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EEG-based Spatial Navigation Estimation in a Virtual Reality Driving Environment

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***Abstract*—The aim of this study is to investigate the difference of EEG dynamics on navigation performance. A tunnel task was designed to classify subjects into allocentric or egocentric spatial representation users. Despite of the differences of mental spatial representation, behavioral performance in general were compatible between the two strategies subjects in the tunnel task. Task-related EEG dynamics in power changes were analyzed using independent component analysis (ICA), time-frequency and non-parametric statistic test. ERSP image results revealed navigation performance-predictive EEG activities which is is expressed in the parietal component by source reconstruction. For egocentric subjects, comparing to trails with well-estimation of homing angle, the power attenuation at the frequencies from 8 to 30 Hz (around alpha and beta band) was stronger when subjects overestimated homing directions, but the attenuated power was decreased when subjects were underestimated the homing angles. However, we did not found performance related brain activities for allocentric subjects, which may due to the functional dissociation between the use of allo- and egocentric reference frames.**

Keywords —spatial navigation, allocentric, egocentric, reference frame, electroencephalograph (EEG)

I. Introduction

Spatial navigation is a crucial ability for living, since way-finding and environment exploration always happens in our daily life. Spatial navigation is a complex task which requires to integrate information from different sensory inputs and to construct the spatial representation of the environment. According to the computation of reference of frames, there are two classes of internal spatial representation systems: the allocentric representation system and the egocentric representation system [1-3].

In the egocentric reference system, the spatial location of an object is specified with respect to the navigator or observer. The spatial representation of an object depends on the position or orientation of the observer and the representation changes along with the observer's position or orientation. On the other hand, people who prefer to use an allocentric reference frame describe the spatial location of an object with respect to features or landmarks of the environment [3]. Visuospatial navigation is a task that involves complex cognitive functions which employ multiple brain regions. Brain activations in bilateral hemisphere including frontal, parietal, pre-motor, occipital, and temporal areas revealed an association with spatial navigation [4-6]. Moreover, the neuropsychological studies suggested the functional dissociation between the use of allocentric and egocentric reference frames [7-9].

In our previous study [20], we found that EEG spectrum power changes were significantly different between the navigation strategy groups. Subjects who preferred to use the allocentric spatial representation showed stronger activation in occipital area during path integration whereas subjects using the egocentric reference frames showed stronger activation in parietal area during path integration.

The aim of this study is to investigate the difference of EEG dynamics on navigation performance. We first distinguished subjects using the egocentric reference frames from subjects using the allocentric reference system during navigation by a spatial tunnel task [9]. Then we estimated their navigation performance during the task respectively. The tunnel task was built in a 3D virtual reality based driving-simulation environment. Since there was no extra landmarks in the tunnel, subjects' navigation strategies were not biased by the environment and therefore we could classify subjects into two different navigation strategy groups according to their use of cognitive reference frames while passing through the tunnel. The 32-channel EEG activities were recorded during subjects navigated in the tunnel and responded to the homing direction selections and homing angular estimation. EEG signals were processed and revealed in the spectro-temporal domain. Effects of the navigation strategy and performance on neural rhythms were compared and assessed in details.

The paper was organized as follows. We introduced the apparatus and materials of the study in Section II and explored the EEG dynamics with innovative methods by combining Independent Component Analysis (ICA), time-frequency spectral and power spectrum analysis in Section III. Section IV showed the performance-predictive EEG activities associated with the use of egocentric reference frames. And finally the discussion and conclusions were presented in Section V.

II. Experimental Apparatus

A. Subjects

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Eighteen right-handed subjects were paid to participate in this research (age: 20-28 years, mean: 25 years). None of subjects had a history of neurological or psychiatric disease and without drug or alcohol abuse. Subjects gave their written informed consent to participate in the study, which was approved by the Institutional Review Broad of Taipei Veterans General Hospital.

B. EEG Recording

The physiological data acquisition used 32 unipolar sintered Ag/AgCl EEG electrodes. All the electrodes were placed in an elastic cap according to the international 10-20 system. EEG data were recorded with the Scan NuAmps Express system (Compumedics Ltd., VIC, Australia) and digitized at 1000 Hz and 16-bit quantization level.

C. Stimuli and Procedure

The subjects sat comfortably in a car which was mounted in the center of a dimmed quiet room. Five projection screens circularly surround the car with a distance of 100 cm and provide 206° frontal field of view (FOV), and 40° back FOV to construct a virtual driving environment. All virtual scenery and physical motion were built and simulated by the tool of World Tool Kit (WTK). Subjects were required to perform a tunnel task [11] and instructed to keep relax and without movement as possible during the task.

We used the VR based tunnel-driving environment to investigate the EEG dynamics in spatial navigation. Animations of passages through a 3D virtual tunnel consisting of a turning segment which is between the two straight segments were presented on the screen to simulate automatic car driving with a constant velocity (see Fig. 1). The VR scene only provided subjects with visual flows of spatial translation and rotation. No other landmarks or references existed in the tunnel scenery to affect subject's navigation strategy. The turning segment of the tunnel scene was randomly turned left or right in degree of 30, 60, and 90. Subjects were required to keep the track of their implied virtual 3-D position with respect to their starting position during passage. At the end of each passage, a three dimensional homing arrow was appeared in the empty space in front of subject and subjects were required to indicate the homing direction by pressing the left or right buttons and the arrowhead was pointed roughly in the direction of the tunnel origin. The selection of the homing direction was associated with the subject's navigation strategy, the use of the reference frame. For example, for a right turn task, subjects with allocentric reference fame would indicate that the original entrance was in his left hand-side. Once the subject pressed the button to point the homing direction, the arrow started to rotate from 0 degree until subjects pressed the button again and the arrow was stopped and pointed to the more correct homing angle. Each subject was asked to practice the task around 5 min to familiar with the task. Each subject was required to complete 4 20-minute sessions in the experiment and each session contained about 45 trails. Between two sessions, subjects could take rest for about 5-10 minutes.

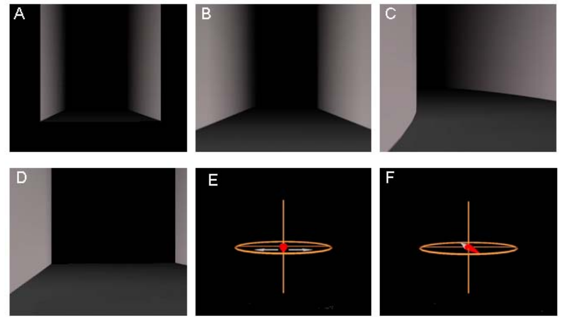

Fig. 1. The episodes of virtual tunnel environment. (A): the entrance; (B): the forthright segment; (C): the meander segment; (D): the exit; (E): the cue for indicating homing direction and (F): the cue for indicating homing angle.

III. Data Analysis

A. Analysis of the Behavior Data

Subjects were first classified into allocentric subject and egocentric subject according to their pointing direction. Three subjects were excluded due to their inconsistency on pointing direction (<90% of total trials). To investigate the task performance, signed pointing error was analyzed across all subjects. Trails of signed pointing error exceeding three times of standard deviation were simply removed as outliers. Trials with left turn were simply mirrored, to collapse task performance across left and right turns. Then we classified all trails into three classes according to its signed pointing error. Trails with their pointing error in the range of ±0.5 standard deviation were labeled as well-estimation. Trials with their signed pointing error less than -0.5 and greater than 0.5 standard deviation were labeled as under-estimation and over-estimation.

B. EEG Analysis

The continuous EEG signals were analyzed by the means of MATLAB (The Mathworks, Inc.) and the open source EEGLAB toolbox (http://sccn.ucsd.edu/eeglab). The EEG signals were first down sampled to 250Hz for data compression and filtered to 0.5-50Hz by a low-pass filter with a cut-off frequency of 50 Hz to remove the line noise (60 Hz and its harmonic) and a high-pass filter with a cut-off frequency of 0.5 Hz to remove the DC drift. Signal intervals containing electrode noise, large bursts of muscle artifacts were identified by visual inspection using the EEGLAB visualization tool and eliminated to enhance the signal to noise ratio.

C. Independent Component Analysis

Independent component analysis (ICA) methods have been extensively applied to the blind source separation problem and also demonstrated that was a suitable solution to the problem of EEG source segregation, identification, and localization. [13-15]. EEG signals were transformed into statistical maximally independent components (ICs) accounting for eye blinks, other eye movements, or muscle artifacts according to their scalp maps and activity profiles. Only brain activity related ICs were selected for further analysis.

D. Event Related Spectral Perturbations (ERSP)

ERSP is a kind of time-frequency analysis, which was first proposed by Makeig [16], can reveal those time-locked but not necessary phase-lock event related activities. ERSP analysis transforms time-course signal into spectral-temporal domain by short term fast Fourier transform (FFT). Log power spectra were computed and then were normalized by subtracting the baseline (straight tunnel segment) log mean power spectral. Significance of deviations from power spectral baseline was assessed by bootstrapping, a nonparametric permutation-based statistical method. Non-significant points were masked as zero; only significant ($p<0.05$) perturbations were remained.

IV. RESULT

A total of 20 subjects completely finished this experiment. 11 of them were categorized into allocentric subjects, and 7 participants were categorized into egocentric subjects. The rest three subjects were not able to be classified into any category because their homing direction selections varied trials by trials

A. Behavior Performance

Fig. 2 illustrates the distributions of allocentric subjects' signed pointing error of all trials among three cases of tunnel degree (30°: 6.94±7.04, 60°: 0.01±9.60, 90°: -5.21±14.20). Fig. 3 shows the distributions of egocentric subjects' pointing error of all trials among three cases of tunnel degree (30°: 3.84±7.30, 60°: -4.29±9.43, 90°: -11.51±12.72). The pointing errors were in the range of [-20, 50] degrees. The mean pointing error revealed an overall bias to overestimate small and to underestimate large required pointing angles in both allocentric and egocentric subjects.

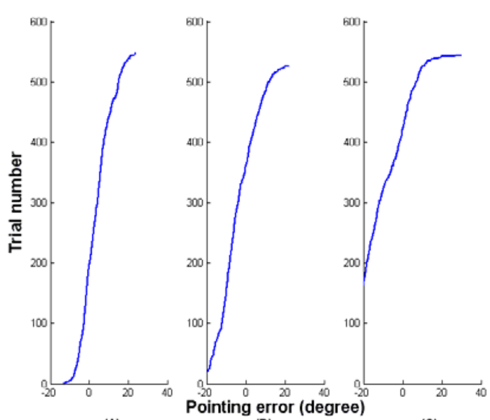

Fig. 2: The pointing error of allocentric subjects (A): turning degree of 30, (B): turning degree of 60, (C): turning degree of 90.

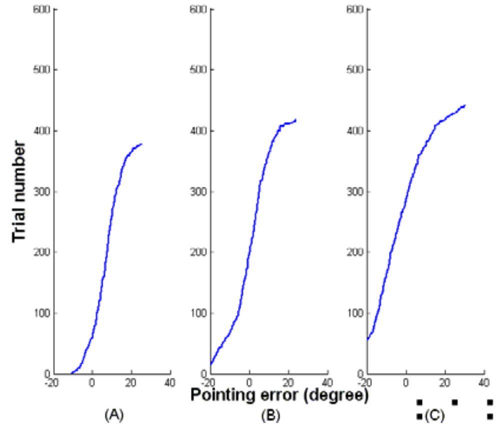

Fig.3: The pointing error of egocentric subjects (A): turning degree of 30, (B): turning degree of 60, (C): turning degree of 90.

B. The Performance related brain activity

Results demonstrated that the navigation performance related changes on brain activities were located in the parietal component of the egocentric subjects. For egocentric subjects, comparing to trials with well-estimation of homing angle, the power attenuation at the frequencies from 8 to 30 Hz (around alpha and beta band) was stronger when subjects overestimated homing directions, but the attenuated power was decreased when subjects were underestimated the homing angles. However, we did not found performance related brain activities for allocentric subjects, which may due to the functional dissociation between the use of allo- and egocentric reference frames. Fig. 3 shows the grand mean ERSP images of parietal component of egocentric subjects. Results showed that alpha and beta band powers slightly decreased during passing through the tunnel. Since the duration of tunnel passage is less than 10 sec, ERSP images here only showed the changes at the first 10 sec of the trails.

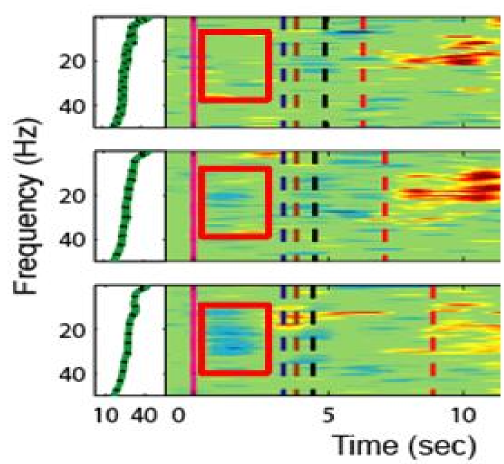

Fig. 4: The grand mean of the ERSP images of egocentric subject in parietal component for tunnel degree of 30. Top panel: ERSP of under-estimation. Middle panel: ERSP of well-estimation. Bottom panel: ERSP of over-estimation.

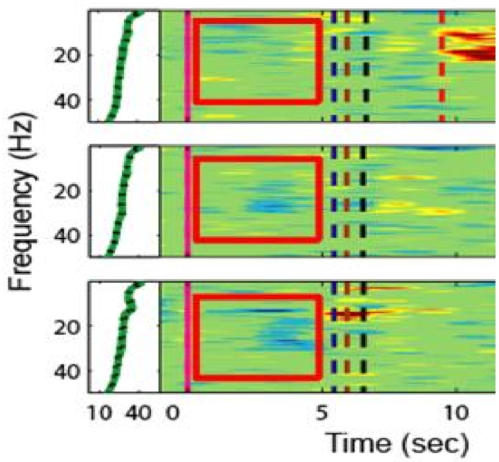

Fig. 5: The grand mean of the ERSP images of egocentric subject in parietal component for tunnel degree of 60. Panels were as Fig. 4.

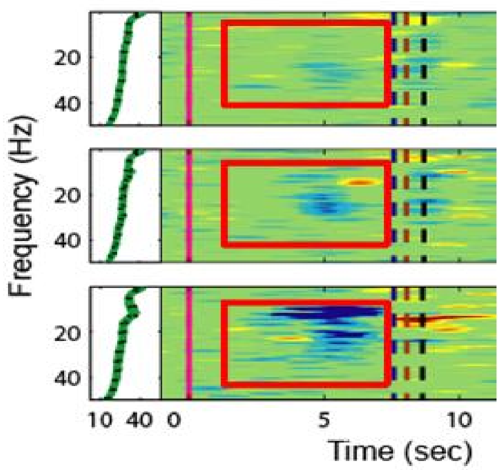

Fig. 6: The grand mean of the ERSP images of egocentric subject in parietal component for tunnel degree of 90. Panels were as Fig. 4.

V. DISCUSSION AND CONCLUSION

There has little direct experiment evidence for the correlation between the task performance and EEG data. Based on our past study, we designed an experiment to see whether there is a correlation between task performance and EEG data.

In this study, the relationship between the grand mean of ERSP of parietal component of egocentric subject and task performance is discovered. Alpha band power slightly decreased when subjects passing through the tunnel turn. Moreover, it is evident that the alpha band power strongly decreased in underestimated the homing angles among three cases of tunnel degree. However, we did not found performance related brain activities for allocentric subjects, which may due to the functional dissociation between the use of allo- and egocentric reference frames.

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