Neural Responses during Navigation in the Virtual Aided Design Laboratory: Brain Dynamics of Orientation in Architecturally Ambiguous Space

Eve A. Edelstein[1 4], Klaus Gramann[2], Jurgen Schulze[3], Nima Bigdely Shamlo[2], Elke van Erp[2], Andrey Vankov[2], Scott Makeig[2], Laura Wolszon[3], Eduardo Macagno[1]

[1] Division of Biological Sciences, University of California, San Diego
[2] Swartz Center for Computational Neuroscience, University of California, San Diego
[3] California Institute for Telecommunications and Information Technology, University of California, San Diego
4 HMC Architects, San Diego

Abstract: The cues that assist people as they navigate spaces and form memories of places, have direct relevance to the design of buildings, neighborhoods and urban settings. The means by which mental representations of cognitive maps are formed has been the subject of study by architects, psychologists, and neuroscientists alike. This project united the expertise and methods of these disciplines, exploring the brain's response to architectural cues, and wayfinding strategies in order to gain further insights into the processes associated with wayfinding, the feeling of being lost, and successful re-orienting. Brain activity was recorded while subjects moved through a realistic, human scale, 360 degree immersive 3D virtual environment. Event-related spectral perturbation of independent components (ICs) derived from independent component analysis (ICA) suggested differences in brain dynamics when subjects knew their orientations versus when they were lost. Ongoing studies continue to explore the synchronization of virtual reality (VR) scenes, paths of movement through, and high density electroencephalographic (HD-EEG) responses as a novel means to measure the neural foundations of navigation function in full-scale realistic environments. Unlike magnetic resonance imaging, which records earlier brain responses in prone, immobile subjects, this pioneering technology relates navigation events to concurrent brain responses while subjects move freely within the VR cave.

Keywords: navigation, orientation, wayfinding, virtual reality, electroencephalography, allocentric, egocentric, route following.

Background

A deeper understanding of the brain processes underlying the formation of memories may provide new clues to the design of more effective wayfinding strategies for complex built environments. Several decades of brain research describe the neural bases underpinning the formation of memories of space and place. Animal studies in the 1970s first demonstrated “place cells” within the hippocampus were responsive to both memories of events and of memories of a place. Cells within this region of the temporal lobe were responsive to an animal’s previous experience in a specific location, direction, and orientation (O’Keefe & Nadel, 1978). Recently Moser and colleagues discovered that memory of space also activates a hexagonal network of “grid cells” in the nearby entorhinal cortex in response to landmarks and self-motion, forming a neural system that associates memories of places and events (McNaughton et al., 2006). This process is thought to be involved in the transformation of place memories along with associated visual scenes, objects and events, to create a mental image of an environment, commonly termed a ‘cognitive map’.

Human brain recordings reveal similarities to animal studies. Brain activity measured via high-density electroencephalography (EEG) has been used to distinguish synchronous activity of distinct cortical brain sources involved during different navigation strategies. The alpha frequency band (8-13 Hz), has long been thought to reflect cortical readiness to process incoming information, and has been observed during complex maze tasks and during route planning periods. Moreover, recordings from patients undergoing surgery for epilepsy were consistent with animal studies, demonstrating similar place responsiveness to virtual scenes (Ekstrom et al. 2006) and (4-8 Hz) theta band activity during navigation tasks. The study of patients who become disoriented in urban environments and inside buildings may provide considerable insight into the neural processes that support the learning of spaces, and formation of memories as one moves through spaces, as well as the navigation strategies that lead to the formation of cognitive maps. Neuroimaging studies of patients with temporal lobe disorders demonstrate that some are unable to recognize or perceive landmarks. Others have no deficits in object or spatial perception, but cannot associate landmarks with directional information, relying heavily on maps and plans that they may draw for themselves (Aguirre & D’Esposito, 1999). Factors that influence memory—including dementia or Alzheimer’s disease—can also selectively affect memory involved in navigation tasks. With such knowledge, the selection of architectural cues may be better able to address the brain’s process during navigation.

Multiple processes are involved in storing and retrieving memory of routes between spaces and the geometric relationship of places. Subliminal recognition of visual object cues, and differential processing of relevant versus irrelevant landmarks are likely involved. Two commonly held theories have been proposed to describe how people navigate. Egocentric referencing pieces together memories of places along the route of travel, and was initially thought to be the basis from which geometric or allocentric “birds-eye” cognitive maps are formed. However, a cognitive sequence from egocentric to allocentric mapping may not be necessary, and that subjects differ in their relative degree of reliance on body-centered versus environment-centered reference frames (Wolbers et al. 2004) . During a computer navigation task, Gramann et al. (submitted) found blocking of posterior alpha activity during turns in those subjects using an allocentric reference frame, compatible with more intense cortical activation of occipitotemporal, parietal, and retrosplenial cortical areas supporting visuospatial orienting. In contrast, subjects using an egocentric reference frame had stronger alpha blocking in or near the right primary visual cortex. These findings are consistent with functional brain imaging studies and support the use of high-density EEG to track cortical patterns during navigation.

Such research suggests direct implications for design in that wayfinding systems may need to serve both of the above navigation strategies in order to meet the needs of different users. Navigation paths through complex settings such as large commercial buildings, urban environments, and academic schools and centers have great need for improved navigation cues. Wayfinding systems have value beyond the reduction of stress or anxiety so often experienced when one feels lost. Studies have noted the significant value of staff time recovered when users can find their own way through large campuses. McCarthy (2004) found that staff time used giving directions to lost patients was associated with 4,500 hours each year and an associate cost equivalent of $220,000 per annum. There is also a vital need for accurate and rapid wayfinding for both patients and medical staff in hospitals that tend to have highly complicated layout of pathways reflecting dense functional programs, rigorous operational requirements and requirements for the separation of public, private, and professional spaces. Of importance is consideration of the risk and benefit of design that makes obvious navigation paths obvious for the separation of clean spaces, particularly during infection outbreaks, such as in the SARS epidemic.

Methods

An increasing number of virtual reality studies have been conducted to predict how people move through spaces and remember places. Many such studies rely on theoretical modeling systems and others on simplified images of navigation paths that test wayfinding theories. In order to further investigate human navigation strategies, this study developed an interactive cave environment that presented realistic scaled renderings of actual architectural environments. Separate experimental conditions were created to compare behavior and brain dynamics in environments with no prominent visual cues versus environments that included rich visual cues. A wayfinding task was designed to test neural responses to ambiguous spaces (with no visual cues to direction or orientation) versus unambiguous spaces (where landmarks, architectural features, interior finishes, or color provided clear clues). Visual ambiguity was systematically controlled by varying the symmetry of the surrounding environment, lighting effects and shadows, or other visual cues that might serve orientation. The unambiguous rooms included exterior and interior statues and colored doors that clearly marked the entry to three rooms, each with different furnishing and functions. The ambiguous space comprised a double loaded corridor devoid of wall color, shadows, or objects. Thus, a subject positioned in the back corridor had no visual cues as to their location or orientation within the building, or the arrangement of the adjoining rooms.

Subjects were instructed to learn and memorize the location of all rooms and corridors during free exploration, and to demonstrate their knowledge via drawn plans before and after testing began. Each subject then completed 96 trials in which they navigated from the front lobby (unambiguous) or back corridor (ambiguous) toward stated goals in the adjoining rooms (in pseudo-random order). Tracking of the movement path assessed subject orientation via measures of behavioral responses including navigation errors, time to goal, and length of path to goal.

The interactive Virtual-Reality Aided Design (VAD) laboratory comprises a circular 15 panel dual projection 3D immersive environment that surrounds the subjects and enables interaction and movement within the rendering of built spaces. The test environment comprised a realistic, full-scale 3D rendering of the actual building on campus that houses the 360 degree 'StarCAVE'. Software was developed to playback the scene viewed by the subject as they moved through the virtual exercise.

High-density 256 electrode EEG was recorded using active electrodes (Biosemi, Netherlands) providing sufficient signal to noise ratio without interference from complex magnetic and electrical systems running the CAVE environment. The amplifier system was positioned in a backpack and connected via one fibre optic cable to a recording system outside the cave. The virtual environment was adapted to subject's movement by means of a electromagnetic motion capture system recording subjects head and hand movements. Software was developed to synchronize online 256 channel EEG, motion from sensors attached to the head and hand of the subjects, and the VR-data stream to track movement along the routes, the virtual cues and scenes observed as the subject moved through the rendering, and the physiological brain responses as the landmarks were encountered. All data streams were synchronized online and in real-time via a UDP network allowing for interactive rendering of the virtual environment while subjects navigated through the rendering. With such methods modifications to the visual features of cues and their location relative to the path and other cues can be explored in terms of their effectiveness in wayfinding design.

EEG data were analyzed by means of independent component analyses (ICA) and clustering on source location and time course of brain dynamics during orientation, using the software package EEGLAB developed at the Swartz Center for Computational Neuroscience, UCSD (Makeig et al. 2007). New signal and image processing systems allowed brain and muscle activities to be independently analyzed and localized as subjects moved during the task (Gramann et al. 2008).

Findings

An initial group of subjects were used to test and develop the system itself, and provided valuable information about procedures necessary to synchronize VR, EEG, and behavioral protocols. Analysis of the map drawings demonstrated slight improvements of map accuracy after the experiment as compared to the initial drawing. However, the environment used was relatively simple and subjects were able to draw an accurate map after a few trials of self exploration. The number of incorrect turning decisions showed a trend to be higher in subjects preferring an egocentric as compared to subjects preferring an allocentric reference frame. However, due to the small sample size the difference reached no significance.

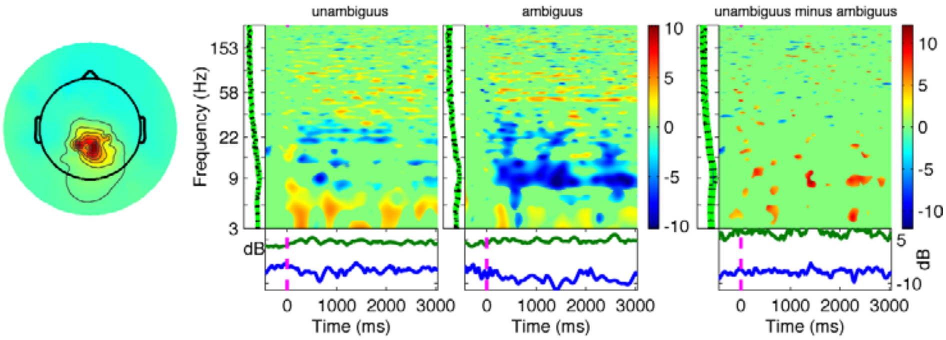

Figure 1. Independent Component Analysis of EEG responses in parietal brain region. Condition 1 shows event-related spectral perturbation (ERSP) for trials when the subject was cognizant of his position within the environment (front corridor) as compared to Condition 2 when the subject had no landmarks available for orientation. The left-most column shows significant differences between the two conditions (bootstrapping with $p<0.05$). ERSP in dB for frequencies from 3 Hz to 250 Hz in log-scale for a component localized in or near the superior parietal cortex (Precuneus, BA 7). Red colors indicate significant increases and blue colors indicate significant decreases in spectral power from baseline (time period before onset of the trial). Green colors indicate no significant difference from baseline activity.

A wide-spread cortical network was involved in navigation from a first person perspective including occipital, occipitotemporal, parietal, and frontal areas. Brain dynamics in a subset of these areas revealed significant differences between oriented and disoriented trials with most pronounced differences in the lower alpha and theta-band. When comparing the brain dynamics for epochs with starting positions in the ambiguous environment with starting positions in the unambiguous environment the results revealed differences in or near the parietal and occipito-temporal regions as indicated by equivalent dipole models using realistic boundary element head models (BEM). Figure 1 below exemplifies the difference in a wide range of frequencies for a component localized to the parietal cortex for a subject being disoriented as compared to when he knew where he was in the environment. (See Figure 1.)

Conclusions

The results indicated a progressively subtle use of visual cues as subjects navigated the ambiguous space. In the case where obvious cue were not presented, subjects looked for any distinguishing features that might indicate location, including shadows around doors, or patterned finishes. This suggests a continuum of cue effectiveness dependent on the surrounding context and the opportunity to repeatedly search for cues.

Brain dynamics accompanying navigation in the 360 degree VR environment from a first person perspective involved a network of cortical areas known to subserve spatial orienting. Differences in brain dynamics dependent on the ambiguity of the starting position were found in parietal and occipitotemporal cortex with significant stronger synchronization in the theta and stronger desynchronization in the lower alpha band. This pattern likely reflects the involvement of the parietal cortex in utilizing visuo-spatial information from a first person perspective and the involvement of parietal and occipitotemporal areas in processing heading changes and planning of future paths. Interestingly, disorientation was associated with increased alpha desynchronization likely reflecting increased attentional demands for processing less informative visuo-spatial information.

With further understanding of the neural sources associated with wayfinding, this interactive and synchronized VR / EEG system offers a novel means to test the effectiveness of cues to visual and spatial relationships in a virtual environment while mapping brain and behavioral strategies that may provide greater knowledge of cognitive mapping processes (Gramann et al., 2005; Gramann et al., 2006).

References

Aguirre GK, D'Esposito M. (1999) Topographical disorientation: a synthesis and taxonomy. Brain, 122, 1613-28.

Ekstrom A, Kahana M, Caplan J, Fields T, Isham E, Newman E, Fried I (2003) Cellular networks underlying human spatial navigation. Nature, 425,184-188.

Gramann, K., Bigdely-Shamlo, N., Vankov, A., Van Erp, E., Sejnovski, T.J., Poizner, H., & Makeig, S. (2008). Mobile High-Definition Brain Imaging of Brain and Muscle Dynamics During Orienting towards Learned Object Locations. Poster NSF-Site Visit, The Temporal Dynamic of Learning Centers, UCSD, San Diego, April 2008.

Gramann K, Müller HJ, Schönebeck B, Debus G. (2006) The neural basis of ego- and allocentric reference frames in spatial navigation: evidence from spatio-temporal coupled current density reconstruction. Brain Res,1118(1), 116-29.

Gramann K, Müller HJ, Eick EM, Schönebeck B. (2005) Evidence of separable spatial representations in a virtual navigation task. J Exp Psychol Hum Percept Perform, 31(6),1199-223.

Makeig S, Onton J, Sejnowski T, Poizner H. (2007). Prospects for mobile, high-definition brain imaging: Spectral modulations during 3-D reaching. Neuroimage, V1,S40.

McCarthy, M. (2004) Healthy design. The Lancet, 364, 405-406.

McNaughton BL, Battaglia FP, Jensen O, Moser EI, Moser MB. (2006) Path integration and the neural basis of the 'cognitive map'. Nat Rev Neurosci. 7(8), 663-78.

O'Keefe J. and Nadel L. (1978) The Hippocampus as a Cognitive Map. Oxford University Press. Oxford.

Wolbers T, Weiller C, Büchel C. (2004) Neural foundations of emerging route knowledge in complex spatial environments. Brain Res Cogn Brain Res. Nov;21(3):401-11.