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Deep in thought while driving: An EEG study on drivers' cognitive distraction

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A B S T R A C T

Our research employed the EEG to examine the effects of different cognitive tasks (math and decision making problems) on drivers' cognitive state. Forty-two subjects participated in this study. Two simulated driving sessions, driving with distraction task and driving only, were designed to investigate the impact of a secondary task on EEG responses as well as the driving performance. We found that engaging the driver's cognitively with a secondary task significantly affected his/her driving performance as well as the judgment capability. Moreover, we found that different features of the secondary task had different effects on EEG responses and different localizations in the frontal cortex. Our hemispheric analysis results showed that the most affected area during distracted driving was in the right frontal cortex region; thus, it is suggested that the activation in the right frontal cortex region may be considered the spatial index that indicated a driver who is in a state of cognitive distraction.

1. Introduction

Driving is a complex task that depends on a set of cognitive skills in association with the contributions of planning, memory and motor control and visual capabilities. These capabilities vary from one individual to another depending on the cognitive skills and level of attention (Shinar, 1993).

In past decades, driving distraction is increasingly identified as one of significant causes of traffic accidents and has the same effect on driving performance as drugs and alcohol. In fact, NHTSA estimated that various drivers' distraction sources caused about 20–80% of crashes and near-crashes (Stutts & Association, 2001). More recently, a wide naturalistic driving study of 100 cars found that inattention was a cause in 78% of all crashes and near crashes, thus considering it the largest crash causation factor in their analysis (Dingus et al., 2006).

Driving distraction, generally, is defined as the deviation of driver's attention away from operating safe driving toward a competing activity (Young, Lee, & Regan, 2008). Therefore, the cause of driving distraction could be due to any cognitive

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process such as daydreaming, mind wondering, mathematical problem solving or decision making issues in addition to using in-vehicle information systems (IVI's) such as Audio systems, navigation systems and cell phones that may affect driver's attention on driving. When drivers are cognitively distracted, visual information processing becomes lower which markedly impairs driving performance in detecting targets across the entire visual scene (Lee, Lee, & Boyle, 2009; Recarte & Nunes, 2000, 2003). Many studies have investigated the impact of a secondary task on driving performance. These studies have used mobile phone related task (general usage of the mobile phone), conversation with passengers, and other tasks as a secondary task (Brookhuis, de Vries, & de Waard, 1991; Chaparro, Wood, & Carberry, 2004; Crundall, Bains, Chapman, & Underwood, 2005; Lamble, Kauranen, Laakso, & Summala, 1999; Levy, Pashler, & Boer, 2006). The two major types of distraction are visual distraction and cognitive distraction. Visual distraction can be defined as "eyes-off-road", and cognitive distraction as "mind-off-road" (Victor, 2005). Both types of distraction can affect driving performance such as lane variation, steering control, response to hazards, and visual perception efficiency. Moreover, visual and cognitive distraction interacts with each other and can occur in combination. The current study will focus on driver's cognitive distraction.

Cognitive distraction and inattention will be used interchangeably in our context of study. From the general definition both are considered as the decrement of mental concentration to a specific task (Anderson, 2009).

To better understand driver psychological behavior and the sources of driver cognitive distraction, researchers have attempted to develop models that captured brain electrical activity (EEG) (e.g., Dong, Hu, Uchimura, & Murayama, 2011 and Lin, Ko, & Shen, 2009). Such models provide a better understanding of the effects of distraction on driver behavior through capturing changes in EEG activity. Measures of brain electrical activity (EEG) are the most valid measures used for distraction measurement (Lin et al., 2009). EEG has the advantage of high temporal resolution which allows for the ability to perform cognitive studies and instantaneously evaluate the corresponding brain activity. EEG recording is completely non-invasive and can be applied repeatedly to patients, normal adults, and children with no risk or limitation (Teplan, 2002). Galán and Beal (2012) in their study in evaluating whether the EEG could estimate the attention and the cognitive workload in predicting success or failure of math problem solving, suggested that EEG might be a valuable tool for assessing cognitive workload.

Due to the rapid increase of in-vehicle technologies, the psychological changes in drivers are more complex and hard to detect. Therefore, a study by Schier (2000) has described the need of using more advanced technologies to study the rapid changes of the driver cognitive state during driving. The study has investigated the suitability in using EEG-based technologies simultaneously with a driving simulator through the activities in the alpha frequency band (8–13 Hz) between driving and driving-replay sessions. It has been agreed that the alpha band is the most dominant band for studying attention (Klimesch, Doppelmayr, Russegger, Pachinger, & Schwaiger, 1998; Schier, 2000 and Wolfgang, 1999). Dynamic changes in alpha activity corresponding to the changes in driving events have been documented (Schier, 2000). Furthermore, this study concluded a high effectiveness of the exploratory experimental work in demonstrating the practicality of such EEG recordings during simulated driving.

Many studies have investigated the human factor in road crashes. Lee et al. (2009) have investigated the effect of drivers' cognitive load on the relation between internal and external attention control; as reviewed, the cognitive load has a high influence on withdrawing driver attention and decrease the driver's ability in detecting road hazards through a cue-based pedestrian paradigm. He has found that the cognitive load delayed the driver response and reduced his fixation to pedestrians and external cues.

A good index of cognitive distraction that is widely accepted in EEG measurements consists of theta activity (4–8 Hz), alpha activity (8–14 Hz) and Beta activity (14–35 Hz) (Lin, Chen, Ko, & Wang, 2011). Theta and beta activity in brain frontal lobes are associated with cognitive processes such as judgment, problem solving, working memory, decision making and mathematical problem solving (Lin et al., 2011). The increasing amplitudes of these particular bands are often a result of brain engagement in such activities.

The role of attention on EEG activity has been extensively studied. Klimesch et al. (1998) studied induced alpha band power changes in EEG signals and attention through an oddball task. After separating alpha into 3 sub-bands – lower, medium and upper – they found that only the lower alpha reflected the attentional demands. Also from his study on the reflection of cognitive and memory performance on alpha and theta EEG bands (Wolfgang, 1999), he suggested that alpha in different sub bands was highly influenced by attentional and semantic memory processes. One of the most important findings was the increasing in the upper alpha bands desynchronization during the semantic judgment task but there was no response from theta activity. The highest activities of alpha corresponded to the judgment task seen in the prefrontal left hemisphere, and this was supported by findings from a PET study (Endel, Shitu, Craik, Morris, & Sylvain, 1994). An important conclusion was that the increase in theta power and decrease in alpha power indicated poor cognitive and memory performance. On the other hand, the decrease in alpha power indicated high attention to a specific task while increase in theta power indicated distraction (low attention) to a specific task.

As a matter of fact, drivers' cognitive distraction is the most difficult to assess and evaluate among the three types of driver distraction due to the inability of directly observing what is going on in the driver's brain. One possible solution to the problem is to capture changes in driving behavior using objective measures that will also serve as a qualitative assessment associated with cognitive distraction and visual distraction (Angell et al., 2006; Engström, Johansson, & Östlund, 2005). Such objective measures in tracking driving behavior and performance have been widely used to confirm the effects of different types of driving distraction. For example, (Horberry, Anderson, Regan, Triggs, & Brown, 2006) focused on two speed-related variables (mean speed and deviation from the posted speed limit) in measuring driving behavior changes. They reported that in-vehicle tasks have high negative impact on the studied driving behavior measures. A study by Boril and colleagues on the effects of cognitive load and driver emotions on driving speed used lane control capability as a driving performance indicator. They suggested that the secondary cognitive task and drivers' emotion severely impacted driving performance as they found a high reduction in the steering wheel control ability (Boril, Omid Sadjadi, Kleinschmidt, & Hansen, 2010).

In this study, we investigated the changes in drivers' cognitive state through the changes in recorded EEG signals. As the subjects were placed into different driving situations, changes in their EEG responses were obtained to track changes that reflected changes in their cognitive state induced in the experimental design. Employing the EEG provided a reliable indicator of the fluctuations in drivers' cognitive state during driving. As such, the obtained data might eventually be incorporated into real-time systems that could intervene or warn a driver if he/she is drifted to a cognitive state that may compromise his/her safety.

The objectives of this study are to:

1. Investigate the effects of a secondary task that employs cognitive resources on driving behavior.
2. Determine cognitive changes as measured by EEG signals of a secondary task while driving.
3. Identify specific regions and frequency bands involved in the activity of simultaneously completing a secondary task and driving.
4. Provide high spatial resolution EEG data comparing cognitive states of driving and driving while distracted.
5. Provide hemispheric analysis of driver cognitive distraction by comparing EEG changes over the frontal left and right hemispheres during driving.

2. Experimental apparatus

2.1. Subjects

Forty-two healthy volunteers (33 male and 9 females) aged between 18 and 24 years old (mean 21.76 and SD 1.65) participated in the study. All subjects had no history of psychiatric issues. Every subject had normal or corrected-to-normal vision and reported normal hearing. Participation was voluntary. All subjects had no experience in driving simulators; therefore they were allowed to practice driving in the driving simulator for approximately 10 min before the EEG net was mounted. Participants were informed that they could stop participating in the experiment at any time without any penalty.

2.2. Dynamic driving environments

A simple driving simulator (with a steering wheel, foot pedals and gear leaver) with a computerized virtual-reality (VR) based highway-driving environment (City Car Driving 2.4.4) was employed as an objective measure of driving behavior. To provide the same condition for all participants, the driving environment was limited to one simulator vehicle on a highway road (de Waard & Brookhuis, 1991; De Waard & Studiecentrum, 1996; Lal & Craig, 2002), using the same car (Toyota Corolla, with an automatic gear change) with medium-controlled traffic level. In addition, all participants had 15 min of practice in the simulator to familiarize themselves with the simulator and simulated driving. The screen presented an 'out-car' view to the driver. The screen was 1 meter from the driver, and at the same level with the steering wheel. The dynamic driving environment provided a safe, time saving and low cost approach to study human cognition under realistic driving events (Schier, 2000). Subjects could interact directly with the environment and receive the most realistic driving conditions during the experiments.

2.3. Experiment scenario

2.3.1. Driving task (primary task)

Participants completed 2 sessions of driving, and EEG recording took place during both sessions. Each session was 30 min as depicted in Fig. 1. In the first session after EEG recording apparatus has been set up, participants were instructed to drive for 30 min and pay attention to driving rules such as driving below 80 km/h speed, using indicator lights when needed, etc. This session served as the control session. In the second session (referred to as distracted driving session from here onwards), participants were instructed to pay attention to the road throughout the entire 30-min session and at the same time they had to listen carefully to a secondary task (briefly described in Section 2.3.2) administered by the experimenter standing beside. The two sessions were counter-balanced – half of the participants started with the control session while the other half started the driving with distraction session.

2.3.2. Cognitive task (Secondary task)

The secondary task was a mix of logical reasoning in the form of analogies (decision making) and real-life problems involving measures (math) (see Table 1 for examples of questions presented to the participants). This secondary task was included in the experiment as a way to create cognitive distraction among the participants.

As illustrated in Fig. 1, the distracted driving session was segmented into intervals of "*attentive*" and "*distracted*" driving. There were six segments where participants were interrupted in their driving with the secondary task. Participants were

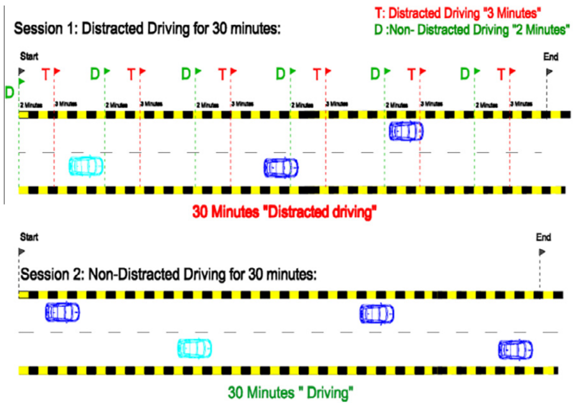

Fig. 1. An illustration of the experimental design. The top arrow indicates the flow of distracted driving while the bottom arrow indicated the flow of the control session.

Table 1
Example questions in the secondary task.

Question	Answer
Odometer is to mileage as compass is to: A. speed B. hiking C. needle D. direction	D
Elated is to despondent as enlightened is to A. aware B. ignorant C. miserable D. tolerant	B
Careful is to cautious as boastful is to A. arrogant B. humble C. joyful D. suspicious	A
Pride is to lion as shoal is to A. teacher B. student C. self-respect D. fish	D
I want to make 12 cakes. If I know that 6 kg of flour is enough for 36 cakes, how much flour will I need?	2 kg
When a bucket is full it holds exactly 1/2 liters. A jug holds 500 milliliters. How many full jugs of water will I need to fill the bucket?	1 jug
Find the cost of 4.5 kg of sugar at 20 p per 500 g.	180 p

asked to answer the questions as accurately as possible. Because we were interested in capturing brain activity when one was engaged in thinking, participants were allowed to take time to answer the questions. Participants were informed at the very beginning that when interrupted with the secondary task they should listen carefully to the questions, stay calm with minimal movements, pay as much attention as possible to the road and think silently.

2.4. Data collection

A 128-channel EGI Hydro-Cel GSN electrode net connected to NetStation 4.2 software was used in collecting EEG signal. The physiological data acquisition employed 128 EEG electrodes with a vertical reference at Cz electrode. The use of the vertical Cz reference, which is the center of the scalp based on 10–20 international EEG system, was to minimize the EEG deflections in the nearness of Cz due to potential synchronization of firing activities within closely spaced brain regions and volume propagation of the EEG signal. Before acquisition, the contact impedance between EEG electrodes and cortex was calibrated to be less than 5 kΩ. The EEG data were recorded with sampling rate of 500 Hz and then re-sampled down to 250 Hz for the simplicity of data processing.

The measures of driving performance used in this study were the deviation between the center of the vehicle and the center of the cruising lane, number of accidents and speeding offenses to indirectly quantify the level of the subject's attention (Brookhuis et al., 1991); (Chaparro et al., 2004). We compared the driving performance between both control and distracted driving sessions. When the subject was distracted (checked from subject's driving performance report), car deviation increased, speed awareness decreased and a higher probability of causing accidents was observed.

As a way to confirm that the secondary task employed in the study did in fact induce cognitive distraction, participants were administered the secondary task for a second time as a solo task after completing the two driving sessions in the simulator. Answers obtained from the two conditions (driving and non-driving) were collected and compared to determine the level of subject's attention in each condition.

2.5. Pre-processing

The results were pre-processed by removing eye movements and high-powered eye blinking. EEG-data (128-channel) were off-line corrected from ocular and muscle artifact using Gratton method (Gratton, 1998). The correction is based on correcting the affected EEG-data regarding to a pre-defined EOG channels (channel 14 at the upper right eyebrow) then subtracting the original signal from the defined one.

As most cognitive functions that involved making judgments and problem solving occur in the frontal lobe, the number of electrodes is reduced to the frontal area. Thus, 16 EEG electrodes have been selected for further analysis as depicted in Fig. 2.

2.6. Feature extraction with Singular Value Decomposition (SVD)

Since most of cognitive activities occur at the frontal lobe (Lin et al., 2009), let us assume matrix A represents the outputs of the 16-EEG channels distributed over this region. Next, the data of the 16 channels is segmented into the three stages of the experiment, namely, driving stage, driving with distraction stage, and driving after distraction stage and the data of each stage is arranged in a 16 rows-matrix. Now, each of the 16 rows of the data matrix of a particular stage is partitioned into six segments of one minute each and used as rows in a new data matrix, B. The size of the matrix B is $(16 \times 6)\,\mathrm{x}(n)$ where n is the number of samples in 1 min of EEG data. Accordingly, three data matrices indicated as B_{dri} for the driving without distraction, B_{dis} for driving with distraction, and $B_{dri\text{-}dis}$ for driving after distraction, are obtained and used with the singular value decomposition (SVD) for the detection of energy orientation in 96-dimensional Euclidian space.

2.6.1. Singular Value Decomposition (SVD)

In the current study, Singular Value Decomposition (SVD) was used to extract identity features from our EEG data for further analysis. For more details of this method, please see (Golub & van Van Loan, 1996; Golub & Zha, 1995 and Kamel, Sayeed, & Ellis, 2008).

3. Result

3.1. Driving performance

Significant changes were observed in driving performance (lane deviation and number of accidents). The mean and standard deviation of these measures were presented in Table 2. A higher value for these measures indicated poorer performance as they measured the number of instances of deviating from the driving lane and near-crashes or accidents. Paired *t*-test analyses suggested significant impaired driving performance during the distracted-driving sessions – there were more instances of lane deviation ($t(41) = -3.53$; $p < 0.01$) and near-crashes or accidents ($t(41) = -2.05$; $p < 0.05$).This suggested that engaging drivers in a secondary cognitive task while driving significantly affected driving performance.

3.2. Task response

The task was administered to participants during and after driving in the simulator in order to determine the performance of solving such problems while driving (Mean = 11.19; SD = 3.46) and not driving (Mean = 14.81; SD = 3.22). Paired-sample

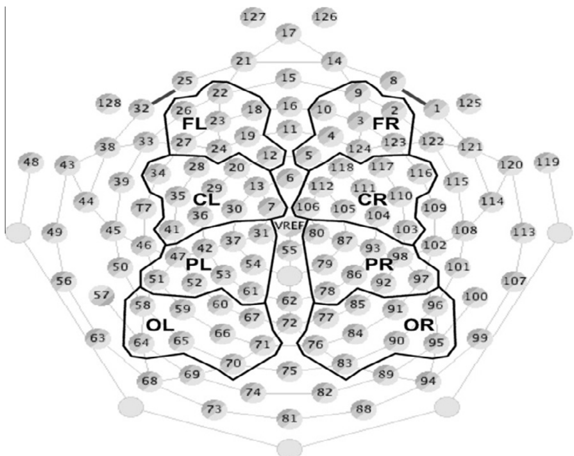

Fig. 2. Location of electrodes for 128 EEG system. Respectively, FR and FL highlight the right and left frontal lobes selected for the analysis.

Table 2
Pair-sample T-test of driving performance measures results.

	Driving		Distraction		*p*-value
	σ	SD	σ	SD	
Lane keeping	3.57	1.93	4.85	2.48	.001
Accidents	.52	.77	.78	1.04	.047

t-test results indicated significant differences in correctly answering the questions in the two conditions ($t(41) = 10.04$; $p < 0.001$). Participants did better on the secondary task when they were not driving in the simulator. Evaluating these results with results from the previous Section 3.1 provided support that the secondary task employed in the current study was able to induce cognitive distraction when one was driving.

3.3. EEG measures

Greater differences were observed in EEG bands (theta, alpha and beta) for forty subjects ($N = 40$), we would like to mention that two subjects data were excluded due to the huge noise in the recordings. This observation suggested an increase in brain activity in the frontal lobe during distraction while and after giving the cognitive task. This finding is consistent with roles of the frontal lobe rule in attention, problem solving and decision-making (Burgess, Alderman, Volle, Benoit, & Gilbert, 2009). Table 3 includes the mean and the standard deviation of both distracted-driving and non-distracted driving sessions in right and left frontal lobe while performing math task and decision making task.

Table 4 summarizes results of paired-sample *t*-test for extracted features from recorded EEG data during both driving and distracted-driving sessions and the effects of the secondary tasks. The data of left and right frontal hemispheres were analyzed separately as well as the data from each secondary task – decision making and math problems.

Table 3
The mean (μ) and standard deviation (σ) of the averaged EEG frequency bands in the right and left frontal lobe in the non-distracted driving session (Dri) and distracted driving session (Dis) when participants solved math problems (math) and decision making problems (DM).

Distracted-driving		μ	σ	Driving	μ	σ
Right	Amp	182,998.7	109,067.1	Amp	144,929.5	107,679.7
	Theta	204,386	110,870.9	Theta	160,376.3	98,061.1
	Alpha1	117,448.5	127,679.1	Alpha1	100,199.3	150,981.4
	Alpha2	107,429.2	124,809	Alpha2	98,039.49	147,433
	Beta1	180,865.1	134,128.4	Beta1	84,999.06	98,584.17
	Beta2	811,997.6	533,767.2	Beta2	307,378.4	123,184.3
	Amp_math	151,654.6	109,404.4	Amp_math	83,106.74	57,213.95
	Theta_math	175,603.2	128,971.9	Theta_math	106,673.2	76,597.83
	Alpha1_math	76,870.53	81,379.39	Alpha1_math	44,627.53	46,149.31
	Alpha2_math	67,736.99	74,238.71	Alpha2_math	28,537.75	29,647.29
	Beta1_math	152,926.6	183,319	Beta1_math	62,687.7	67,759.76
	Beta2_math	753,896.5	547,129.7	Beta2_math	265,613.3	133,318.1
	Amp_DM	92,550.3	115,104.7	Amp_DM	92,550.3	115,104.7
	Theta_DM	121,214.3	126,205.7	Theta_DM	121,214.3	126,205.7
	Alpha1_DM	190,198.9	321,401.9	Alpha1_DM	190,198.9	321,401.9
	Alpha2_DM	190,872.9	323,115	Alpha2_DM	190,872.9	323,115
	Beta1_DM	193,588.4	301,662.9	Beta1_DM	193,588.4	301,662.9
	Beta2_DM	699,386.2	528,195.7	Beta2_DM	699,386.2	528,195.7
Left	Amp	146,416.83	65,319.93	Amp	110,591	38,749.83
	Theta	155,259.56	60,393.78	Theta	131,222.2	62,671.81
	Alpha1	63,318.57	55,718.14	Alpha1	62,121.21	58,431.38
	Alpha2	67,929.7	53,164.63	Alpha2	68,655.71	57,215.55
	Beta1	116,735.88	51,660.44	Beta1	105,350.7	50,933.2
	Beta2	600,959.33	174,923.31	Beta2	482,481.9	114,166.9
	Amp_math	306,004.8	656,427.2	Amp_math	275,721.6	830,530.6
	Theta_math	304,722.3	710,808.9	Theta_math	185,142.4	497,604.3
	Alpha1_math	141,332.5	352,090.7	Alpha1_math	259,654.5	921,451.7
	Alpha2_math	188,857.8	538,009.4	Alpha2_math	313,170.8	930,441.6
	Beta1_math	273,542.1	557,105.7	Beta1_math	267,446.6	558,293
	Beta2_math	894,511.8	835,757.4	Beta2_math	582,017.7	565,597.6
	Amp_DM	149,488.3	142,793.5	Amp_DM	303,055	510,969.9
	Theta_DM	182,036.8	194,258.6	Theta_DM	360,153.6	626,402
	Alpha1_DM	89,806.08	87,280.16	Alpha1_DM	24,927.79	30,402.4
	Alpha2_DM	93,743.8	167,142.7	Alpha2_DM	338,274.2	766,925.6
	Beta1_DM	165,006.6	178,051.7	Beta1_DM	105,081.3	193,669.5
	Beta2_DM	605,381.1	396,548.7	Beta2_DM	569,828.8	366,953.6

Table 4
p-value and t-value from Pair- sample T-test of all frequency bands and the amplitude from EEG data recorded in both driving (Dri) session and distracted-driving (Dis) session corresponding to the distraction tasks (logical reasoning (DM) and real-life problems involving measurements (Math).

Tested pair		p-value	t-value
Right	Dis_Amp – Dri_Amp	$p < 0.05$	2.858
	Dis_Amp _Math – Dri_Amp _Math	$p < 0.001$	3.605
	Dis_Theta – Dri_Theta	$p < 0.05$	−2.223
	Dis_Theta _Math – Dri_Theta _Math		−2.995
	Dis_Alpha1 – Dri_Alpha1		−2.801
	Dis_Alpha1 _Math – Dri_Alpha1 _Math	$p < 0.001$	−3.541
	Dis_Alpha2 _Math – Dri_Alpha2 _Math		−4.188
	Dis_Beta1 _DM – Dri_Beta1 _DM		−2.21
	Dis_Beta2 _Math – Dri_Beta2 _Math		3.242
	Dis_Beta2_ _DM – Dri_Beta2 _DM		−2.902
	Dis_Amp _DM – Dri_Amp_DM	No significance	
	Dis_Theta _DM – Dri_Theta_DM		
	Dis_Alpha1 _DM – Dri_Alpha1_DM		
	Dis_Alpha2 – Dri_Alpha2		
	Dis_Alpha2 _DM – Dri_Alpha2_DM		
	Dis_Beta1 – Dri_Beta1		
	Dis_Beta2 – Dri_Beta2		
Left	Dis_Amp – Dri_Amp	$p < 0.05$	−2.392
	Dis_Theta _DM – Dri_Theta _DM		−2.003
	Dis_Alpha2 _DM – Dri_Alpha2 _DM		−1.971
	Dis_Amp _Math – Dri_Amp_Math	No significance	
	Dis_Amp _DM – Dri_Amp_DM		
	Dis_Theta – Dri_Theta		
	Dis_Theta _Math – Dri_Theta _Math		
	Dis_Alpha1 – Dri_Alpha1		
	Dis_Alpha1 _Math – Dri_Alpha1 _Math		
	Dis_Alpha1 _DM – Dri_Alpha1 _DM		
	Dis_Alpha2 – Dri_Alpha2		
	Dis_Alpha2 _Math – Dri_Alpha2 _Math		
	Dis_Beta1 – Dri_Beta1		
	Dis_Beta1 _Math – Dri_Beta1 _Math		
	Dis_Beta1 _DM – Dri_Beta1 _DM		
	Dis_Beta2 – Dri_Beta2		
	Dis_Beta2 _Math – Dri_Beta2 _Math		
	Dis_Beta2 _DM – Dri_Beta2 _DM		

The results in Table 4 suggested significant changes in EEG activity in both left and right frontal hemispheres, and these differences highlighted the influence of the secondary task used in the experiment. The largest changes were in EEG amplitudes in both right ($t(41) = 2.858$; $p < 0.05$) and left ($t(41) = -2.392$; $p < 0.05$) frontal lobe hemispheres, theta band ($t(41) = -2.223$; $p < 0.001$) and lower alpha ($t(41) = -2.801$; $p < 0.05$). The significant changes illustrated the increase in the level of human cognitive workload which reflects the distraction caused by the secondary tasks.

The effects from each secondary task were studied separately in order to investigate their effects on the driver's brain activity while driving. For that purpose, the data corresponding to distraction tasks (math and DM) were extracted and analyzed. Table 4 suggested that the math task significantly affected EEG amplitude ($t(41) = 3.605$; $p < 0.001$), theta band ($t(41) = -2.995$; $p < 0.05$), both lower and upper alpha bands ($t(41) = -3.541$; $p < 0.001$, $t(41) = -4.188$; $p < 0.001$) and upper beta band ($t(41) = 3.242$; $p < 0.001$) in the right frontal hemisphere while there were no significant changes related to math task in the left frontal hemisphere. On the other hand, t-test results suggested that there were significant effects produced by the DM task in both right and left frontal hemispheres in specific EEG bands influenced. In the right hemisphere, lower beta ($t(41) = -2.21$; $p < 0.001$) and upper beta ($t(41) = -2.902$; $p < 0.001$) while in the left hemisphere, there were significant changes in theta ($t(41) = -2.003$; $p < 0.05$) and upper alpha ($t(41) = -1.971$; $p < 0.05$).

The results in Table 4 suggested that the right frontal hemisphere was most affected by the secondary tasks compared to the left hemisphere. Corresponding to the tasks given, solving the math task created a more localized effect in the right hemisphere only while solving decision making (DM) task engaged the frontal region in both hemispheres.

4. Discussion

An EEG-based method for detecting driver cognitive distraction was presented. In this study, drivers' cognitive distraction was studied using cognitive secondary tasks. Previous studies have investigated driver cognitive distraction using visual stimuli such as studies by (Dong et al., 2011; Lin et al., 2009, 2011) in which the researchers distracted subjects using a mathematical equations that appeared in front of the subjects and sudden car deviation task. In studies from Klimesch et al. (1998) and Sonnleitner, Simon, Kincses, Buchner, and Schrauf (2012), they presented 9 Landolt rings on a screen in front of the subjects and asked them to determine the position of the ring by pressing a button located on the side. An auditory task was also used in studying the cognitive changes of the drivers in these studies. Following the visual task, Sonnleitner et al. (2012) presented an auditory task consisted of a story recorded on audio tape and the subjects were requested to detect specific words. In a study by Wester, Böcker, Volkerts, Verster, and Kenemans (2008), an auditory task consisted of 130 environmental sounds used to study the changes in drivers' attention by asking the participants to identify the different sounds in the audio recording.

The current study provided strong support that there was a significant effect of the cognitive secondary task on driving performance and the drivers' cognitive state. The effects from the secondary task meant to distract the drivers can be seen clearly in the lane keeping ability and accidents occurrence level. This effect was caused by the increase in the drivers' cognitive workload caused by the secondary tasks, and also suggested that resources for driving and solving the secondary task were shared. Schier (2000) also observed the general increase of cognitive workload while using simulated driving.

As seen in Table 4, there were significant changes of EEG activity (amplitude) over the left and right frontal hemispheres. As supported by (Dong et al., 2011; Victor, 2005 and Lin et al., 2009) the increase in theta bands could be considered as an index of distraction. Our data suggested that the math task had a higher impact on changes in brain activities compared to the Decision Making task, suggesting that comparatively the math task affected more regions in the brain. In this study, significant changes in theta band suggested that drivers were severely distracted by the secondary task, which was corroborated by the significant decrease of the drivers driving performance. Furthermore, these findings added to what other previous studies have found where changes in theta band in the frontal lobe were considered as an index of driver cognitive distraction (Dong et al., 2011; Lin et al., 2009; Victor, 2005). In addition, the significant increase in lower alpha band in the frontal lobe was an index of attention as suggested by many studies (Dong et al., 2011 and Lin et al., 2009). It has been reported in Wolfgang (1999) that the increase in alpha was an indicator of sustained cognitive workload. The effects of two different cognitive tasks on the driver brain activities as observed in the general changes in beta 1 (14–25 Hz) and beta 2 (25–35 Hz) bands were consistent with (Anderson, 2009; Lin et al., 2011 and Dong et al., 2011) where the dual task effect on driving distraction was also obtained and significant changes in beta bands were detected.

Results from the current study strongly suggested that a cognitive secondary task (such as the one employed in this study) had a high impact and served as a source of distraction to the driver cognitive state and driving performance. One of the strengths of the current study was that we were able to obtain high spatial resolution of the cognitive changes in the driver brain due to a distraction tasks. The results of the hemispheric analysis for task-related effect provided crucial information in determining the most affected area by the distraction, thus localizing the task-related effect to higher spatial resolution (as shown in Table 4). The spatial resolution generated by data from this study is an important contribution that strengthened the interpretation of drivers' cognitive distraction related to specific cognitive tasks. As illustrated, the right frontal lobe was the most affected region during the course of distraction especially for the math task and the dual task which were reflected in the significant changes in both lower alpha (alpha 1) and upper alpha (alpha 2) bands as supported by Galán and Beal (2012) in which the authors studied the estimation of EEG amplitudes in predicting math problem solving outcomes.

In addition, the changes in alpha bands (lower and upper) in the right frontal lobe are an index of attention (Lin et al., 2011). While there were no significance changes related to math task over the left frontal lobe, it is consistent with the role of left and right frontal cortex (Blair, Knipe, & Gamson, 2008). It has been reported that the right frontal cortex is more engaging with the math tasks than the left part (Blair et al., 2008 and Galán & Beal, 2012).

Famous auto companies like Saab, Mercedes-Benz, Toyota, Volvo and Nissan have developed many applications for road safety interventions. These intervention systems measure a driver's condition such as drowsiness, distraction, sleepiness and fatigue based on physical measures including head orientation, gaze position and eye-blinking patterns, while driving performance was detected via vehicle deviation and speed regularity. Regardless of the accuracy of such systems, the visual and audible alerting could add more workload to the driver, which may be more distracting than helpful. Therefore, modern vehicles are in need of a system that could track out changes of drivers' cognitive state that corresponds to different real-road driving scenarios. In this study, we introduce a critical analysis of the changes of drivers' cognitive state and provide precise localization of the effects of different cognitive task using EEG. In addition to the current driving safety intervention, developing EEG-based systems for drivers' cognitive distraction detection and mitigation will be a huge step toward accidents-free roads. The localization as a major finding of this study paved the way to reducing the number of electrodes on future systems that may include head sensors and make such systems more acceptable in the drivers' community. The results produced here might be useful when developing cognitive distraction mitigation systems.

We would like to acknowledge some limitations faced by the current study. Participants completed the secondary task again after driving in the simulator and our results suggested an improvement in their total scores. Although we interpreted such observation as better performance because of the participants being able to fully focus on answering the questions, we do not exclude the possibility that the improved performance could also be due to practice effects. Higher scores from the second assessment could have been due to participants' exposure to the questions before and having a second chance to either correct an earlier mistake or having more time to figure out the correct solution. In addition, the use of one simulated car in the experiment for all participants has over-simplified the driving task and considered a limitation of this study.

Future direction of the current work would be to characterize levels of cognitive distraction using a variety of daily cognitive tasks typically encountered by drivers. Electrode wise analysis should be conducted to find higher spatial estimation of the driver cognitive distraction.

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