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Real world ambulatory boundary effect within MTL oscillation during movement in human brains

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Abstract:

Through daily life, complex tasks require the neural encoding of spatial location for oneself and others. Previous research studies in rodents have shown that rodents have neural representations of themselves in addition to other rodents. (Ovchinnikov, 2010) However, there is still a need to understand how the human brain processes spatial location for itself and others. Furthermore, it is important to research which parts of human cognition can affect location encoding mechanisms. The current study uses existing data to determine the correlation between environmental boundaries and human brain activity. Using spatial observation and navigation tasks, the study investigated whether a physical boundary can affect neural encoding using implanted electrodes, representing the participants' location and others' location while in a closed environment. Results showed that representations were strengthened when the encoding of location had a greater behavioral significance and was contingent upon the momentary cognitive state of the individual.

Together, these findings support the existence of a shared encoding mechanism within the human brain that signifies the whereabouts of both individuals in communal settings. Moreover, they illuminate novel insights into the neural processes that govern spatial navigation and the perception of others in practical situations.

Keywords: human brain, MTL oscillation, boundary, Movement, self-navigation

Introduction

Previous studies have shown that environmental boundaries are critical for spatial cognition and forming memories in rodents. In this process, the environmental boundary is thought to assist them in navigation by eradicating noisiness. In human studies, boundary-related neural signatures have only been observed at the level of cell populations using, for example, functional magnetic resonance imaging and intracranial electroencephalographic (IEEG) recordings in participants that remained stationary throughout the experiment. Furthermore, these studies did not address another person's location encoding throughout the experiment. Therefore, gathering data during a real-world movement test is essential, as it can help explore the human brain's mechanism and spatial cognition for moving humans and observation others. Based on speculation, a human brain should generate more low-frequency oscillatory power when the participants approach the boundary: walls. We hypothesized that the human brains should generate an increase in low-frequency oscillatory power when participants approach the boundary (i.e., walls in the room). Based on past studies, the theta wave, considered a low-frequency oscillation, is related to navigation and spatial memory. (Schater, 1977) In addition, increased theta power was observed during tasks that required memory and spatial cognition.

Methodology

Five participants who completed the study were between the ages of 31 and 52 years old. Previously, they had already been implanted with RNS systems for epilepsy. To mitigate the influence of a subset of individuals, we conducted individual analyses of boundary-related oscillatory power changes for each participant. Our findings revealed that the effects were uniform among all participants, as each exhibited the anticipated pattern of outcomes.

Tracking the location and orientation of both the participants and the experimenter was achieved through the utilization of the OptiTrack system and the OptiTrack MOTIVE application during the observation task. A total of twenty-two high-resolution infrared cameras were affixed to the ceiling to monitor the whereabouts of a rigid body-position marker consisting of reflective markers affixed to the headwear of both the participants and the experimenters. The sampling frequency of these cameras was set at 120Hz.

Throughout the study, a supplementary camera from the motion-tracking system captured a wide-angle video of the room.

Movement speed was determined by quantifying the positional change in the horizontal plane (x/y coordinates) between two sampling sites using the motion-tracking data. Between two sampling locations, angular velocity was measured as angular displacement in the horizontal plane (yaw). Acceleration was measured as the variation in the velocity of motion between two locations of sampling.

To differentiate periods of movement from non-movement (standing), we categorized periods with movement speeds equal to or exceeding 0.2 m s−1 as movement periods, and those with movement speeds below 0.2 m s−1 as periods of no movement. This classification was implemented to accommodate residual head movements that do not correspond to changes in position. Movement-onset time points denote intervals during which the velocity of a given object transitions from “no movement” (less than 0.2ms−1) to “movement” (at least 0.2ms−1) and then remains at or above 0.2ms−1 for a minimum of one second.

To differentiate between movements toward and away from boundaries, we initially determined the distance to the nearest boundary for each sampling point. Subsequently, we computed whether this distance acclimated to a change (‘towards boundary’) or a rise (‘away from boundary’) between two sampling points.

The self-navigation and observation task

All participants completed the task in a rectangular room. Each participant was asked to start a 15-minute self-navigation task and follow up with another 15-minute observation task. The room had 20 signs, each with a specific color and numbers 1 to 5, all attached to the walls. Three circular but invisible target locations, each designated by a letter, were randomly positioned in the room. Each participant was given a command to walk to one specific sign and search for a hidden target location. All participants’ movements were monitored in real-time through the camera, which was mounted on the walls.

The self-navigation and observation task.

Each participant sat in the corner of the room and observed the experimenter walking around. The participants were instructed to track the experimenter’s location and press the button whenever the experimenter crossed one of the hidden target locations. The experimenter must follow a predefined path, which was instructed by a computerized voice through an in-ear Bluetooth headset, which is not audible to the participant performing the observation task.

Using the Pupil Core headgear for mobile eye monitoring (Pupil Labs GmbH), eye-tracking data were collected. The movement of the pupil was recorded at an approximate frequency of 200Hz with a 0.6° accuracy. This enabled the position of the pupil to be determined at each time point within a normalized two-dimensional reference frame measuring 192 pixels by 192 pixels (a video of the eye). The data were imported using Pupil Player and captured using the Pupil Capture application.

To discern saccades from fixations, the experiment uses the Cluster Fix utility for MATLAB at each time point. This tool distinguishes between the two types of eye movements by employing a k-means cluster analysis on the distance, velocity, acceleration, and angular velocity of the eye movements. The fixation and saccade prevalence were quantified as the proportion of the total duration of the experiment during which fixations and saccades were observable, expressed as a percentage.

Electrode Localization

All participants underwent postoperative cranium computed tomography with high resolution. By co-registering this computed tomography image with a preoperative high-resolution structural magnetic resonance image (T1- and/or T2-weighted sequences) for every participant, the exact anatomical location of every electrode contact was ascertained. A diversity of MTL regions contained recording contacts, such as the perirhinal cortex, entorhinal cortex, para-hippocampal cortex, and hippocampus.

Data analysis

All data gathered from experiments were quantitative data from iEEG recordings. MATLAB was then used to process and analyze the recorded data. A time-frequency test was conducted by the BOSC toolbox, which focuses on individual frequencies between 3 HZ and 90 HZ. The BOSC detection enables the calculation of power and detection of significant oscillations by inputting the raw signal and sampling rates. Oscillatory power was calculated for specific frequency bands and normalized by z-scoring for each recording channel. Significant oscillations were detected for frequencies between 3 Hz and 20 Hz, with prevalence defined as the percentage of time these oscillations were observed.

Behavioural Task Performance

For the self-navigation task, we calculated a participant’s ‘detour’ during the ‘target search’ period. In the observation task, performance was quantified by the distance between the experimenter’s location and the nearest target location at the moment of a participant’s keypress. Trials were classified as ‘high’ or ‘low’ based on a median performance split during all trials.

Data Subsampling and Statistical Comparisons

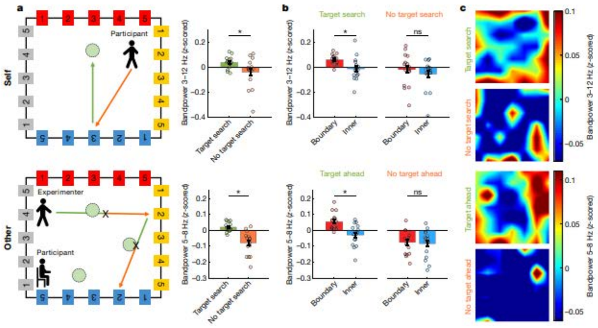
Data were subsampled to correct for potential differences in the amount of data between' boundary' and' inner' room areas to enable reliable statistical comparisons between 'boundary' and 'inner' room areas. One-sided permutation tests with 10,000 permutations were used for statistical comparisons, with a procedure to compare two paired arrays of values or determine if the mean of a variety of values is significantly different from zero. Heat maps displayed band power differences across the room area, smoothed using MATLAB's 'interp2' function.

Results

Having observed effects in both the theta and gamma frequency bands, we investigated the possibility that gamma oscillations were accompanied by theta phases, as was observed in prior research. Theta gamma coupling was most pronounced during self-navigation for the 6–10 Hz theta phase coupled to the 60–80 Hz gamma amplitude. During navigation, a comparable pattern was observed; nevertheless, theta oscillations seemed to be accompanied by gamma amplitudes at lower frequencies (40–60Hz). Moreover, the gamma amplitude was most significantly correlated with a theta phase of around 90 degrees, and self-navigation and observation both utilized this 'preferred' theta.

In conclusion, our findings indicate that oscillatory activity in the human MTL is influenced by the spatial location of both the subject and another individual.

In particular, the theta and gamma oscillatory powers of an observer increase when that observer approaches a boundary in close proximity to another individual, irrespective of the observer's own position. To the best of our understanding, these results present the initial indications of a mechanism within the human brain that encodes the spatial location of another individual. Such a mechanism would be crucial in shared environments and social situations where it is essential to monitor the whereabouts of others.



Discussion

Our results show that oscillatory power is higher in magnitude when the participant approaches the boundary. During the observation task, the results were similar. Oscillatory power increased when close to the boundary. A clear trend is that the band power from 60-80 hz remains high during the standing periods. The power of low-frequency oscillations was considerably greater during instances in which subjects were in the interior room region than when they were near a boundary (defined as being less than 1.2 meters away from the wall). Notably, a comparable outcome was observed during the observation task: the experimenter's position influenced the MTL activity of the seated participants, with considerably more pronounced oscillatory power observed during intervals when the experimenter approached a boundary in comparison to the interior space. The effect was most pronounced in the theta frequency band during both self-navigation and observation; for the observation task, the strongest 'boundary' versus 'inner' power differences were observed between 5–8 Hz, whereas for self-navigation, a slightly broader frequency band (approximately 3–12 Hz) was observed (both self-navigation and observation, $P<0.001$) The variance in time allocated to the 'boundary' and 'inner' room areas did not provide an explanation for boundary-related oscillatory effects. This was because the quantity of data in each condition was controlled for in all analyses through the iterative selection of random subsets of size-matched data. Oscillations of theta were segmental and occurred intermittently (10–20% of the time). In contrast, there was no significant increase in the occurrence of these bouts in the vicinity of boundaries. This indicates that the increases in boundary-related theta power were primarily caused by a rise in oscillatory amplitude and not by the prevalence of bouts.

The participant perceived the experimenter's linear motions as consisting of two phases, each with a distinct behavioral significance: initially, "target ahead" periods, during which the experimenter approached a presumed target location and encoding the momentary location of the experimenter was critical for task completion (i.e., determining when to press the button); and secondly, "no target ahead" periods, which occurred subsequent to the experimenter passing a presumed target location. It was observed that the theta power of the participants was considerably greater prior to the experimenter striking a presumed target location, as opposed to a period following the experiment when no presumed target was ahead ($P<0.001$; nCh = 16). Additionally, the theta power of the 'boundary' and 'inner' regions varied prior to a presumed target location but not after it. Therefore, it is conceivable that boundary-related oscillatory representations of location for oneself and others are more pronounced during periods when encoding one's momentary location is more behaviourally significant: 'target search' and 'target ahead' periods necessitate ongoing updating and encoding of one's positional estimate (relative to boundaries or other positional cues) in order to execute the task accurately, in contrast to the comparatively less cognitively demanding task of walking towards a target.

Conclusion

The hypothesis was proved to be correct. The low oscillation rate (theta power) was proven to become stronger when the participant was close to the boundary. The experiment has provided evidence to support the statement that oscillatory activity in the medial temporal lobe was modulated by proximity to room boundaries during the self-navigation and observation tasks. More specifically, the low frequency of oscillatory power increased. At the same time, the participant or the experimenter approached the near room boundaries, which is that they were less than 1.2 meters from the wall. The trend for increased low-frequency oscillation remained consistent across the participants and was not influenced by the time spent near boundaries.

Besides that, the theta power was higher when participants searched for hidden targets than when they were not. Another similar result was shown during the observation task, where theta power was higher before the experimenter reached a target location. These results show that the boundary-related oscillatory representation was stronger when the participant encodes another participant's momentary location. In summary, the research provides evidence that human MTL oscillatory activity is influenced by an individual's proximity to boundaries and cognitive state, emphasizing the role of theta oscillations in spatial navigation and awareness. The findings suggest that the brain encodes spatial information about oneself and others about environmental boundaries, which is critical in tasks involving spatial navigation or tracking others' locations in shared spaces. However, a limited number of things could be improved in this research. The research has claimed to perform "real-world" ambulatory movement, but the experiments are controlled (finding hidden targets). Actual real-world ambulatory movements might be more complex. However, creating an experiment that copies real-world movements is impossible and impractical. Future studies can emphasize how other regions of the human brain can have an impact on navigation and memory, such as the prefrontal cortex or hippocampal formation, interact with the MTL during spatial navigation tasks.

Citation

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