Electroencephalographic Correlates of Spatial Navigation in 3D Virtual Worlds

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Abstract: Human navigation heavily relies on the uptake and processing of spatial information. Here we present results from a high-density electroencephalography (EEG) study showing that subjects demonstrate stable proclivities for coding space based on distinct reference frames (egocentric or allocentric) even though the visual input is identical. Participants traversed virtual tunnels constructed from sparse visual flow and accomplished a homing task (‘*point-to-origin*’). Despite identical visual stimulation subjects displayed individually stable proclivities for an egocentric or an allocentric reference frame, which was also reflected in group-specific EEG dynamics. The results implicate that individual differences should be considered for the development of navigational aids in real and virtual environments.

1 Background

Information uptake and processing of spatial information are core prerequisites for spatial orienting, allowing humans to navigate within real and, to an increasing degree, virtual environments of various complexity levels, ranging from structured buildings to cluttered urban areas. Based on the processing of incoming perceptual information the navigator is able to build up enduring spatial representations of his surroundings, allowing him to remember routes, derive and execute shortcuts, and visualize the layout of a previously traversed pathway. One method to navigate within an environment is ‘*path integration*’ (PI), characterized as the ability to infer one’s current displacement from a given starting point by integrating the translational and rotational variation along the trajectory [MM82]. The spatial representation resulting from PI can be mounted within distinct but interacting spatial reference frames, defined as a ‘means of representing the locations of entities in space’ [Kl98, p.1]. Previous research of our group utilized a virtual 3D navigation task (homing, ‘*point-to-origin*’) providing evidence for human navigators to show an individually stable proclivity for navigating within either a self-centered *egocentric reference frame*, or an environment-centered *allocentric reference frame* [GMES05]. Whereas navigators of the former group code space based on the three intrinsically defined axes of their body (front–back, right–left, and up–down), the latter group mounts the origin and coordinate system externally (comparable to a map-like view, see Figure 1). Both groups not only differ in terms of behavioral performance but also with respect to physiological processes, i.e., electroencephalographic (EEG) brain dynamics during information uptake, consolidation, and retrieval [GMSD06].

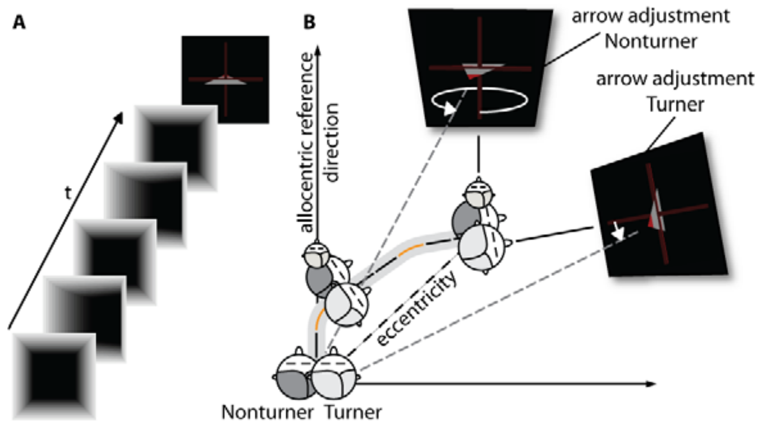

Figure 1: **(A)** Snapshots of the tunnel stimulation material. Subjects were instructed to imagine traversing the tunnel and subsequently adjust a virtual arrow to point directly back to the starting point; **(B)** Arrow adjustments of *Turners* (egocentric reference frame, light grey heads) and *Nonturners* (allocentric reference frame, dark grey heads). Ego- and allocentric reference frames are initially aligned but diverge with orientation changes along the trajectory. Therefore, the arrow adjustments of Turners and Nonturners differ by the angular sum of all turns encountered during the passage.

2 Results and Discussion

High-density 128-channel EEG recordings were analyzed by means of *Independent Component Analysis* (ICA) and subsequent clustering of independent component (IC) processes based on source location and brain dynamics during navigation, using the open-source software EEGLAB [DM04]. Concordant with previous studies, a wide-spread cortical network was found to be involved in navigation based on an egocentric and allocentric reference frame, including occipital, occipito-temporal, parietal, prefrontal and frontal areas. As can be seen in Figure 2, Turners showed more pronounced deviations from baseline activity in precuneus (Brodmann Area 7/31) mirroring the processing of translational and rotational information during curved tunnel segments from a first-person perspective. This area has been shown to be responsible for visuospatial coordinate transformations between various (retino-, eye-, and head-centered) egocentric reference frames [CT06].

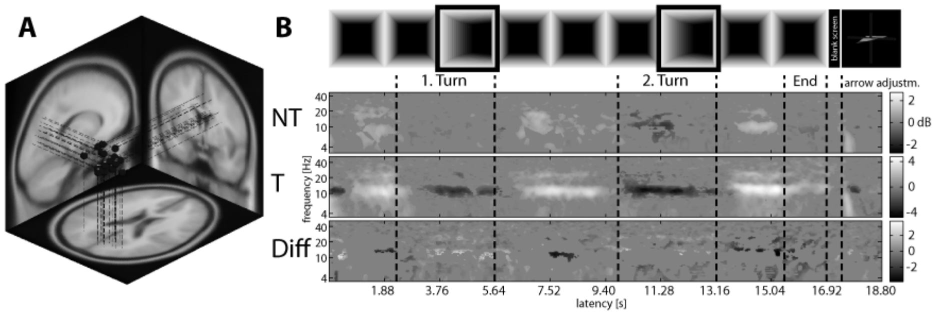

Figure 2: **(A)** Component cluster located in or near right (pre-)cuneus (Brodmann Area 7/31) revealing strategy-specific mean event-related spectral perturbation (ERSP) during the tunnel passage **(B)** for 8 Nonturner subjects (*NT*) and 10 Turner subjects (*T*). Bottom plot (*Diff*) shows significant differences between Nonturners and Turners (NT-T, bootstrapping with $p<0.05$). ERSP in dB for frequencies from 3 Hz to 45 Hz in log-scale. Medium gray indicates no significant ($p > 0.001$) difference in mean log power (dB) from baseline. Lighter and darker shadings correspond to significant increases and decreases, respectively, in spectral power from baseline. Important time points of the tunnel passage are marked with dashed lines, indicating the period when participants perceived and traversed the approaching turn (from 3.76 s); the time period during which the subjects were approaching the end of the tunnel, as well as the time point when the virtual homing arrow was displayed.

The use of distinct reference frames during spatial navigation is accompanied by specific brain activation patterns. Thus, programming of adaptive and intelligent navigational aiding systems (e.g., realized as augmented-reality application) should consider the navigators' intrinsic proclivities for coding space based on specific reference frames. Thereby, cognitive processing of as well as behavioral performance based on 3D spatial information can be facilitated by creating user-optimized conditions.

References

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