close proximity to scalp tissues, that is, the rostral parts of dorsolateral PFC (Petrides, 2005). The sampling rate was 10 Hz.

2.4. Data analysis

The data obtained from participants who did not finish the driving-game task in the given time period (1 participant) or that contained more than 10% non-near-infrared light signals (5 participants) were excluded, leaving 15 participants in the no-passenger group and 19 participants in the with-passenger group. Then according to the rating score on the subjective feeling of sleep (1 = not at all, and 5 = very much), participants in the two groups were then subdivided into *sleepy* (sleepiness score: 4 and 5) and *awake* participants (sleepiness score: 1 and 2). Finally, the data