

Implementation of a Closed-Loop Real-Time EEG-Based Drowsiness Detection System: Effects of Feedback Alarms on Performance in a Driving Simulator

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The management of fatigue is increasingly considered a serious public health and safety concern because impaired vigilance is believed to be a primary contributor to transportation and industrial accidents. Military operations are particularly vulnerable to the effects of fatigue due to the irregular nature of mission-related schedules and the stress of combat conditions. The ability to monitor levels of alertness in real-time, coupled with feedback to the operator or a third party, could prevent accidents and save lives.

The electroencephalogram (EEG) is widely regarded as the physiological “gold standard” for the assessment of alertness. This study explored the feasibility of an integrated approach that combined real-time quantification of EEG indices and audio feedback alarms to assist study participants in maintaining alertness during sleep deprivation.

Continuous EEG (FzPOz and CzPOz-differential) and electrooculogram (EOG) were acquired with a wireless sensor headset throughout the study. Quantification of the EEG in real-time, referred to as the B-Alert[®] system, included identification and decontamination of fast and slow eye blinks, and automated rejection of data points contaminated with muscle artifact, amplifier saturation, lost data packets (from RF transmission), and/or excursions due to movement artifacts. Each one-second EEG epoch was then classified into one of four states of alertness: “high vigilance”, “low vigilance”, “relaxed wakefulness or high alpha”, or “sleepy or high theta.” Classifications were obtained using a discriminant function analysis derived from a large normative database and fitted to each individual's unique EEG patterns with data acquired from baseline conditions. The B-Alert system was previously validated in sleep deprivation studies with performance measures, technician observed drowsiness and responses to a subjective sleepiness questionnaire.

A preliminary time-series analysis model was developed for the study to monitor patterns in the B-Alert indices in real time and deliver alarms to a user when repeated episodes of drowsiness were identified. The B-Alert system presented a series of auditory warning alarms selected to be increasingly urgent as the subject exhibits increased drowsy episodes.

Prior to a sleep deprivation study, fourteen healthy subjects completed a morning baseline session with EEG acquisition during neurocognitive tests and a driving simulator task after four nights of full sleep. On the night prior to their sleep deprivation study, subjects went to bed 1.5 hours after their average time-in-bed based on the four preceding nights and spent 3 hours in bed. Between the

hours of 10 PM and 8 AM surrounding the time in bed subjects were required to leave a message on an answering machine every half hour to confirm that they were awake. Wrist actigraphs were used to verify compliance.

Subjects arrived for their sleep deprivation study approximately 14 hours after awakening (i.e., ~5:30 PM) to complete eight hours of neurocognitive tests and driving simulator tasks. A randomized cross-over design was used to assign subjects into two groups: Feedback First or No-Feedback First. Seven subjects received alerting feedback during the first four hours of the study (Feedback First) and no feedback in the second four-hour battery. Alternatively, seven subjects received no alerting feedback during the first four hours (No-Feedback First) followed by a four-hour Feedback battery.

As expected, sleep deprivation significantly increased drowsiness as measured by B-Alert classifications and impairments in neurocognitive tests and driving simulator performance. The feedback alarms, triggered by EEG indices, proved effective in either stabilizing or improving objective measures of performance during extended sleep deprivation. Most subjects reported that the feedback alarms were beneficial in helping them maintain alertness.

Results for B-Alert EEG Indices: To compare results across the screening, feedback-on and feedback-off periods, the B-Alert high vigilance and drowsy (high alpha + high theta) classifications for all tasks were z-scored using comparable data from a group of 24 subjects during fully-rested baseline sessions. Repeated measures ANOVA revealed a significant increase in the z-scored percentage of drowsy classifications ($F = 7.316$, $p < .02$) between baseline and feedback-off and between baseline and feedback-on ($F = 6.391$, $p < .05$) and a significant decrease in drowsiness when feedback-on was compared to feedback-off ($F = 4.225$, $p = .06$).

Results for driving performance: The mean time drifting, veering and driving out of lane and the total number of accidents and hit pedestrians were computed for the feedback-on and feedback-off conditions. Data were normalized by averaging the driving performance measures obtained for each of the five driving sessions for each subject. Repeated measures ANOVA revealed a significant main effect for the drifting across the four driving sessions ($F = 3.167$, $p < .05$) with a significant interaction for feedback group ($F = 3.842$, $p < .05$).

Timely administration of feedback resulted in increased alertness as measured by changes in EEG indices and performance, particularly during driving simulator and psychomotor vigilance tasks. This suggests that a closed-loop EEG-based system combined with intelligent feedback can improve performance and decrease operator errors resulting from fatigue.