Brain Correlates of Lane Changing Reaction Time in Simulated Driving

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Abstract—**Psychophysical studies have reported correlation between neural activity in frontal and parietal areas and subject's reaction time in simple tasks. Here we study whether similar correlates can also be identified in driver's electroencephalography (EEG) activity when they perform steering actions triggered by exogenous stimuli (e.g. obstacles along the road). We report analysis of the EEG signals of fifteen subjects while they drive in a realistic car simulator. We found that the peak latency of the event-related potentials in frontal and parietal areas significantly correlates with the onset of the steering behavior. Similarly, modulations of the power in the theta band (4-8 Hz) prior to the action also correlates with the reaction times. These results provide evidence of reliable neural markers of the driver's response variability.**

Index Terms—**Scalp EEG, driving task, reaction time, stimulus-driven reaction and event-related potential.**

I. Introduction

Reaction time measures how fast people can respond to the presentation of a sensory stimulus and reflects the functionality of the central nervous system [1]. The reaction time depends on the characteristics of the stimulus and subject's mental states. The task urgency is one of the important characteristics that affect the reaction time, which is correlated with the contextual environment. The translation between the task urgency and the motor reaction is modulated by afferent and cortical systems [2]. Recent studies have shown evidence of a correlation between brain activities and reaction time, particularly in frontal and parietal areas [3], [4]. Furthermore, the latter region is believed to be activated earlier than frontal areas during stimulus-driven behaviors [5]. However these studies have mainly been performed using psychophysical protocols in well controlled situations, leaving open the question whether the same correlates also appear in more complex tasks.

At the same time, the analysis of the brain activity generated during driving has gained increased attention in recent years. This activity reflects underlying cognitive processes and can potentially be exploited to improve driving assistance systems for intelligent cars [6], [7], [8]. For example, recent studies have focused on detecting anticipated and emergency braking [7], [9], steering actions [8] as well as workload and levels of attention [10].

The present study investigates the neural correlates of reaction time in a driving task. We analyzed electroencephalography (EEG) event-related potentials (ERP) and spectral modulations elicited by the appearance of obstacles that trigger lane changes and their relation to the steering reaction. In particular we focus on identifying reliable brain activity markers of the response variability. Their correlation with the responding speed provides evidence linking the reaction time to specific brain patterns. These reported cortical patterns contribute to improve our understanding of the neural basis of stimulus driven behavior during car driving.

II. Methods

A. Experimental protocols

Fifteen subjects (three females, mean age 26.83 ± 3.04) participated in the experiments. They were all MSc or PhD students and had normal or corrected-to-normal vision. All subjects had a valid driving license. None of them reported any known neurological or psychiatric disease. The experimental protocols were approved by the research ethical committee of the EPFL Brain and Mind institute and all participants gave their informed consent.

In the experiment, subjects seated in a car simulator and were asked to drive at high speed (at about 95 KMH) along a virtual 2-lane road. There were no other cars on the road. At any given moment an obstacle blocking one of the lanes could appear in front of the car, see Figure 1. If the obstacle was in the same lane, the subject was required to steer the car to the other lane to avoid the collision; otherwise, the subject should remain in the same lane. The probability of the obstacle to be in the same lane as the car was 25%. The distance between the vehicle and the obstacle at the moment of its appearance was variable in order to study different types of reaction, ranging from rapid responses when the obstacle appears at close distance to self-paced, slower responses when it is far ahead. Given the protocol drivers were expected to maintain high levels of vigilance during the experiment.

To allow subjects to successfully avoid collisions throughout the experiment, the distance between the car and the obstacle at its appearance was chosen randomly from an uniform distribution between 40 m and 70 m. The inter-trial interval (i.e. time between the appearance of two consecutive obstacles) was at least 5 sec (corresponding to a distance of
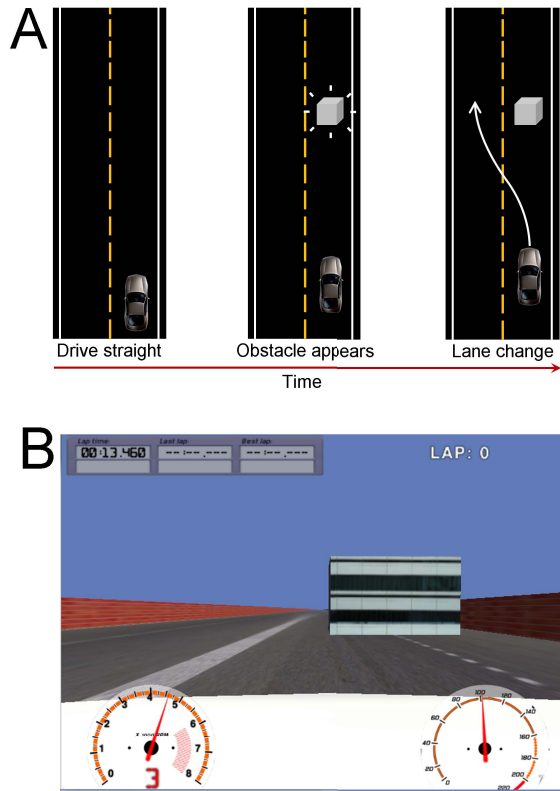
Fig. 1. Experimental protocol. A. Timing of the protocol. Subject drives straight in a two lane motor way. An obstacle may appear either in the same lane (rare condition, 25%) or the other lane (frequent condition, 75%). The subject needs to change lane immediately if the obstacle is in the same lane to avoid collision. B. The screenshot of the 3D environment as presented to the subject in the car simulator.

Fig. 2. Experimental protocol. Realistic car simulator including steering wheel, car pedals and three 3D monitors showing the virtual road environment. The subject wearing a 64-channel EEG cap can also be observed.

150 m). Therefore there was no overlapping between consecutive trials.

Each subject performed six runs in a single recording session, where each of them comprised the appearance of 87 obstacles (i.e. trials). The duration of one run was about 9 minutes and 30 seconds, resulting in a total recording time of about one hour. Overall, we obtained 522 trials per subject yielding 137.6 ± 15.2 trials where a lane change was required. Trials in which the subject steered during the second before the appearance of the obstacle were removed from the analysis. Since subjects may have different number of trials, we uniformly selected (according to the occurrence order) 100 trials for each subject and ordered them by their reaction time (i.e. rank 1 will correspond to the fastest trial, while rank 100 will be the slowest one). We averaged trials having the same rank –yielding 100 ERPs, one for each ranked speed– and computed the correlation between the EEG features and the speed of response.

B. Experimental setup

The experimental set-up consisted of a realistic car simulator as shown in Figure 2. Car related data (e.g. steering, braking, accelerating and location) from the driving simulator was logged at 256 Hz. The simulated driving environment was built using the software *Blender* (http://www.blender.org) and presented using a customized open source racing program (*Vdrift*) on three 27" 3D monitors. These monitors do not require the subject, who were seated at about 120 cm from the screens, to wear 3D glasses.

C. Data recording and processing

The driver's reaction time was estimated as the time it took for the steering values to exceed a threshold within 1 s after the obstacle appearance. The threshold was determined empirically. In this analysis we used the absolute value of steering data to define lane changes, thus the direction of the change (i.e. left-to-right or right-to-left) was not taken into account. In our experimental setup, the values of the steering data ranged from 0.0 to 0.3 (a.u.) corresponding to the range from straight driving to sharp steering turns.

Scalp EEG was recorded from 64 electrodes (Biosemi Active Two, The Netherlands) with an extended 10-20 system montage at a sampling rate of 2048 Hz, which was downsampled to 512 Hz after recording. The most peripheral electrodes were discarded to reduce the influence of artifact contamination, yielding a total of 41 channels kept for further analysis. EEG and car-related recordings were synchronized for off-line analysis using an event signal sent from the driving simulator to the EEG recording device via parallel port.

For analysing ERPs, we filtered the EEG data in the frequency band [1 10] Hz with a 4th order non-causal Butterworth filter. The spectral analysis was performed in the range [1 50] Hz. Common average reference was used as spatial filter. Power spectral density (PSD) of the single trials was computed by 1024-point discrete Fourier transform with a sliding Hamming window of 250 ms, and 218.75 ms overlapping was used in order to balance the smoothness and resolution in the time domain. For analysing ERPs and PSDs, EEG was segmented into epochs spanning from -1 s to 1.5 s
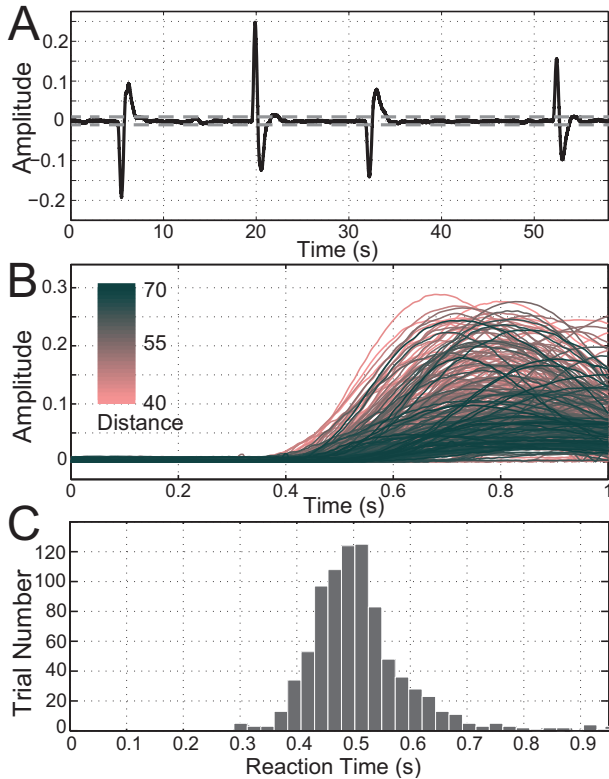
Fig. 3. Steering behavior. A: Typical steering signal including lane changes from right to left and left to right. The dash lines indicate the threshold for extracting reaction times during the lane change events. B: Steering profiles for all subjects. Individual lines correspond to the average across trials that have the same initial distance to the obstacle. Traces are color coded so that darker colors indicate larger distances. C: Histogram of the reaction time for all subjects.

with respect to the obstacle appearance (t=0). The PSD for each trial was referenced to a baseline defined as the average activity in the time window [-375 0] ms.

III. RESULTS

A. Behavior analysis

A typical trace of the steering signal is shown in Figure 3.A. Values are close to zero when the vehicle is moving straight with clear spikes indicating lane changes during the experiments. The car moves either left (negative) or right (positive) to avoid the obstacle, and afterwards the steering value returns zero to continue moving straight.

Figure 3.B shows the driver steering profiles after obstacle appearance for all subjects. Trials were colored from shorter to larger distances using light to dark tones, respectively. Unsurprisingly, trials in which the obstacle appeared at shorter distances (light traces) exhibit a faster reaction time and larger steering amplitude than those with farther obstacles.

Based on these results we set the steering threshold to estimate the reaction time to the value of 0.01. The distribution of the reaction time is shown in Figure 3.B. The median response time for all the trials is 0.496 s, and the

mean value ($\pm$ standard deviation) is $0.519\,\mathrm{s} \pm 0.109\,\mathrm{s}$. For the EEG analysis we discarded the extremes of the distribution, corresponding to trials with reaction times smaller than 400 ms or larger than 650 ms, amounting to 6.88% of all the recorded trials.

B. ERP analysis

Event-related potentials (ERPs) of channels FCz and CPz are shown in Figures 4.A and B, respectively. The reaction time of the trials is indicated by the darkness of the curves, the darker the faster. Each curve indicates the averaged ERP across all subjects based on the reaction time, i.e., from 0.4 s to 0.65 s after the presence of obstacles.

FCz electrode shows a positive peak at about 270 ms followed by a negative peak at about 515 ms. Slower trials (light traces) appear to have later peaks than the faster ones. A more marked pattern appears in channel CPz, where a large negative deflection appears at about 300 ms. As before, the peak latency of this component seems modulated by the driver's reaction time. Significant correlation between the peak latency of the early peak –appearing before action onset– and the driver's reaction time was found for both channels. The latency of the positive peak in FCz have a correlation coefficient of 0.427 ($p < 10^{-4}$), while the negative peak in CPz yields a correlation of 0.683 ($p < 10^{-13}$). The p value was obtained using Student's t-distribution with the assumption of bivariate normal distribution.

Consistently with the ERPs, scalp-wide grand average activity at 300 ms shows strong negative modulation in parietal areas, with a broader positivity over frontal areas, as shown in Figure 4.E. Similarly, figure 4.F shows the correlation between the peak latency of the early ERP component (prior to 400 ms) for each electrode. The results show positive correlations in both parietal and frontal regions, with highest correlation value in the former area. These spatial specific correlation patterns suggest that these sites are modulated in the stimulus-driven reaction and are informative about the behavioral reaction time.

C. Power spectral density

The grand average of the PSD in FCz and CPz are shown in Figure 5.A. We found no evident modulation in the first 200 ms after the obstacle appearance. In contrast, both electrodes show increased theta power (4-8 Hz) after this period. Typically, this increase in power centers at about 300 ms and disappears before the steering onset (i.e. after 400 ms). A decrease in the beta power (20-35 Hz) is also clear in these two electrodes, appearing at about 300 ms, continuing during lane change behavior. In addition, a late increase at about 500 ms can be observed in the low frequency (1-4 Hz) activity in FCz. This pattern is not obvious in CPz.

The correlation between the band power (theta and beta) and the reaction time of the steering are analyzed as well, which is similar as reported in the section of ERP analysis. The average band power in the time window between 200 ms to 400 ms was computed and used to obtain the correlation coefficient between the reaction time.
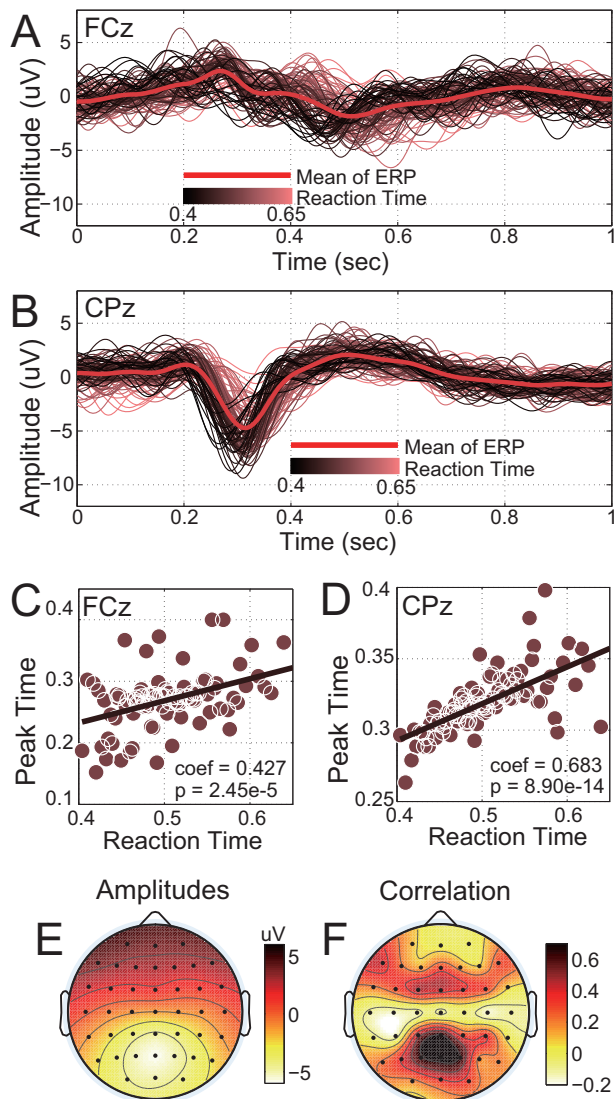
Fig. 4. Event-related potentials and their correlation with reaction time. A and B: ERPs in electrodes FCz and CPz, respectively. Reaction time for each trace is color-coded with darker colors indicating shorter trials. The grand average is shown by the thick red curve. C and D: Correlation coefficients between reaction time and the latency of the early ERP peak in electrodes FCz and CPz. E: Topography of ERP amplitude for all trials at 300 ms. F: Topographical representation of the correlation coefficients between ERP peak latency and reaction time.

Topographical analysis of spectral modulations for the theta and beta bands is shown in Figure 5.C. Each plot shows the average band power in the window from 200 ms to 400 ms. The theta power increase is stronger at parietal areas, peaking at CPz and Pz, also appearing in frontocentral and frontolateral regions. The pattern for the beta band shows broader modulations, particularly in parietal regions. The medial central (electrode Cz) and lateral frontal regions do not show evident beta modulation.

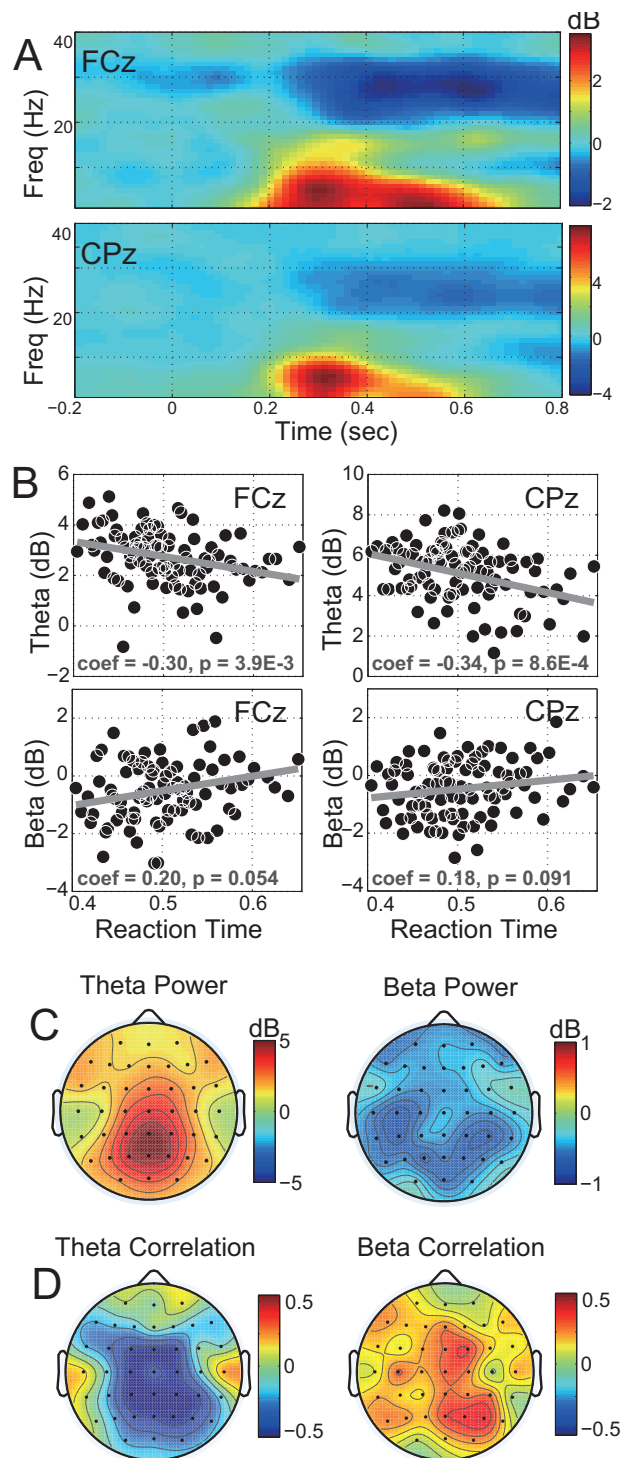The reaction time and the power modulation in the theta

Fig. 5. Spectral analysis. A: PSD of electrodes FCz and CPz upon appearance of the obstacle. B: Correlation between the reaction time and the band power in the theta (4-8 Hz) and beta (25-30 Hz) bands for FCz and CPz. C: Topographies of the average theta power and beta power in the window [200 400] ms. D: Correlation coefficient for theta power and beta power for the whole montage.

band is significantly correlated, with correlation coefficient -0.3 in FCz (p <0.005) and -0.34 in CPz (p <0.001). The correlation coefficients in theta are negative, which indicate that the trials with faster reaction are accompanying with stronger increase in theta. The beta power is positively correlated with the reaction time (the correlation coefficient is 0.2 and 0.18 for FCz and CPz respectively), i.e., the faster reaction the more decrease in beta, however, these correlations is not statistically significant ($p > 0.05$). In the topography of correlation coefficients, we observe that both frontocentral (except Cz) and parietal regions are highly correlated with reaction time. The coefficients in frontolateral regions are close to 0.2, but much lower than frontocentral and parietal regions. In the beta band, the most correlated regions are also frontal and parietal.

IV. Discussion and Conclusion

This study provides evidence of reliable neural markers of the driver's response variability. In agreement with previous studies performed in simpler experimental protocols [4], these correlations can be observed in parietal and frontal areas. We found significant correlation between the driver's behavioral response and the brain activity prior to the steering action, at the level of the ERP peak latency and power modulations in the theta band.

In our experiments, the characteristic of the external stimuli is varied from trial to trial, due to the distance between the vehicle and the appearing obstacle. The shorter distance leads to higher demand of lane change, not only from the visual perception of closer object (larger) but also the higher temporal urgency of the task, which needs to be reacted more rapidly [11], [12], [13], [14], [15]. Current debates exist about the mechanism of the reduction of response latency in urgent situations, either caused by different CNS pathways or a common pathway but more rapid response latency [13], [14]. The brain patterns obtained in the present study are similar among the reactive trials no matter the diversity of reaction times, in terms of ERP peaks and oscillatory power modulations, given the truth that all responding trials require action within certain period, i.e., the vehicle will be damaged if no response is taken place. Thus our results prove that the brain patterns keep the same among fast and slow reactions but the intensity of these patterns are varied and associated to the responding speed. The verification of different CNS pathways in urgent and non-urgent conditions could be further assessed by adding extra conditions, i.e., stimulus-driven lane change but without danger (if it is not executed) and voluntary intended lane change without any external stimulus.

The frontal and parietal regions are activated during attentional tasks in both human subjects and monkeys [16], [17], and particularly the frontal-parietal coherence reflects the transformation from the sensory representation in parietal cortex into the adjusting behavioral responses in frontal regions [18]. The findings in this study show correlation of responding speed in both frontal and parietal regions, i.e., intensive modulation is associated with faster behavior. Recent evidences show earlier and more dominant neural association in parietal in such exogenous processing comparing with frontal area [19], [20]. Future studies will explore the causal influence between different frontal and parietal regions to find the information flows that are correlated with the reaction time, given the advantage of high temporal resolution of EEG data.

Concluding, the current findings complement recent studies that have identified correlates of other cognitive processes in realistic driving, including drowsiness [6], [21], [22], [23], emergency braking [9], [24], error-awareness [25], anticipation of self-motivated steering [8] and braking actions [7], as well as visual attention [26]. We purport that future driving assistive systems can exploit information derived from these signals –decoded through a brain-machine interface system–, in combination with information from in-car sensors to tailor the support they provide both to the perceived conditions of the environment as well as the internal state of the driver [27].

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