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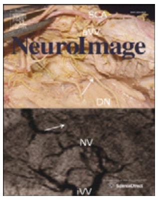

# Kinesthesia in a sustained-attention driving task

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ABSTRACT

This study investigated the effects of kinesthetic stimuli on brain activities during a sustained-attention task in an immersive driving simulator. Tonic and phasic brain responses on multiple timescales were analyzed using time–frequency analysis of electroencephalographic (EEG) sources identified by independent component analysis (ICA). Sorting EEG spectra with respect to reaction times (RT) to randomly introduced lane-departure events revealed distinct effects of kinesthetic stimuli on the brain under different performance levels. Experimental results indicated that EEG spectral dynamics highly correlated with performance lapses when driving involved kinesthetic feedback. Furthermore, in the realistic environment involving both visual and kinesthetic feedback, a transitive relationship of power spectra between optimal-, suboptimal-, and poor-performance groups was found predominately across most of the independent components. In contrast to the static environment with visual input only, kinesthetic feedback reduced theta-power augmentation in the central and frontal components when preparing for action and error monitoring, while strengthening alpha suppression in the central component while steering the wheel. In terms of behavior, subjects tended to have a short response time to process unexpected events with the assistance of kinesthesia, yet only when their performance was optimal. Decrease in attentional demand, facilitated by kinesthetic feedback, eventually significantly increased the reaction time in the suboptimal-performance state. Neurophysiological evidence of mutual relationships between behavioral performance and neurocognition in complex task paradigms and experimental environments, presented in this study, might elucidate our understanding of distributed brain dynamics, supporting natural human cognition and complex coordinated, multi-joint naturalistic behavior, and lead to improved understanding of brain–behavior relations in operating environments.

## Introduction

Sensory feedback is one of the most important components in sustaining attention (Sarter et al., 2001). With respect to everyday driving, an early report (Gioia and Morphew, 1968) claimed that 90% of the information that is used by drivers depends on vision, but the accuracy of this estimate was then debated by Sivak (1996). In fact, perception inference is largely automatic (Kasschau, 1985), effectively helping drivers obtain relevant information and enabling them to focus on a given task (Kemeny and Panerai, 2003; Kim et al., 2012). Kinesthesia is an important sensory source. Various degrees of vehicle motion can contribute to the generation of kinesthetic and vestibular sensations that inform drivers about the direction and speed of vehicle motion, its location, and the surrounding environment. Motion cues have been shown to improve driving performance (Kemeny and Panerai, 2003; Wallis et al., 2007). We hypothesize that a kinesthetic input might alter observed brain activity.

Monitoring the neurophysiological activities that are induced by motion in a naturalistic environment using vibration-sensitivity equipment, such as functional magnetic resonance imaging (Friston et al., 1996) or positron emission tomography (Nehmeh and Erdi, 2008), represents a severe measurement challenge. The electroencephalogram (EEG) is currently the clearly preferred device for imaging the brains of humans as they perform tasks that involve natural movements in a real-world environment (Liao et al., 2012).

Recently, many laboratory-based investigations (Banks et al., 2004; Boyle et al., 2008; Campagne et al., 2004; De Rosario et al., 2010; Eoh et al., 2005; F.-C. Lin et al., 2012; Jap et al., 2009, 2011; Khushaba et al., 2011; Lal and Craig, 2001; Lal and Craig, 2002; Lal et al., 2003; Lin et al., 2005, 2006, 2010; Otmani et al., 2005) have led to foundational insights into the brain functions that are associated with sustaining attention on the task of safe driving. They demonstrated the feasibility of accurately estimating shifts in a driver's levels of arousal, fatigue,

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and vigilance, as represented by changes in their task performance, by evaluating EEG changes. Most relevant studies have found an increase in theta power (4–7 Hz) (Campagne et al., 2004; De Rosario et al., 2010; Eoh et al., 2005; Huang et al., 2009; Jap et al., 2009, 2011; Lal and Craig, 2001, 2002; Lal et al., 2003; Otmani et al., 2005), the frequency of theta burst (Banks et al., 2004; Eoh et al., 2005) or the duration of episodes of theta activity (Banks et al., 2004; Boyle et al., 2008) as the task performance declined or a progressive deterioration of the driver's attention. Alpha activity (8–12 Hz) is another useful index of task performance, but it varies among studies. Increases of the alpha power, the density ratio of the sum of theta and alpha to beta, and the density ratio of alpha to beta were observed as the driving error increased (Campagne et al., 2004) or fatigue occurred (Eoh et al., 2005; Jap et al., 2009; Otmani et al., 2005). The aforementioned studies, however, have not quantitatively explored the effects of motion stimuli to human behavior and brain dynamics.

Previous studies showed that the motion and vestibular stimuli elicited an evoked potential over the fronto-central areas such as Fz, Cz, and Pz (Elidan et al., 1991; Loose et al., 1999; Nolan et al., 2012; Probst et al., 1997; Rodionov et al., 1996). The cortical regions involve in the processing of motion/vestibular cues include the posterior parietal cortex, insular, frontal cortex, somatosensory cortex, cingulate cortex, and striate/extrastriate cortex (Deutschlander et al., 2002; Lopez and Blanke, 2011). Furthermore, functional magnetic resonance imaging (fMRI) studies (Bremmer et al., 2001; Scheef et al., 2009) reveal increased activation at the posterior parietal, premotor cortex and visual cortices when the brain is engaged in processing motion. These brain regions that are observably affected by motion or vestibular stimuli largely overlap with the regions associated with performance lapses. However, the interaction effect of kinesthetic feedback and performance lapse on the brain activity remains unknown.

Therefore, this study thoroughly elucidated how kinesthesia affects brain activity, especially when momentary cognitive lapses were experienced. This study implemented an event-related lane-departure paradigm (Huang et al., 2009) on a realistic dynamic driving simulator (Lin et al., 2010) to explore detailed EEG dynamics associated with motion cues under different levels of performance. Each subject participated in a simulated driving session without kinesthetic feedback and a separate session with kinesthetic feedback on different days, in which subject' behavior and EEG signals were recorded simultaneously. Owing to volume conduction through the cerebrospinal fluid, skull and scalp, EEG data collected from any point on the scalp may include activity from brain, extra-brain and artifactual sources. This signal-mixing problem reduces the signal-to-noise ratio of desired EEG brain signals, making EEG analysis and interpretation rather challenging tasks (Jung et al., 2001; Makeig et al., 1997). Moreover, as is well known, brain responses to stimulus presentations may vary widely across subjects in both time course and spatial origins. Therefore, equivalent EEG sources across subjects must be identified to assist in an anatomic and functional interpretation of the component process. By using independent component analysis (ICA), this study separated the data of each subject into temporally independent components (ICs) (Jung et al., 2001; Makeig et al., 1997). Several studies have demonstrated the efficacy of clustering ICs according to their cortical locations estimated from the scalp topographies (Makeig et al., 2002; Marco-Pallares et al., 2005; Milne et al., 2009; Onton et al., 2005). Thus, based on a source localization/imaging method, this study estimated the cortical locations of individual ICs from their scalp maps by individual columns of the ICA unmixing matrix. ICs obtained from all of the subjects were then grouped into distinct clusters with a high intra-cluster similarity (Delorme and Makeig, 2004) based on commonalities of scalp topographies, equivalent dipole source locations, and time–frequency properties (Delorme and Makeig, 2004). The neural generators of task-relevant oscillatory brain activity were then identified, based on equivalent dipole locations of ICs. Finally, this study compared the EEG spectra of ICs of interest under different experimental conditions (w/or w/o kinesthetic feedback) at various levels of behavioral performance, as determined by the required time to react to a random lane-departure event.

## Materials and methods

### *Experimental environment and paradigm*

This study implemented an event-related lane-departure driving paradigm (Huang et al., 2009) on a dynamic simulator (Lin et al., 2010) to explore detailed EEG dynamics associated with motion cues under different levels of task performance. The immersive virtual reality (VR) scenario (Fig. 1A) simulated nighttime driving at a constant speed of 100 km/h on a four-lane divided highway. The VR program (Fig. 1B) randomly introduced lane-perturbation events to cause the virtual vehicle to drift from the center of the cruising lane, and participants had been instructed to steer the vehicle back to the cruising lane as fast as possible after becoming aware of the deviation. If the subjects did not respond to the lane-perturbation event, falling asleep for example, and then the vehicle could hit the left and right curb of the roadside within 2.5 s and 1.5 s, respectively. The vehicle would then continue to move along the curb until it returned to the original lane. The inter-trial interval was set to 5–10 s. The experiment was begun in the early afternoon (13:00–14:00) after lunch and lasted for about 90 min when the circadian rhythm of sleepiness was at its peak (Ferrara and De Gennaro, 2001). Subjects' cognitive states and driving performance were monitored via a surveillance video camera and the vehicle trajectory throughout the experiment.

### *Experimental session with and without a kinesthetic feedback*

To investigate the effect of kinesthesia on brain activity in the sustained-attention driving task, each subject was asked to participate two driving sessions on different days. Each session lasted for about 90 min. One was the driving session (noted as K$^{-}$) with a fixed-based simulator but with no kinesthetic feedback, so the subject had to

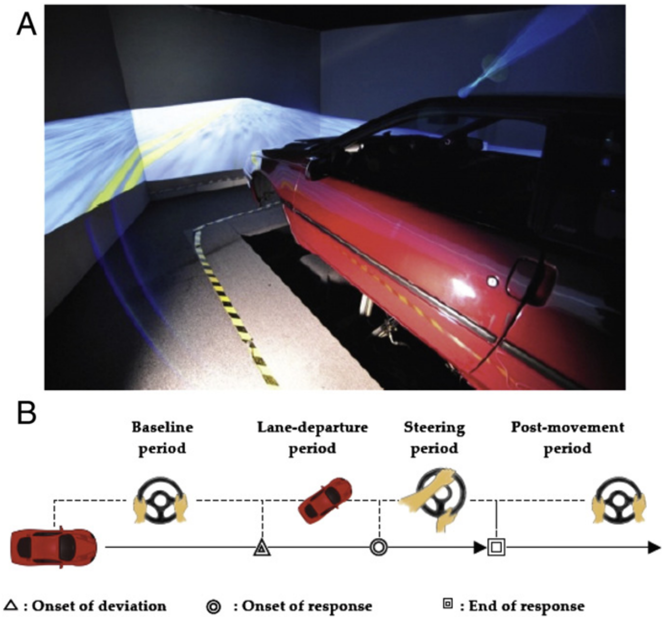

**Fig. 1.** (A) Immersive driving environment, including a real car frame that is mounted on a Stewart platform and a projected night-time driving scene (Lin et al., 2010). (B) Event-related lane departure paradigm (Huang et al., 2009). Onset of deviation occurs when the vehicle begins to deviate. Onset of response occurs when the subject initiates compensatory steering. End of response occurs when the vehicle returns to the center of the cruising lane and the subject ceases to rotate the steering wheel.