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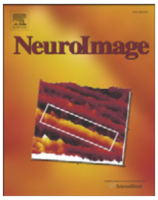

Tonic and phasic EEG and behavioral changes induced by arousing feedback

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ABSTRACT

This study investigates brain dynamics and behavioral changes in response to arousing auditory signals presented to individuals experiencing momentary cognitive lapses during a sustained-attention task. Electroencephalographic (EEG) and behavioral data were simultaneously collected during virtual-reality (VR) based driving experiments, in which subjects were instructed to maintain their cruising position and compensate for randomly induced lane deviations using the steering wheel. 30-channel EEG data were analyzed by independent component analysis and the short-time Fourier transform. Across subjects and sessions, intermittent performance during drowsiness was accompanied by characteristic spectral augmentation or suppression in the alpha- and theta-band spectra of a bilateral occipital component, corresponding to brief periods of normal (wakeful) and hypnagogic (sleeping) awareness and behavior. Arousing auditory feedback was delivered to the subjects in half of the non-responded lane-deviation events, which immediately agitated subject's responses to the events. The improved behavioral performance was accompanied by concurrent spectral suppression in the theta- and alpha-bands of the bilateral occipital component. The effects of auditory feedback on spectral changes lasted 30 s or longer. The results of this study demonstrate the amount of cognitive state information that can be extracted from noninvasively recorded EEG data and the feasibility of online assessment and rectification of brain networks exhibiting characteristic dynamic patterns in response to momentary cognitive challenges.

Introduction

Many studies on human sustained attention have confirmed that individuals engaging in monotonous tasks find it difficult or often impossible to maintain a constant level of alertness (Mackworth, 1948). Lapses in alertness become more frequent and prolonged under conditions of sustained wakefulness or lack of sleep, and may have both subtle and catastrophic consequences for operation safety and effectiveness in a wide variety of operational environments. Several studies have demonstrated that fluctuations in human performance and alertness are accompanied by distinct power spectrum changes of the electroencephalogram (EEG) reordered noninvasively from the scalp (Makeig and Inlow, 1993; Makeig and Jung, 1995, 1996; Jung et al., 1997; Makeig et al., 2000; Schier, 2000; Lal and Craig, 2002, 2005; Peiris et al., 2006; Tassi et al., 2006; Davidson et al., 2007; Huang et al., 2001, 2007a,b, 2008, 2009). Jung et al. (1997) further demonstrated the feasibility of accurately estimating shifts in a subject's alertness level, as indexed by changes in their performance level on a simple auditory target detection task, by monitoring the changes in EEG power spectra or other measures.

Researches have also attempted to help cognitively challenged individuals combat drowsiness and/or prevent lapses in concentration. Dingus et al. (1997) and Spence and Driver (1998) proposed using warning signals to maintain drivers' attention. The warning signals could be auditory (Spence and Ho, 2008; Lin et al., 2009), visual (Liu, 2001), tactile (Ho et al. 2005) or mixed (Lee et al. 2006). Belz et al. (1999) compared the efficacy of these warning signals and showed that drivers were less sensitive to visual alarms since the driver needed to pay attention to road conditions and the dashboard. Some studies have demonstrated that a warning stimulus improves the behavioral performance of subjects performing simulated driving experiments (Graham, 1999; Belz et al., 1999; Lin et al., 2009). However, these studies mainly focused on the effects of arousing signals on behavioral performance. To our best knowledge, no study has assessed the EEG correlates of improved task performance following arousing signals. This study explores EEG dynamics and behavioral changes in response to arousing auditory signals presented to individuals experiencing momentary cognitive lapses during a

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sustained-attention task. To this end, a realistic driving simulator based on an immersive virtual-reality (VR) technology and a six degree-of-freedom (DOF) motion platform was used to study participants' cognitive changes during a monotonous highway driving task. This facility enables systematic testing of the limitations of normal human performance and continuous monitoring of EEG dynamics in sustained-attention tasks in a safe, yet realistic environment.

During the simulated highway-driving experiments, auditory feedback was randomly delivered to participants when they failed to steer the wheel to compensate for lane-deviant incidents (so called drowsy epochs). EEG dynamics and behavioral changes following the arousing auditory signals were compared with those of cognitive drowsy epochs during which no warning signals were given to the subjects. This method allows statistical testing of the efficacy of auditory feedback and significant EEG changes associated with behavioral arousal.

Method

A. Subjects

Eleven healthy subjects aged from 20-28 years (ten males and one female) with normal hearing participated in the VR-based highway driving experiments. All subjects were free of neurological and psychological disorders and of drug or alcohol abuse. No subject reported sleep deprivation on the day preceding the experiment, and none had worked night shifts during the last year or traveled through more than one time zone in the previous two months. All experiments were conducted in the early afternoon after lunch. All subjects were informed about the experimental materials, features and driving task process. They practiced the driving task for 10 min to become acquainted with the experiment procedures. They were also requested to complete the questionnaire after the experiment.

B. Experimental equipment

The VR-based highway driving experiments were conducted in a driving simulator consisting of a real vehicle mounted on the 6-DOF motion platform in a sound-reduced room. The driving simulator mimics realistic driving situations. This study adapted an event-related lane departure driving paradigm originally proposed by Huang et al. (2005, 2007a,b, 2009) that allows objective and quantitative measures of momentary event-related brain dynamics following lane-departure events and task performance fluctuations over longer periods (e.g., on the order of one min). The VR scenes simulated driving at a constant speed (100 km/hr) on a highway with the car randomly drifting away from the center of the cruising lane to simulate driving on non-ideal road surfaces or with poor alignment (Huang et al., 2007a,b, 2009; Lin et al., 2008). Other than a straight and monotonous road, no traffic or other stimuli appeared in the VR scene, which was intended to simulate a driving situation likely to induce drowsiness. The information refresh rate of the highway scene was set at 60 Hz, accurately reflecting a car driving at a fixed speed of 100 km/hr. The scenes moved according to the car displacement and the wheel handling of the subject.

During the experiments, EEG activities were recorded from thirty scalp electrodes (Ag/AgCl electrodes with a unipolar reference at the right earlobe) by the NuAmp system (Compumedics Ltd., VIC, Australia). The EEG electrodes were placed based on a modified international 10-20 system. The contact impedance between EEG electrodes and the cortex was calibrated to be less than 10 kΩ.

The EEG data was recorded with a 16-bit quantization level at a sampling rate of 500 Hz and preprocessed with a low-pass filter of 50 Hz and a high-pass filter of 0.5 Hz.

C. Experimental paradigm

Statistical reports show that drowsiness often occurs after less than one hour of continuous driving and is not necessarily caused by long hours of continuous driving. Thus, each driving experiment lasted 90 min, including an initial 5 min alert (when the subjects were requested to be fully alert and attentive) trials and an 85 min experiment time. Lane-departure events were randomly introduced every 8~12 s, causing drift at a constant speed towards the curb or into the opposite lane with equal probability (Huang et al., 2007a,b). Subjects were instructed to steer the vehicle back to the center of the original cruising lane as quickly as possible. The experiment recorded vehicle trajectories and the time of every lane-departure event.

Fig. 1A shows the event-related lane departure task. The car randomly drifted away from the center of the cruising lane, the drift controlled and triggered by the WorlToolKit (WTK) program to simulate a drowsy driving condition. The empty circle represents when unexpected lane-departure events occurred, marked as the "deviation onset". In the meantime, subjects were to steer the car back to the center of the cruising lane immediately (double circle), marked as the "response onset". The moment subjects stopped turning the wheel (circle with cross) was marked as the "response offset". Subject response time (RT) was the time between the deviation onset and the response onset.

Fig. 1B presents the feedback-delivery criterion for this experiment. During the first 5 min, subjects were asked to stay alert and the average RT of these **alert** trials was computed. If subjects' reaction times were over three times the mean RT (1.51~2.54 s, depending on subjects), the system triggered a 1,750 Hz tone-burst to the subject in half of these drowsy trials (marked as the "current trial (CT)" in Fig. 1A). The auditory feedback was repeatedly delivered to the behaviorally drowsy subjects until they responded with a movement of steering wheel to compensate the lane-deviation. The lane-departure event after the "current trial" was labeled as the "the following trial (CT+1)". If the warning feedback was delivered to the subject, the trial condition was defined with warning. The trials were labeled without warning if the warning sound was not delivered. The auditory warning signal volume was set at a fixed level (68.5 ± 1.5 dB, 14 dB above background noise), which was very noticeable, yet not too loud.

D. Data analysis

The EEG data was sampled at 500 Hz with a 16-bit quantization. The acquired 30-channel EEG signals were first inspected to remove bad EEG channels, and then down-sampled to 250 Hz. Then, the continuous EEG signals were segmented into continuous EEG time courses for all channels, segmented into 115-s epochs, from 15 s preceding to 100 s following deviation onsets. The epochs contaminated by noise signals (muscle activity, blinks, eyes movement and environmental noise interference) were also removed manually prior to further analysis.

Independent Component Analysis

The EEG signals were decomposed into temporally independent time courses presumably arising from distinct brain sources by independent component analysis (ICA) (Bell and Sejnowski, 1995; Makeig et al., 1997) using EEGLAB (Delorme and Makeig, 2004). The Infomax ICA algorithm was used to separate ~30 source components from ~30 channels of EEG signals based on the assumption that the summation of EEG signals at the sensors was linear and instantaneous, i.e. the propagation delays were negligible, and the time courses of sources were statistically independent (Makeig et al., 1996, 1997; Jung et al., 2001a). As reported by many previous studies (not limited

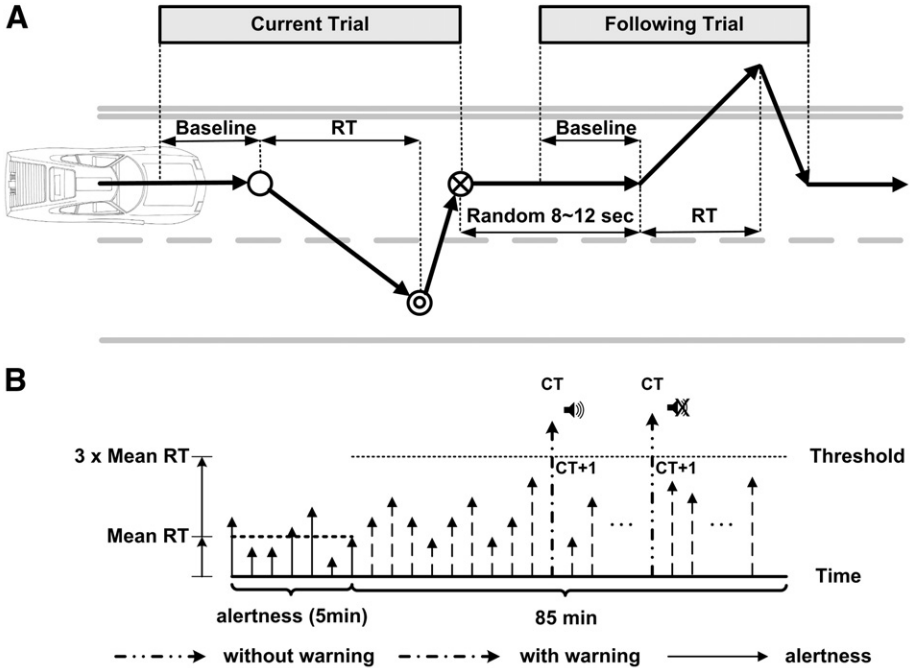

Fig. 1. Experimental design. (A) Event-related lane-keeping tasks. The solid black arrows represent the driving trajectory. The empty circle represents the deviation onset. The double circle represents the response onset. The circle with the cross represents the response offset. The baseline is defined as the 3-s period prior to deviation onset. Drivers' response time (RT) is the time interval from the deviation onset (the empty circle) to the response onset (the double circle). A trial begins from the baseline starting point and ends at deviation offset (circle with a cross). The next deviation begins 8~12 s after response offset. [Adapted from Huang et al., 2007a]. (B) Criterion for delivering auditory feedback during driving tasks. The height of an arrow represents the response time of a single trial. The warning feedback was delivered to the subject when a trial's RT was longer than three times the average RT of trials within the first 5 min of the task, when the subject was presumably alert and fully attended to lane-departure events.

to Makeig et al., 1996, 1997, 2002; Jung et al., 2001a,b), ICA effectively separates EEG artifacts (such as blinks, muscle activity, electrical noise, and cardiac signals) from distinct EEG processes which are arguably represented, in many cases, as functionally independent cortical source activities. To find comparable independent components (ICs) across subjects, we grouped components obtained from multiple subjects into clusters based on their scalp maps, equivalent dipole locations and baseline power spectra of component activations. Components of interest were selected based on significant spectral differences between lane-departure epochs with and without auditory feedback using a nonparametric permutation-based statistical method (Delorme and Makeig, 2004).

Statistical Analysis

The RT and EEG power were not normally distributed, so nonparametric statistic tests were used for the data analysis. The Wilcoxon rank-sum test (Matlab statistical toolbox, Mathworks) was used to evaluate the effects of auditory feedback on RTs. Bootstrapping (EEGLAB toolbox, UCSD) was used to test the statistical significance of EEG power changes at specific frequency bins. To test group statistics, the intrinsic inter-subject RT differences were reduced by dividing RTs by the mean RT of the trials within the first 5 min of each session. The EEG spectra were also normalized by dividing the spectral power by the standard deviation of the spectral distribution.

Tonic and phasic changes in the EEG spectrum

This study measures the dynamics of EEG spectral changes in response to auditory feedback on both tonic and phasic time scales (Klimesch, 1999; Makeig and Jung, 1996; Huang et al., 2008). Tonic changes refer to changes in component baseline power following auditory feedback on a longer time scale (sub-minute to minutes). Phasic changes refer to event-related brain activity associated with agitated behavior in response to feedback on a shorter time scale (sub-second to seconds) (Huang et al., 2008).

Results

A. Behavioral performance comparison between non-responsive epochs with and without auditory feedback

Fig. 2A shows the RT distributions for three consecutive epochs. This study compared the reaction times of three continuous trials starting with each event onset. Current trials (CT) refer to lane-departure events in which the participants failed to respond with compensatory wheel steering. In 50% of these non-responsive trials, the auditory tone of 1,750 Hz was delivered to the participants (plotted in red). The following trials (CT+1) and the next trials following these (CT+2) refer to trials following the current drowsy trials. The trials and the next trials following CT+1 were removed from the analysis if another auditory feedback was delivered to the subjects due to their poor performance. Thus, the numbers of trials decreased from 182 (CT+1) to 128 (CT+2) trials and from 196 (CT+1) to 132 (CT+2) trials with or without auditory feedback, respectively. The number of alert trials in which subjects responded promptly was 216. Fig. 2B shows the RT boxplots under different conditions.

Fig. 2A shows that the RTs of current non-responsive trials started from three times the average RT of alert trials because of the feedback delivery criterion. The RTs of trials following auditory feedback were significantly shorter than those of trials without feedback (Fig. 2B, difference = 1.38, $p<0.001$). This result suggests the auditory feedback was effective for arousing drowsy subjects; but the feedback-agitated RTs were still significantly longer than those of the alert trials ($p<0.01$).

In the CT+1 (Fig. 2A, middle panel), the RTs of trials with warning condition were significantly shorter than those trials without warning condition ($p<0.01$). In the CT+2 (Fig. 2A, right panel), the

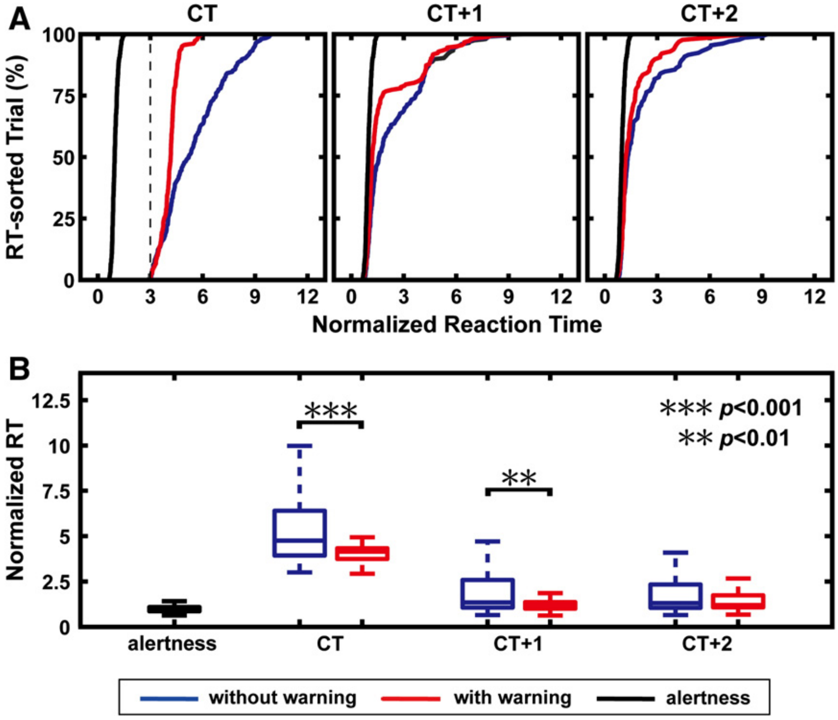

Fig. 2. Comparison of response times to lane-departure events with and without feedback delivered after long-RT trials (marked as current epochs here). (A) The curves represent the cumulated percentage (y-axis) of the *current trials (CT)*, *the following trials (CT+1)*, and *the next trials following these (CT+2)* sorted by normalized RTs (x-axis). The blue, red, and black curves represent the sorted trials without warning, with warning, and alert, respectively. The black vertical dash line at *current trial* represents the warning onset. (B) Box plot of RT distributions of the *CT, CT+1,* and *CT+2*. The middle horizontal line is the median of the distribution, and the top and bottom of the rectangle are the third and first quartile, and the dash line ends are the maximum and minimum after outlier removal. The stars (*) represent the statistical significant levels, ** for $p<0.01$ and *** for $p<0.001$.

averaged RT of trials with feedback were shorter than that of trials without feedback, but the difference was not statistically significant ($p = 0.16$).

B. EEG dynamics following arousing auditory feedback

Continuous spectral fluctuation following auditory feedback

As mentioned above, independent component(s) of interest were selected based on significant spectral differences between lane-departure epochs with and without auditory feedback. Across subjects, ICA consistently found that an independent brain process with an equivalent dipole located in the fronto-central lobe exhibited distinct power changes in the delta- and theta bands. This is associated with fluctuations of self-reported emotion states during music appreciation exhibiting significant power changes in the theta (4-7 Hz) and alpha (8-12 Hz) bands following auditory feedback and subject response. Fig. 3 shows the mean scalp map and the alpha- and theta-band spectral time courses of the bilateral occipital component cluster following (red curve) vs. not following (blue curve) auditory feedback. The spectral baselines of the alert epochs were also plotted for comparison. All the epochs were aligned to the response onset and transferred to frequency domain by FFT with a 4-s window and a 200-ms step. The time courses of the alpha- and theta-band spectra were plotted from 10 s before to 95 s after the response onset. The green horizontal dots marked the time points when the spectral difference between with warning and without warning epochs was statistically significant ($p<0.01$).

Before response onset, the theta- and alpha-power baselines of the drowsy epochs (blue and red curves) were considerably higher than those of the alert epochs (black curve). After response onset, the alpha power *abruptly* decreased by over 10 dB (from 38 to 26 dB), whereas the theta power decreased (from 31 to 25 dB) to the level *momentarily* comparable to the baseline power of alert epochs. The spectral difference between the epochs with and without feedback was statistically significant from 5-10 s in the alpha band to 5-14 and then 21-32 s in the theta band.

One caveat of this analysis was that lane-departure onsets and subject compensatory motor responses of subsequent epochs induced a significant spectral suppression, as shown in the first 5 s after response onset in Fig. 3. This phasic spectral suppression induced by deviation and subject response onsets was probably responsible for the lack of significant spectral difference between with and without feedback epochs at 0-5 and 14-21 s in the theta band. To avoid this confusion, the next analysis explores only the changes in the baseline power of these three consecutive lane-departure epochs ***before*** lane-departure onsets.

Spectral changes in response to auditory feedback in bilateral occipital components

Fig. 4 shows the mean scalp map of the bilateral occipital cluster and its component power spectral baselines of drowsy epochs with and without auditory feedback. All the epochs were transferred to frequency domain by FFT with a 1.5-s sub-window and calculated from the EEG data recorded 3 s before to the onset of lane deviation. At each frequency bin, significant deviations from the spectral baseline of alert epochs and the differences between spectra with and without feedback were assessed using a nonparametric permutation-based statistical method (Delorme and Makeig, 2004). The frequency bins under which the spectral differences were statistically significant ($p<0.01$) were marked by horizontal lines. In general, across three (CT, CT+1 and CT+2) trial groups, the red and blue horizontal lines show that the grand average of power spectral baselines exhibited tonic broadband increases below 25 Hz in long-RT trials (regardless of feedback presence) relative to alert epochs plotted in black. The spectral differences were statistically significant ($p<0.01$) and most prominent in the theta and alpha bands with over

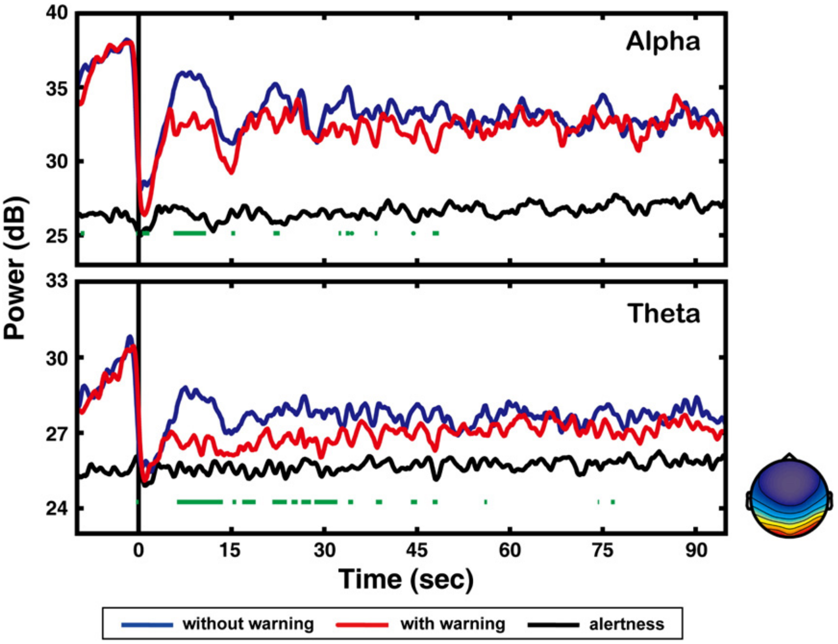

Fig. 3. Averaged (across subjects, sessions and trials) spectral time series of bilateral occipital components following long-RT trials. The upper and lower panels show spectral fluctuations, estimated using a moving discrete wavelet transform (DWT) with a 4-s time window, of alpha and theta bands, respectively. All trials were aligned to the response onset (vertical black solid line). The red, blue, and black curves are the averaged spectral fluctuations of trials with warning, without warning, and alert trials, respectively. The horizontal green lines mark the frequencies where spectral differences between the red and blue traces were statistically significant.

5 dB and 10 dB increases from the baseline power of alert epochs. The spectral changes were considered tonic because the spectral augmentations were accessed across three consecutive lane-departure events 40 s or longer apart. The spectra of the epochs following feedback were lower than those of the epochs not following feedback (Fig. 4, red vs. blue time series in the middle and right panels), suggesting that auditory feedback induced a spectral decrease in the baseline power in subsequent trials.

In the CT group (Fig. 4, left panel), the blue and red curves were almost identical as they both represented the baseline power of drowsy trials and the auditory feedback was not delivered to the subjects until a few seconds later.

In the CT+1 group (Fig. 4, middle panel), although the overall spectral baselines of the drowsy epochs (blue and red horizontal lines) decreased from those of the preceding (current) epochs (Fig. 4, left panel), they were still significantly higher than those of the alert epochs. The findings indicate that the subjects were tonically drowsy. Furthermore, the green horizontal line shows that the grand average of power spectral baselines of epochs following auditory feedback were significantly lower than those of trials not following auditory feedback in the theta band ($p<0.01$).

In the CT+2 group (Fig. 4, right panel), no significant spectral difference was found between following and not following auditory feedback (alpha: $p=0.07$ in the alpha band, and $p=0.13$ in the theta

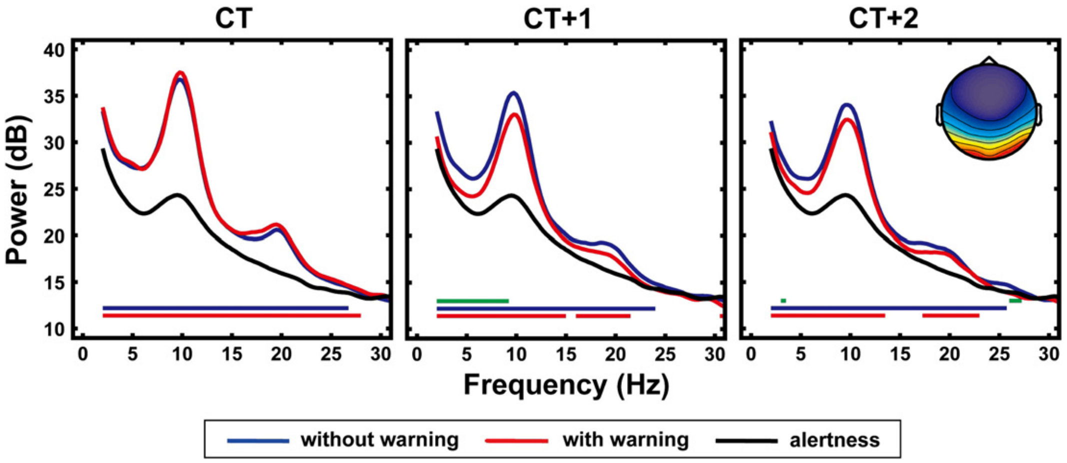

Fig. 4. Component spectra of trials with and without feedback, compared to the spectra of alert trials. The activities primarily arose from the bilateral occipital regions. The black traces represent the baseline EEG spectra of the *current trials (CT)*, the *following trials (CT+1)*, and *the next trials following these (CT+2)*. Note that the 'current' trial means the trial with a response time greater than three times the mean RT and the feedback was delivered only at the 'current' trial. The blue and red curves are the spectra of trials without and with warning, respectively. The green horizontal lines mark the frequencies where the spectral differences between trials with and without feedback were statistically significant. The blue (or red) horizontal lines indicate the spectral differences between the trials without (or with) feedback and the alert trials that were statistically significant (with $p<0.01$). Note that the spectra shown in this figure were calculated from the EEG data recorded 3 s before to the onset of lane deviation.

band). This result was consistent with the behavioral performance shown above.

Component spectra sorted by RTs

Fig. 2A shows that (middle and right panels) the RTs still varied widely following auditory feedback. Epochs with extremely long RTs and short RTs matched well with those of drowsy epochs in which subjects did not receive any auditory feedback in the preceding lane-departure epochs. A detailed analysis of the baseline power of epochs sorted by RTs might provide more insight into the EEG dynamics associated with different performances. To this end, all epochs were first grouped into three (A: long-RT, B: moderate-RT, and C: short-RT) regions as shown in Fig. 5 (small panel on the left). The numbers of epochs with and without feedback groups in each region were matched. Regions A and C each accounted for 20% of total epochs. The remaining epochs with moderate RT were grouped into the Region B, which accounted for 60% of total epochs. In Regions A and C, the RTs had no significant difference between with warning and without warning conditions (Region A: $p = 0.4$, Region C: $p = 0.05$). However, in Region B, the RTs had significant difference between with warning and without warning conditions ($p < 0.001$). Then, the baseline power of these RT-matched epochs was examined.

The middle panels of Fig. 5 show the baseline power of the current three RT-sorted regions. Across all epochs (Figs. 5A-C), the baseline power of the current drowsy epochs was significantly higher than that of alert epochs. Furthermore, the baseline power of epochs with auditory feedback was almost identical to those epochs without feedback as the feedback was not delivered until seconds later. In moderate-RT epochs, the baseline power of epochs following the feedback was significantly lower than that of epochs without feedback in the theta band.

The right panels of Fig. 5 show the baseline power of the following epochs in three regions. In Region A of the CT+1, the mean RTs of epochs with feedback and without feedback were 4.2 and 5.85 times the mean RT of the alert trials, respectively but the difference was not significant ($p = 0.4$). No significant spectral difference appeared between epochs with and without feedback in this long-RT group (Fig. 5A, right panel). In Region B of the CT+1 (Fig. 5B, right panel), the mean power baseline of epochs with feedback was significantly lower

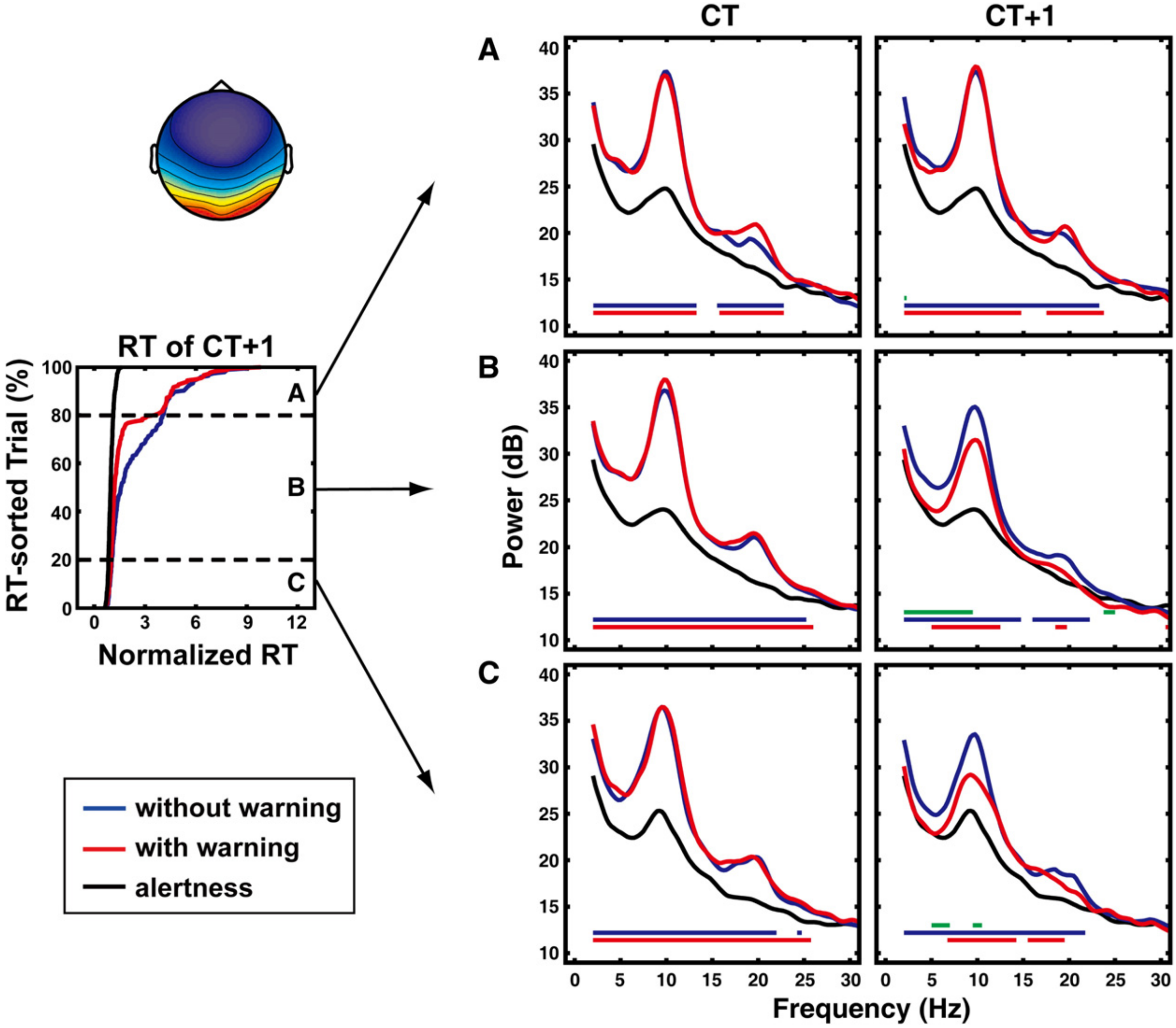

Fig. 5. Component spectral analysis. The left middle panel shows the sorted normalized RTs of trials following long-RT trials, labeled *the following trials* in the figure. The trials that followed long-RT trials (CT+1) with and without warning signals are plotted in red and blue, respectively. The CT+1 trials were divided into three groups (A, B, and C) based on RT values. The right panels show the baseline (prior to lane-departure onsets) spectra of long-RT trials; the right panels show the baseline spectra of the following trials (red traces) with or (blue traces) without feedback delivered to long-RT trials. The horizontal color lines mark the frequencies where spectral differences between trials with and without feedback were statistically significant were statistically significant ($p < 0.01$). (A) Long-RT trials (80%- 100% of the total RT-sorted trials). (B) Moderate-RT trials (20%-80% of the total RT-sorted trials).(C) Short-RT trials (0%-20% of the total RT-sorted trials).

than that of epochs without feedback in the theta and lower-alpha band ($p<0.01$). The mean RT of epochs following feedback (0.61 times of the normalized RT) was also shorter than that of epochs without feedback ($p<0.001$). In Region C of the CT+1 (Fig. 5C, right panel), no significant difference in RTs was found between the epochs with and without feedback ($p=0.05$). The mean baseline power of epochs with feedback was significantly lower than that of no-feedback epochs at 6-7 Hz (1.8 dB, $p<0.01$) and 10 Hz (alpha: 3.6 dB, $p=0.01$).

Spectral changes of other components

Fig. 6 presents baseline power of the central, left motor, right motor, and parietal clusters. As in the bilateral occipital cluster, the mean theta and alpha baseline power of drowsy epochs (blue and red traces and horizontal lines) were significantly higher than those of alert epochs (black trace). However, no spectral difference was found between with and without feedback groups (no green horizontal dots).

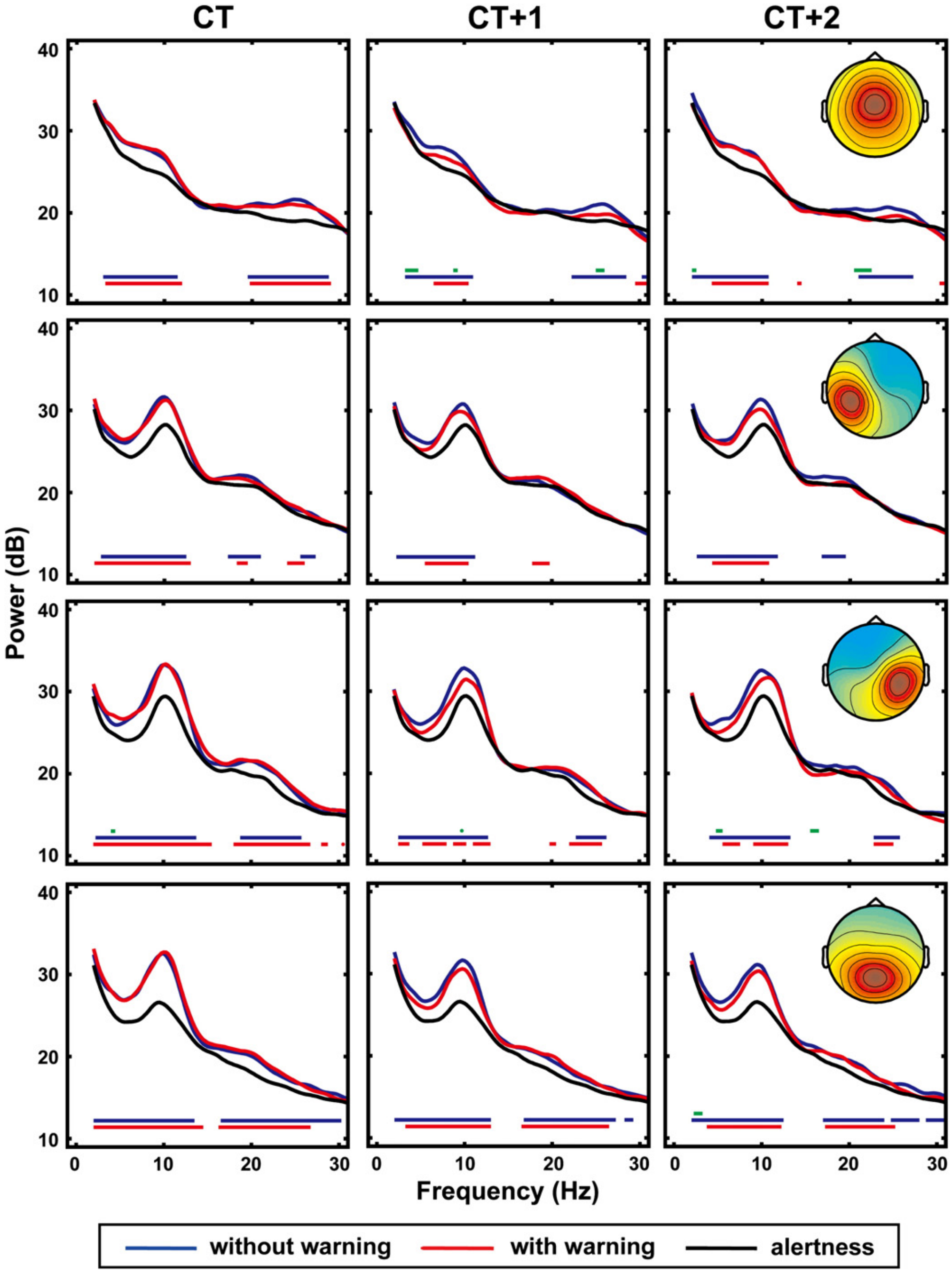

Fig. 6. Component spectra of trials with and without feedback, compared to the spectra of alert trials. Component activities distinctly arose from (from top to bottom) the central midline, the left somatomotor, the right somatomotor, and the central parietal components, respectively. The figure also shows the scalp maps of component clusters. The red, blue, and black curves are the averaged baseline spectra of trials with warning, without warning, and alert trials, respectively. As in Fig. 3, the green horizontal lines mark the frequencies where spectral differences between trials with and without feedback were statistically significant. The blue (or red) horizontal lines indicate spectral differences between the trials without (or with) feedback and alert trials that were statistically significant (with $p<0.01$). These four components did not exhibit any statistically significant spectral differences between trials with and without feedback.

Discussion

Tonic spectral changes associated with poor task performance

Studies have shown that varying human alertness, revealed in behavioral performance changes, is associated with altering oscillatory brain activities in several brain regions (e.g. central, parietal and occipital areas etc.). Such fatigue related changes in brain rhythms can be assessed by the EEG with Fourier methods and time-frequency analysis. Specifically, the intensity of the alpha (Santamaria and Chiappa, 1987; Huang et al., 2007a,b) or theta (Beatty et al., 1974; Makeig and Inlow, 1993; Makeig and Jung, 1996; Jung et al., 1997; Lal and Craig, 2002) band power has been reported to considerably increase with degraded behavioral performance in different sustained-attention experiments. For example, Makeig and Jung (1996) showed that the time courses of theta power were paralleled by performance changes in target detection rate in an auditory target detection task.

This study adapted an event-related lane-departure driving paradigm proposed by Huang et al. (2005, 2007a,b, 2009) into a VR-based driving simulator consisting of a 360-degree scene and a real car mounted on a 6-DOF Stewart platform. The driving simulator provided a natural and immersive driving experience for subjects. An independent component with equivalent dipole sources located in the occipital cortex showed tonic increases in the alpha and theta band power in long-RT (poorly-performed) epochs, consistent with results from an auditory detection task (Makeig and Jung, 1996). Furthermore, both the source locations and the tonic spectral augmentation accompanying declined performance (Figs. 3 & 4) were remarkably similar to those of the fatigue-related components found in a visual compensatory task which attempted to use frequent compensatory trackball movements to maintain a drifting disc close to a bulls-eye at the screen center (Huang et al., 2008).

Other independent component clusters with equivalent dipole sources located in the central, parietal, occipital, somatomotor, and supplementary motor cortices also exhibited power increases in the theta and alpha bands during periods of poor (long-RT) performance, consistent with previous studies on drowsiness. The comparable spectral activations found in multiple cortical areas were tentatively interpreted as one or more fatigue-related neuro-modulators mediating the spectral activations of several brain regions by intra-cortical or thalamo-cortical feedback loops (Chuang et al., 2009).

It is worth mentioning that the lapse defined in this study was carefully selected to characterize the nature of poor performance in this simulated lane-deviation driving task. Different paradigms and experimental setups might require different ways to define lapses which could ranged from delayed responses to target stimuli (Dorrian et al., 2005; Weissman et al., 2006; Chee et al., 2008), response errors (Padilla et al., 2006), to failure to respond (Peiris et al., 2006). A detailed comparison between consequences of different definitions of lapses can be found in Chee et al. (2008, 2010).

Effects of auditory feedback on task performance

Several studies have explored using auditory, visual and tactile feedback to help cognitively challenged individuals combat drowsiness and/or to prevent concentration lapses (Dingus et al., 1997; Belz et al., 1999; Liu, 2001; Ho and Spense, 2005; Ho et al., 2005; Lee et al., 2006; Spence and Driver, 1998; Spence and Ho, 2008; Lin et al., 2009). For example, Lin et al. (2009) recently showed that the mean RT of lane-departure driving sessions with auditory feedback was 1.15 s shorter than those sessions that did not deliver any feedback to participants. Several studies have also reported that the arousing feedback helped drivers react promptly (Meyer, 2001; Verwey and Zaidel, 1999) and reduce the probability of collisions (Verwey and Zaidel, 1999; Sanders and McCormick, 1993). However, these studies mainly focused on the effects of arousing feedback on behavioral performance. To our best knowledge, no study has assessed brain activity associated with improved task performance following arousing signals. The goal of this study was to investigate and correlate brain dynamics and behavioral changes in response to arousing auditory signals presented to individuals experiencing momentary cognitive lapses. To this end, the subject response time was assessed as an index of the decrement or increment of behavioral performance (Philip et al., 1999; Campagne et al., 2004) to first verify the efficacy of auditory feedback.

Behavioral results of this study show that the sorted RT curves of drowsy epochs (with or without feedback) were all significantly longer than those of alert trials (cf. Fig. 2). Furthermore, the auditory feedback agitated prompt compensatory responses and aroused the subjects such that the RTs of next lane-departure epochs were also shorter than those of long-RT epochs not followed by auditory feedback, demonstrating the advantage of using arousing feedback in a sustained-attention task. However, the RTs of epochs following feedback were still longer that those of alert epochs, suggesting the subjects were not aroused to full alertness. This might be partially due to the auditory neuron not easily adapting to the pure tone or pure tone burst (Ulanovsky et al., 2004). In auditory cortices, the majority of neurons respond to complex sounds and only a small number of neurons respond to the pure tone or pure tone burst (Rauschecker, 1997). Previous studies have also suggested that warning signals delivered by a single modality may not be sufficient to totally awake subjects, suggesting that warning signals be delivered through multimodalities, such as combining warning sounds and vibrations (Ogilvie and Harsh, 1994). Our previous work (Lin et al, 2009) explored the most effective pure tone to agitate drowsy subjects in a sustained-attention task. Our future work includes testing more effective arousing sounds to awake drowsy participants (Belz et al., 1999; Graham, 1999).

Effects of auditory feedback on brain activities

The bilateral occipital component exhibited significant tonic and phasic decreases in power spectral baselines in theta and alpha bands following auditory feedback in the event-related lane-departure task (cf. Fig. 4). Brain oscillations in the theta and alpha bands have been previously associated with fluctuations in task performance (Makeig and Jung, 1996; Jung et al., 1997; Lin et al., 2008; Pal et al., 2008; Huang et al., 2008). As mentioned above, the baseline power of alert epochs below 25 Hz was considerably lower than those of poor performance (or drowsiness). The direction of spectral changes following auditory feedback was expected toward the baseline power of alert epochs, suggesting that auditory feedback assisted subjects in reducing their drowsiness level, reflected in both behavioral performance and brain activities. Spectral changes of the bilateral occipital component cluster were also consistent with behavioral results. However, the baseline power of epochs following auditory feedback did not completely return to those of alert epochs, suggesting that stronger or additional feedback might be necessary.

Upon closer inspection of RT distributions of epochs following feedback (cf. Fig. 5), auditory signals increased the number of short-RT epochs by decreasing the number of moderate-RT epochs. Furthermore, even though the RTs of next short- and moderate-RT epochs following feedback did not show appreciable decreases compared to their counterparts without feedback, their baseline power was significantly lower than those of non-feedback epochs (cf. Figs. 5B & C, right panels). Region C of Fig. 5 also shows little difference between epochs following or not following auditory feedback. These results might indicate that monitoring the power spectra following feedback could assess subtle EEG dynamics in response to events or feedback, which might not be appreciable or assessable by simple reaction time measures used in impoverished stimulus/response experiments. Auditory feedback had little or no effect on the baseline power and RTs of long-RT epochs (Fig. 5A), indicating that the severely drowsy subject might not perceive the presence of auditory feedback. The thalamus gate has been known to block all sensory inputs during sleep (Portas et al., 1998; Chee et al., 2008). Whether the thalamus gate would be digitally blocked or decreased sensory inputs analogically from drowsy to sleep is still unclear. The thalamus gate control mechanisms need to be further assessed in detail in the future.

Fig. 3 and Huang et al. (2008) in a visual compensatory tracking task notably show that, not only does auditory feedback involve phasic changes in the alpha- and theta-band power, but also stimulus onsets and subject motor response.

Even though deviation onsets, auditory feedback and subject motor responses all affect the time courses of EEG spectra, it is still worth exploring the long-term spectral dynamics following auditory feedback as deviation and response onsets have comparable effects on epochs with and without feedback and thus be neutralized. Fig. 3 shows the time course of theta and alpha power of the bilateral occipital component clusters 10 s before to 95 s after subject response. After response onsets, the theta and alpha power *abruptly* decreased to the level *momentarily* comparable to the baseline power of alert epochs. The spectral difference between epochs with and without feedback was statistically significant in 5-10 s in the alpha band and 5-14 and then 21-32 s in the theta band. The lack of significant spectral difference between with and without feedback epochs at 0-5 and 14-21 s in the theta band might be attributed to phasic spectral suppression induced by deviation and subject response onsets. In other words, the effects of auditory feedback on the theta-band power could last for 30 s or longer.

The duration difference of significant power suppression may be due to nonlinear fluctuations in alpha-band power, compared to theta band power, during the transition from alert to drowsy. Studies show that alpha activities increase and then start to decrease during the wake-sleep transition (De Gennaro et al., 2001a,b; Merica and Fortune, 2004; Chuang et al., 2009). Such alpha fluctuations could result from event-related desynchronization and synchronization of alpha activities (Pfurtscheller and Aranibar, 1977; Pfurtscheller and Neuper, 1994; Pfurtscheller et al., 1996; Huang et al., 2005, 2008) during the responses to car deviation by manipulating the steering wheel.

Conclusions

This study explored the effects of arousing feedback on subject behavioral responses and EEG dynamics in a sustained attention task within a natural and immersive driving simulator. The cognitively challenged subjects exhibited statistically significant improvement in behavioral performance following the auditory feedback. Significant tonic and phasic decreases in power spectra in theta and alpha bands following auditory feedback was found in the bilateral occipital component. The spectral suppression lasted 30 s or longer after feedback presentation. Furthermore, this study also showed statistical significance of differences of the low-frequency EEG power between epochs affected and those not affected by the feedback. These results indicated that monitoring the power spectra following feedback could assess subtle EEG dynamics in response to events or feedback, which might lead to practical applications in noninvasive monitoring of the cognitive state of human operators in attention-critical settings.

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