EEG analysis of the navigation strategies in a 3D tunnel task

Michal Vavrečka, Václav Gerla, and Lenka Lhotská

Faculty of Electrical Engineering
Czech Technical University, Prague
vavrecka,gerla,lhotska@fel.cvut.cz

Abstract. This paper focus on the analysis of the navigation task in a 3D virtual tunnel. We localized the neural structures responsible for egocentric and allocentric reference frame processing in horizontal and vertical plane and also analyzed specific segments of the tunnel traverse. We identified intrahemispheric coherences in occipital-parietal and temporal-parietal areas as the most discriminative features for this task. They have 10% lower error rate comparing to single electrode features. The behavioral analysis of navigation reveals that 35% of the participants adopted two types of egocentric reference frames in the vertical plane.

Key words: frames of reference, spatial navigation, EEG, 3D environment, coherence

1 Introduction

The human ability to represent space, orient in an environment, create spatial mental images and talk about the environment from various perspectives is related to the adoption of various frames of reference. The basic classification of the reference frames involves spatial coordinate systems based on egocentric and allocentric frames of reference [4]. In the egocentric frame the position of objects is encoded with reference to the body of the observer or to relevant body parts [5]. Spatial positions can also be coded in allocentric coordinates that are independent from the observer's current position.

The fMRI research in humans revealed differences between the utilization of egocentric and allocentric frames of reference. Committeri et al. [2] attribute egocentric coding mainly to the dorsal stream (BA 7) and connected frontal areas, whereas allocentric coding requires both dorsal and ventral regions. The recent fMRI study [6] implicates posterior parietal and frontal associated regions involved in processing the egocentric frame. Allocentric navigation is attributed to the specific parietal subregions and also to the hippocampal and retrosplenial region. These studies are based on a static stimuli experiments. Schönebeck et al. [8] researched reference frames in dynamic environment and conducted a task built in a virtual reality environment consisting of a traverse through a tunnel with straight and turned segments. Gramann et al. [10] replicated this scenario and recorded an EEG signal to identify neural correlates responsible for specific

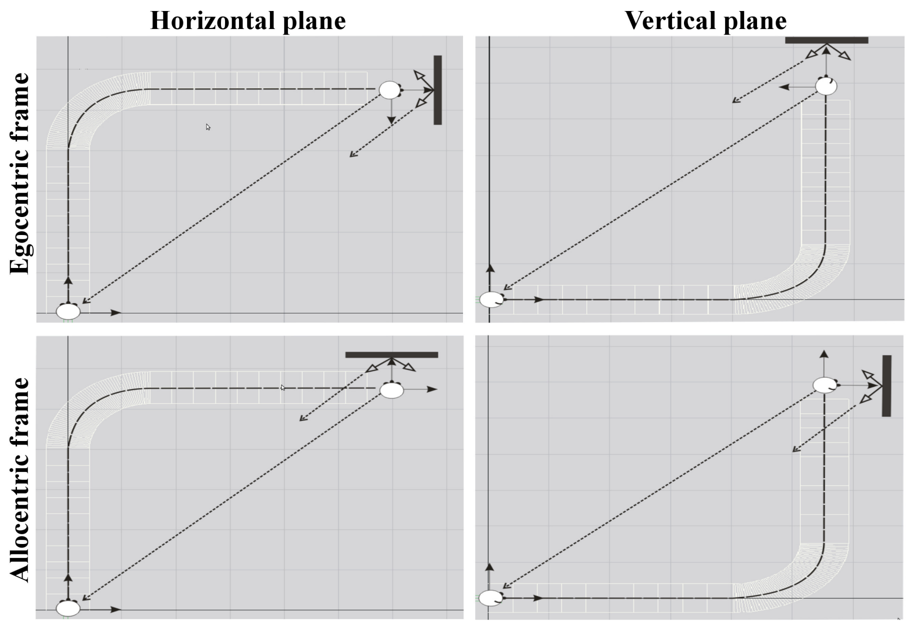

Fig. 1. Visualization of the tunnel task in a 3D environment. The head position is shown at the beginning and the end of the tunnel traverse for specific frames of reference (egocentric vs. allocentric) and specific planes (horizontal vs. vertical). The dark bar represents a computer screen with two arrows standing for the selection period.

frames of reference processing. They localized higher mean source activation in the BA 7 (parietal cortex) for subjects adopting an egocentric frame and BA 32 (anterior cingulate gyrus) for subjects adopting an allocentric frame of reference. In the most recent EEG research [11] based on the tunnel task, stronger alpha blocking was identified in or near the right primary visual cortex (BA 17) for subjects adopting an egocentric reference frame in the turned segment of the tunnel and stronger alpha blocking of the occipito-temporal, bilateral inferior parietal (BA 7), and retrosplenial cortical areas (BA 26,29,30) in the first straight and turned segments for participants adopting an allocentric frame.

Our research is the extension of the mentioned studies. We would like to compare the specific parts of the tunnel traverse in horizontal plane with Gramann et al. results [10] [11], but we want also to administer the tunnel task in vertical plane. Vidal et al. [9] administered a reference frame study in a 3D environment and concluded that the spatial updating process was more accurately performed for a terrestrial strategy (the head turns only in the horizontal plane) and to some extent a subaquatic strategy (the head turns in both the horizontal and vertical plane) than for a weightless (yaw and pitch turns) navigational style. Our goal is the identification of neural correlates responsible for the terrestrial navigation (resembling the allocentric strategy in the tunnel task administered in the vertical plane) and subaquatic navigation (resembling the egocentric strategy in vertical tunnels). We hypothesize different brain areas involved in processing of mentioned reference frames in the vertical plane.

2 Methods

The experimental sample consisted of 38 participants (7 females and 31 males). All subjects had normal or corrected-to-normal vision, they were under no medication affecting the EEG signal and were neurologically intact. The subjects were required to keep the track of their implied virtual 3D position with respect to their starting position within the tunnel traverse (see Fig. 1). A fixation cross was present for 6s prior to each trial. Each tunnel consisted of a 10s traverse through the first straight segment, 6s through the turned segment and 10s through the second straight segment. The bend of the turned passage varied between 30 and 90 degrees at intervals of 15 degrees representing the angular rotation of the participant's head. A total of 20 tunnels were presented to a subject, i.e. 5 tunnels with variable curvature for 4 directions (up, down, left, right). The tunnels were administered pseudo-randomly. There were two three-dimensional arrows displayed on the black screen at the end of each tunnel, representing the correct response within the egocentric or allocentric reference frame. The subject's choice is answers the question: what reference frame did he/she adopt as the navigation system. The answers were evaluated to identify the subject's preferred reference frame. Participants selecting the same frame of reference in above 80 % were considered as representative (native) users of the particular reference frame.

The EEG signal was recorded from 19 electrodes, positioned under the 10-20 system. We performed a visual inspection of each EEG signal prior to data analysis in order to detect obvious technical and biological artifacts. The signal was divided into the segments of constant length (1s), and the following parameters were calculated: statistical parameters, mean and maximum values of the first and second derivation of the samples and absolute/relative power for five EEG frequency bands. The EEG coherences, the correlation between the EEG electrodes, and the mean and maximum correlation values for each segment were computed. The wavelet transform was also applied to the signal segments. Daubechies 4 was used as the mother wavelet, and the signals were decomposed into 4 levels standing for standard EEG frequency bands. We also calculated the mean and maximum values of the wavelet coefficients obtained after applying the wavelet transform to the first and second derivative of the EEG signal. The data was processed in PSGLab Toolbox that is developed in our laboratory [7].

The next step was feature selection. The input matrix for each subject consisted of 1916 features (93 features per electrode + correlations and coherences) for the duration of the experiment. We employed PRTools [12] for this part of the analysis. We removed outliers and normalized the data. The features were individually evaluated using the inter/intra distance to preselect 50 best features. In the next step we applied forward feature selection algorithms to choose 5 best features from the preselected subset. Then we performed 7-fold cross-validation and employed naive Bayes classifier to calculate error rate of the best features.

3 Results

The administration the tunnel task in the vertical plane resulted in new navigation strategies compared to the horizontal plane. The experimental sample consisted of participants natively adopting the egocentric reference frame in both planes (24 %), participants natively adopting the allocentric frame in both frames (22 %) and participants adopting an egocentric frame for horizontal navigation and an allocentric frame for vertical navigation (11 %). Some subjects (30%) reinterpreted the instruction and did the mental u-turn at the end of tunnel and then adopted egocentric strategy. We also excluded 5 subjects (13 %) who answered randomly.

At the first stage we analyzed data from 17 participants adopting egocentric and allocentric strategy in both planes (9 egocentric and 8 allocentric frames of reference). The mean error rate of the best 5 features for both planes was 7.55 %. The dataset for whole tunnel traverse was split to the two subsets and the best features for the horizontal and vertical plane were calculated. The coherences in the theta and gamma band were the most discriminative features distinguishing egocentric and allocentric strategies for the horizontal plane, namely theta and gamma intrahemispheric coherence in the right temporal lobe and gamma coherence in the right frontal lobe. There were also interhemispheric coherences between the orbitofrontal electrodes in the theta band and the temporal electrodes in the delta band. The most discriminating features for the vertical plane were interhemispheric coherence between the temporal lobes in the theta band. Unlike the horizontal plane, there were intrahemispheric coherences between the right parietal and occipital area and the left temporo-occipital area in the beta band. A timeline of best feature (excluding coherences) is shown in Fig. 2. It can be seen that the group mean values differentiate between the navigation strategies.

We did also the analysis for the separate parts of tunnel. The best features for the first segment of the tunnel were concordant with the results for the whole tunnel, namely intrahemispheric theta coherences in left temporal lobe, beta coherence in the right parieto-occipital area and gamma coherence in left frontal lobe. The exception was the gamma activity in the left orbitofrontal lobe as the discriminative feature for the first straight segment. The best feature in the turned segment was the interferometric coherence in theta band between orbitofrontal electrodes. The other features were similar to the first straight segment. The same results were obtained for the second straight segment except the signal changes in the left temporal lobe.

The summarized differences between the allocentric and egocentric groups were visualized on scalp projections. Fig. 3 shows the mean activity in five spectral bands for allocentric and egocentric strategies (columns 1 and 2) and their difference maps (columns 3-8) for the specific planes or parts of the tunnel. There

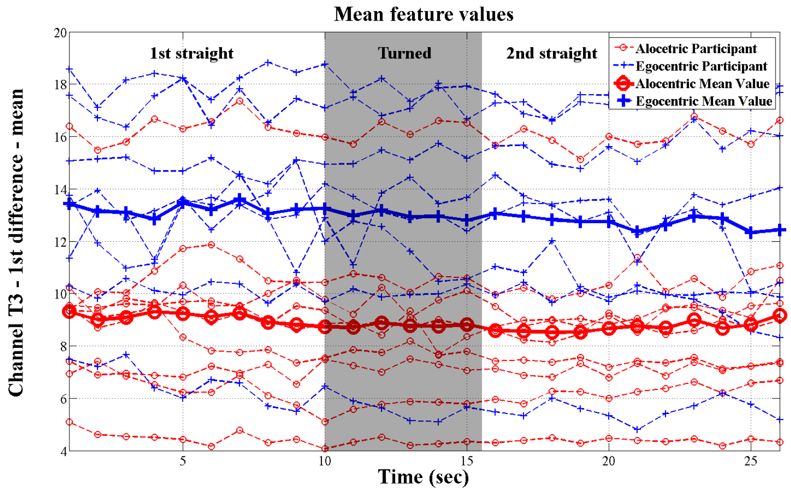

Fig. 2. Timeline of the best feature changes (coherences excluded) within a tunnel traverse. There is a visualization of the mean feature values for specific strategies and averaged feature values for each participant. The x-axis represents time in seconds, and the y-axis represents feature values.

are no visible differences between the horizontal and vertical planes (columns 4 and 5), but there is a change in the beta band activity for the second straight segment of the tunnel (column 8).

4 Discussion

The experiment revealed new findings regarding the adoption of egocentric and allocentric reference frames in a 3D environment. We identified native adoption of terrestrial navigation [9] (resembling allocentric strategy) in the vertical plane for the group of participants navigating egocetrically in horizontal plane. They represented body in the upright position at the end of the vertically oriented tunnels, so there was no angular rotation of the head direction. On the other hand none of the subjects adopted an allocentric frame in the horizontal plane and an egocentric frame (resembling subaquatic navigation) in the vertical plane.

The neurobehavioral results of our study are partially consistent with previous studies. Gramann et al. [10] localized higher mean source activity in BA 7 for the egocentric frame of reference, but the allocentric strategy was linked to activation in the anterior cingulate cortex (BA 32). A different type of analysis based on event-related spectral perturbations [11] revealed stronger alpha blocking in BA 17 for subjects adopting an egocentric reference frame in the turned segment of the tunnel and stronger alpha blocking in BA 7 and BA 26, 29, 30 for participants adopting an allocentric reference frame. We detected differences in beta band coherence in the left occipital-parietal lobe. The coherences were

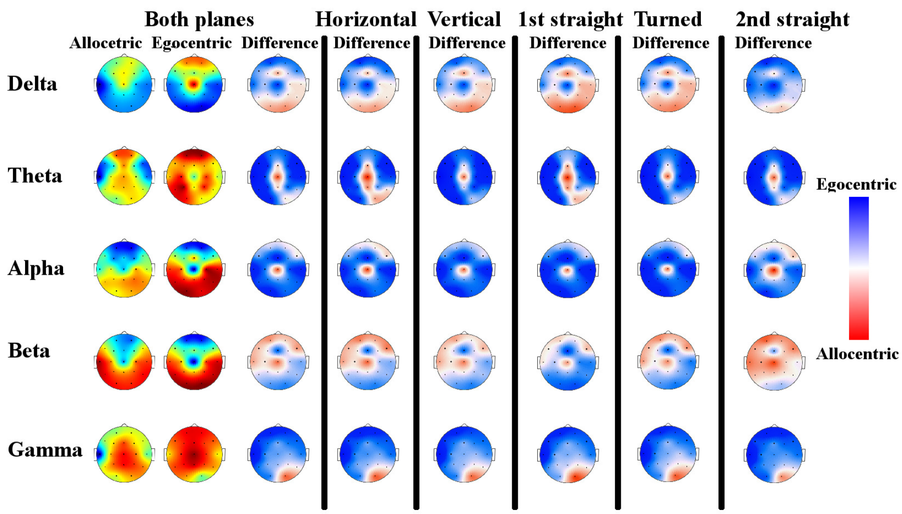

Fig. 3. Difference maps for the horizontal and vertical planes, and for both planes, and specific parts of the tunnel. The rows represent basic spectral bands. Average values for the egocentric and allocentric groups are given in columns 1 and 2. Columns 3-8 stand for difference maps. The values were calculated as the mean of all tunnel traverses.

higher for the allocentric strategy, but the detail analysis of beta activity in the separate electrodes (P4 and O2) revealed higher values for the egocentric group of participant. We can interpret this as coherent low beta activity in this electrodes for the allocentric frame of reference, but the egocentric strategy resulted in non-coherent higher activity in beta band.

The data for the horizontal plane indicates as the discriminative features intrahemispheric coherences in the gamma band in the left temporal lobe. Left intrahemispheric coherence in the gamma band stands for higher coherence of the egocentric group, but further analysis revealed higher gamma activity in both electrodes (T3-T5) for the allocentric group. We can interpret this as low coherent gamma activity for the egocentric frame of reference, while the allocentric strategy resulted in non-coherent higher activity in these electrodes. Gamma activity is associated with cognitive functions and multimodal integration. These results differ from the EEG study that adopts the tunnel task [10]. The list of best features also includes interhemispheric coherences but it is not possible to interpret the contralateral scalp locations in terms of brain structures, because they can reflect indirect, common/shared activity of the subcortical brain regions. In contrast to previous studies, we detected changes in the gamma band in the left frontal areas (electrodes Fp1 and F7) in horizontal navigation and also in vertical plane navigation. There was higher coherence for the egocentric strategy but analyses of specific electrodes revealed low coherent activity for the egocentric frame of reference and non-coherent higher activity in gamma band for the allocentric reference frame. The left frontopolar area is involved in memorizing tasks [3]. Thus, the difference in left frontal gamma coherence that we observed may be related to the different memory processing involved in the allocentric strategy.

At the next stage we compared the discriminative features for the horizontal and vertical plane. The differences between specific planes are manifested in the absence of theta coherence in the orbito-frontal cortex (Fp1-Fp2) for the vertical plane. It may be attributed to the lower number of eye movements in the vertically oriented tunnels. There is also a shift in theta coherence from T5 and T6 for the horizontal plane to T3 and T4 for the vertical plane. The most interesting observation is the absence of coherence in the beta band between P4 and O2 in horizontal plane. The results in the vertical plane cannot be compared with other EEG studies, as this is the first attempt to measure the frames of reference in a 3D environment.

We also compared results for the separate segments of tunnel traverse with the previous studies. For the first straight part of the tunnel Gramann et al. [10] research higher mean source activity in bilateral occipital-temporal network, with additional activation in frontal cortex for the egocentric frame and activation within a bilateral temporal-occipital network for the allocentric strategy. The similar activity for both strategies were located in BA 19,29 and 21. Our results revealed differences in the interhemispheric theta band coherences (T3-T4 and T5-T6) in terms of higher coherences for the allocentric strategy. From the spectral point of view we observed lower theta activity in both temporal lobes for allocentric group. There was also coherence in the beta band between P4 and O2 electrode and coherence in frontal left orbito-frontal lobe as a discriminative feature similar to analysis of the whole tunnel.

In the turned segment Gramann et al. [10] localized higher activity in fronto-parietal network (BA 7), with dominance over the left hemisphere for egocentric strategy and left anterior cyngulate gyrus (BA 32) for allocentric group. We localized areas similar to the first segment, but also coherence in theta band between orbito-frontal areas (Fp1, Fp2) in terms of higher activity for egocentric strategy. Theta activity is associated with the heading changes [1] so the differences between allocentric and egocentric group in theta band should stand for different processing in the turned segment. The analysis of the whole tunnel traverse in specific planes uncovered absence of intrahemipheric theta coherence in orbito-frontal areas for vertical plane that confirms our hypothesis about different eye movements for specific planes.

At the second straight segment Gramann et al. [10] attributed egocentric strategy to the activity bilaterally within a fronto-parietal network (BA 7) including regions that were activated both with the onset of the tunnel movement and during the turn in the tunnel passage. Allocentric strategy was manifested in right hemispheric activation pattern comprising the temporal cortex. We found similar set of features for this part of tunnel as for the turned segment. There were not difference in the theta coherence of frontal areas (Fp1-Fp2) that would confirm the eye movement artifact hypothesis for the turned segment.

5 Conclusion

Administering the tunnel task in the vertical plane provided new insights into the area of spatial navigation. We should conclude that there are differences in the EEG activity for the navigation in the horizontal and vertical plane. Future steps in our research will focus on the difference when two types of egocentric reference frame are adopted within navigation in the vertical plane in order to identify the neural correlates of these strategies.

6 Acknowledgment

This work has been supported by the Ministry of Education, Youth and Sports of the Czech Republic (under project No. MSM 6840770012 "Transdisciplinary Biomedical Engineering Research II") and GAČR grant No. P407/11/P696

References

1. Bischof, W. F., Boulanger, P.: Spatial Navigation in Virtual Reality Environments: An EEG Analysis. Cyberpsychology and Behaviour, 6, 487-496 (2003)
2. Committeri, G., Galati, G., Paradis, A.L., Pizzamiglio, L., Berthoz, A., LeBihan, D.: Reference frames for spatial cognition: different brain areas are involved in viewer-, object-, and andmark-centered judgments about object location. Journal of Cognitive Neuroscience 16 (9), 15171535 (2004)
3. Fuster J.M.: The Prefrontal Cortex, 2nd ed, Raven Press, New York (1989)
4. Howard ,I.P., Templeton ,W.B.: Human spatial orientation. Wiley, London (1966)
5. Galati, G., Lobel, E., Vallar, G., Berthoz, A., Pizzamiglio, L., Le Bihan, D.: The neural basis of egocentric and allocentric coding of space in humans: a functional magnetic resonance study. Experimental Brain Research 133, 156164 (2000)
6. Galati G, Pelle G, Berthoz A, Committeri G.: Multiple reference frames used by the human brain for spatial perception and memory. Experimental Brain Research, 206(2):109-120 (2010)
7. Gerla, V., Djordjevic, V., Lhotská, L., Krajča, V.: PSGLab Matlab Toolbox for Polysomnographic Data Processing: Development and Practical Application. In: Proceedings of 10th IEEE International Conference on Information Technology and Applications in Biomedicine (2010)
8. Schönebeck, B., Thanhauser, J., Debus, G.: Die Tunnelaufgabe: eine Methode zur Untersuchung rumlicher Orientierungsleistungen 48, 339364 (2001)
9. Vidal, M., Amorim M.A., Berthoz, A.: Navigating in a virtual three dimensional maze: How do egocentric and allocentric reference frames interact?, Cognitive Brain Research 19, 244258 (2004)
10. Gramann, K., Müller, H., Schönebeck, B., Debus, G.: The neural basis of egocentric and allocentric reference frames in spatial navigation: Evidence from spatio-coupled current density reconstruction. Brain Research, 1118, 116-129 (2006)
11. Gramann, K., Onton, J., Riccobon, D., Müller, H.J., Bardins, S., Makeig, S.: Human brain dynamics accompanying use of egocentric and allocentric reference frames during navigation. Journal of Cognitive Neuroscience, 22(12), 2836-2849 (2010)

12. Heijden, F.v.d., Duin, R., Ridder D. d. Tax, D. M. J.: Classification, Parameter Estimation and State Estimation: An Engineering Approach Using MATLAB. John Wiley & Sons (2004)