The Role of the Hippocampus and Parietal Cortex in a Rule-Based Environmental Fragmentation Study

by

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Abstract

The purpose of this paper is to primarily investigate the hippocampal encoding of environmental sub-spaces in rodents when the animals were trained to learn a behavioral rule of fragmenting (i.e., mentally dividing or separating) an environmental space. Spaces are defined by the boundaries of the observable environment, relying on visual cues situated at various parts of an enclosure to create different frames of references. Humans are capable of navigating a space using abstract, internal cues when visual, external cues are absent. Therefore, rodents should also be capable of generating behaviors that are evident of fragmentation. The parietal cortex and hippocampus are two regions of the brain that are known to be highly implicated in mapping out spaces in both humans and rodents, which makes these the regions of interest for electrophysiological recordings because they map out the space of the route and space of the room or place, respectively. The behavioral data show that the rodents can learn the rule to mentally fragment a space. The neural firing patterns of the hippocampus follow the reference of the route (i.e., the track of the maze), which was unusual. Taken together, the behavior of the rodents as well as the firing patterns of the neurons are indicative of the animals having learned the rule of fragmentation.

Keywords: learning and memory, fragmentation, hippocampus, parietal cortex, rodents
In 1930, psychologists Tolman and Honzik discovered that learning occurs even when there is no reinforced exposure to a stimulus (Tolman & Honzik, 1930), which contradicted behaviorist interpretations that was dominating the field of psychology during that time. The design of Tolman and Honzik’s study comprised of three different groups of rats that navigated from the start to the end of a complex maze: Group 1 was always given a food reward at the end of the maze; Group 2 was never given a food reward at the end of the maze; and Group 3 was given no food reward for the first ten days, but was given a food reward on the eleventh day. During the first ten days, the researchers observed that the rats in Group 1 had the lowest average error rate and the highest average speed when running from the start to the end of the maze. When the rats in Group 3 were first introduced with a food reward on the eleventh day, they immediately decreased their average error rate and increased their average speed when compared to those averages in Group 1 for the next following days during training. Tolman and Honzik’s experiment provided evidence that because the rats in Group 3 were given ten days to wander to the end of the maze with no incentive, they were able to learn the configuration and route of the maze in the absence of a reinforcer (Jensen, 2006). Tolman supported this claim with another experiment (1938) that ultimately proved that rats were able to make a choice on a four-arm maze, and that this behavior was reflective of having a cognitive and spatial map in the brain for where the food reward was located on the maze. Initially, the rat was given time to freely explore the maze. When placed at a specific arm of the maze during training, the rat learned that every time it turned right, it found a food reward. From the perspective of behaviorism, it was predicted that after training on the same arm of the maze, Tolman’s rat would continue to make a choice of turning right to “get to the reward” even after it was placed on a different arm of the maze that would require a left turn in order to receive the food reward. When Tolman placed the
rat on a different location of the maze, the rat navigated directly to the reward with no errors. This result proved that the expected behaviorist outcome was incorrect and that the rat did indeed held a cognitive map of the maze in its head, and this spatial knowledge helped it to navigate to the food reward effortlessly despite being in a different arm of the maze.

A cognitive map was a term coined by Tolman and described the ability to commit the mental image of a learned environment to memory. This ‘map’ could then be recalled later to navigate through the environment. Given the apartment example as Desi explained, we want to know how the mental fragments contribute to information encoding process. However, a lot of the evidence was still behavioral and we still did not know the mechanisms behind the maps, such as what cells, pathways and brain areas that allowed us to have an internal map of our environment. The purpose of this research is to determine what is happening at the cellular level in the brain as we move through these spaces.

Observing behavior is important, but it cannot thoroughly explain the mental processes executed by the brain during psychological experiments. Therefore, more modern styles of experimentation relied less on introspection and were able to acquire data that were more valid and credible (Stemberg, 1969). Scientists today are able to compare the behaviors of rodents’ cognitive map with the neural form of spatial maps using electrophysiological recordings in the hippocampus, a structure in the brain that has a role in organizing memory in manners of space and time, as well as in the posterior parietal cortex, which has importance in mapping out the track or route during navigation.

The discovery of the cognitive map spurred interest in how spatial environments were encoded by the brain, leading to the discovery of place cells in the rodent hippocampus in 1971 by O’Keefe and his student Jonathan Dostrovsky. Place cells are located in the dorsal
hippocampus, and place fields are approximately the same size as the rodents and are areas where firing of neurons occur frequently. In the intermediate hippocampus, the place fields grow larger—as long as 10 m in length in most ventral areas. Place cells of the hippocampus are known to refer to the frame of reference of the environment. The place cell is a type of neuron in the hippocampus that fires whenever the rat is in a particular place in the environment, which is called a place field. Because each place cell fires for a specific place field, there can be multiple place fields within an environment, as shown on the top right figure. Head direction cells, place cells, and grid cells all have frames of references.

The route is defined as inflection points in behavior or orientation and the distances between them. The hippocampus is different from the parietal lobe in that it has more fields and different frames of reference. The parietal lobe encodes spaces of the route whereas the hippocampus place cells are modulated by the route being taken. That is, the activity for the place in the environment. Firing activity follows the route when cells are recorded in the parietal area.

The parietal cortex is also heavily implicated in spatial navigation. Nitz (2006) showed that the animals can run on the same route from different points in the room, therefore parietal cortex would map out positions in the route, meaning the activity is in a route-centered frame of reference.

The objectives of the study thus involve generating the behavior evident of fragmentation, and finding where in the brain fragments are encoded and determine the form.

**Method**

**Subjects**
Three adult, male Sprague Dawley rats served as the laboratory subjects. Reported data of neural firing patterns are only from two rats.

**Apparatus**

**Functions.** A T-shaped maze (T-maze) was used for the purpose of meeting two functions: 1) to impose the behavioral rule by satisfying the simplest conditions for the rule; and 2) for practicality in giving only two choice-point possibilities which allows for splitting the training room into two compartments. The T-maze also allowed the rats to run many repeated trials of every position throughout the training day.

**Dimensions.** The T-maze was constructed with a round platform attached to end, where the animal was placed during the first trial of every block of a new position and where the animal also returns to after each trial. There were two L-shaped barriers placed at the corners of where the stem of the T and the side of the T meet. The purpose of having the L-shaped barriers on the maze was to prevent the animal from physically cutting corners to one choice of the T and to ensure he runs straight the entire time he is on the stem of the T. The dimensions of the L-shaped barriers measured 2.5 in. x 2.5 in. (length x width) on the side of the T, and measured 3.5 in. x 2.5 in. on the stem of the T (Figure 1A). The entire T-maze was 1.75 in. above the ground, since there were five 1.75 inch-high wooden wedges glued underneath the stem of the T and the sides of the T to give the maze support. The sides of the T measured 26.38 in. x 4 in. x 1.7 in. (length x width x height). The stem of the T measured 4 ft. x 4.25 in. x 2 in. (length x width x height) (Figure 1B). The diameter of the circular platform was 7.25 in., making the circumference 22.78 in. and the area 41.48 in. (Appendix 1).

**Training**
Animals were gently handled and taught to eat a cereal reward (Honey Nut Cheerios®) for 5-10 weeks prior to training. The animals were familiarized to the track environment in a dimly lit room and habituated to the maze apparatus by being placed on it for several times with scattered cereal pieces on the surface of the maze. They were trained to run from one end of the maze to the other end by having experimenters slowly removing available cereal pieces from the central portions of the track. They were trained by approximation to make ballistic runs from the bottom of the maze stem to the arm of the T-maze, where the animals were trained to perform a decision making task. The training consisted of random blocks of five trials at one of four positions: position 1 (Pos1), position 2 (Pos2), position 3 (Pos3) and position 4 (Pos4) (Figure 2). The food reward was given contingent on the animal choosing the correct side of the crossing T to go to (i.e., when he either makes a left turn or a right turn at a specific position). Pos1 and Pos2 demanded a left turn, whereas Pos3 and Pos4 required the animal to make a right turn. Thus, the behavioral rule determined the receipt or non-receipt of the reward, and effectively split the room into two fragments; this created an invisible rule-determined border line that lies directly between Pos2 and Pos3. The number of blocks was slowly increased to a total of 28, making a total of 140 trials a day that the animal has to run. The 28 trial blocks are split into 7 sets of 4 blocks within each such set, and each of the 4 positions was utilized according to a random assignment.

When performance on the first trial of each block was found to exceed 80% correct, further platform positions were brought into play. These included positions or platforms Pos5, Pos6, and Pos7 (Figure 3), which were experienced by all animals in that order.

The reason that Pos5, Pos6, and Pos7 were used was to prove that the rat was not just simply remembering which side to turn. When the animals were trained on Pos1, Pos2, Pos3, and
Pos4, the percentage correct may show that they have learned the rule, but it was also possible that the animals have learned four different associations between the positions and turns. For example, when they reach the decision point and see the view of the environment from Pos2, they know to turn left. From this perspective, Pos 1 and Pos 4 have nothing to do with each other. Thus, the initial reactions and turns the rats make at Pos, Pos 6, and Pos 7 are informative as the whether they have learned the rule based fragmentation, or is just using a simpler set of four associative learning rules.

**Surgery**

Once the rats’ performance achieved a hit rate that was significantly above chance at all positions (i.e., having reached a certain criteria of 80% correct over 9 consecutive days), the animals were prepared for the electrophysiology component of the experiment.

**Electrophysiology**

We record from the posterior parietal cortex and the CA1 subregion of the hippocampus. Therefore, the electrodes were placed stereotaxically centered on posterior 3.8 mm, lateral 2.2 mm over the course of recording days. The electrodes are slowly descended over the course of recording days to pick up single neurons.

**Behavioral Data Analysis**

**All Trials Performance.** The data for the three animals’ performance for turning correctly (i.e., left turn for Pos 1 and Pos 2, and right turn for Pos 3 and Pos 4) at all four positions will be assessed. The data will also be analyzed for the animals data averaged together.

**First Trials Performance.** In order to testify against the argument that the animals are simply learning four independent associations, we separated the performance to specifically analyze the performance for percentage correct at all positions for only just the first trials.
**Pos1 and Pos4 vs. Pos2 and Pos 3.** To further support our claim that the animals have learned the fragmentation rule, we compared the percentage correct of their performance for turning either left or right for Pos1 and Pos 4 to Pos 2 and Pos 3.

**Performance at first trials for Pos5, Pos6, and Pos7.** To prove that the rats have learned the fragmentation rule, the performance for the first time the rats are introduced to new potions will be recorded. These new positions are Pos5, Pos 6, and Pos7.

**Neural Data Analysis**

**Firing Activity of Parietal Cells.** We examined cells that were consistent with findings that the parietal cortex maps out space as the animal progresses through the route or track space. We also looked for action specific cells as well as action planning cells, which was unexpected.

**Firing Activity of Hippocampal Cells.** For the hippocampal place cells, we expected to see neurons firing according to the reference frame of the room or environment. Instead, we found three examples of neurons with unexpected and unusual firing activity patterns. These include neurons with high firing activity for just the first trials of each position, place cells that actually fire with the reference frame of the track instead of the room, and the neurons that change in their in-field firing rates as we move the positions.

**Population Correlation Matrices.** We looked at the population of the neurons as a whole. Does the population activity reflect the patterns we see in single neurons? How do the hippocampus and parietal cortex differ in firing? We used an analysis called the correlation matrix. We divided the track space into 100 bins that are the same points for each position. We compare the average firing activity in each bin in one position to the average firing activity in each bin to another position. The diagonal represents the same point on the track for 2 different positions in the room.
Results

Behavioral Data

All Trials Performance. The results show they perform significantly above chance at all four positions (Figure 4A). When the animals are averaged together, the However, this data may be the case that the animals are only learning four independent associations and have not actually learned the rule. (Figure 4B).

First Trials Performance. We separated the performance to specifically analyze the performance for percentage correct at all positions for only just the first trials. Even when separated, the animals perform significantly above chance (Figure 5A). Pos2 and Pos 3 are slightly worse than Pos 1 and Pos 4, but the rats are still performing well and that is also true when the data is averaged across the three animals (Figure 5B). If the rats were only guessing, then the first trial data would only be at 50% for all positions, which is not the case.

Pos1 and Pos4 vs. Pos2 and Pos 3. We find in our results that the percentage correct of their performance for turning either left or right for Pos1 and Pos 4 to Pos 2 and Pos 3 were all significantly above chance for all three rats (Figure 6A). When averaged together, we see that the performance for Pos1 and Pos4 are statistically significantly higher \( p < 0.05 \) than that of Pos2 and Pos3.

Performance at first trials for Pos5, Pos6, and Pos7. The rats performed 89%, because one rat was unable to correctly choose the correct turn for one of the positions.

Neural Data

Firing Activity for Parietal Cells. We examined cells that were consistent with findings that the parietal cortex maps out space as the animal progresses through the route or track space. We also looked for action specific cells as well as action planning cells.
**Firing Activity for Hippocampal Cells.** For the hippocampal place cells, we expected to see neurons firing according to the reference frame of the room or environment. Instead, we found three examples of neurons with unexpected and unusual firing activity patterns. These include neurons with high firing activity for just the first trials of each position, place cells that actually fire with the reference frame of the track instead of the room, and the neurons that change in their in-field firing rates as we move the positions.

Again, the blue bins represent the average firing activity for the point on the track, and the y-axis is the rate of firing activity. The magenta line represents the average firing activity for only the first trials for that point on the track. The blue represents the overall mean for all the trials. We can see that for all positions, the first trials fire at a higher rate than the overall mean.

Because we know from the literature that place cells map out the space of the room, we expected to see that in our analysis. However, we were surprised to see that the cells were actually mapping out the space on the track, similar to what the cells in the parietal cortex are doing. This second piece of surprising evidence shows that the hippocampal place cells are doing the same thing as the cells that map out route in the parietal cortex.

Despite this surprising finding in the hippocampus, it appears that many of the cells that traveled with the track differed in their in-field firing rates. What we see is that when the animal is entering a different space, which are the four different locations where the positions are in, the hippocampus can change in how much the cells are firing. This neurons fires low to high as it moves from POS1-POS4, others patterns can also be from high to low firing. This shows that even though the HC is mapping out the space on the track, it is still encoding information for where the animal is in the room. Therefore, this indicates the hippocampal place cells are mapping out both the room and the route simultaneously.
Population Correlation Matrices. We found high correlations as the animal runs throughout the progression of the route until right before he makes a turn. The pattern of firing activity diverges. First we’ll look at the population correlation matrices for the hippocampal neurons. The graphs highlighted in dark blue are comparisons of two positions within the same fragments, while the graphs highlighted by the light blue color are comparisons of two positions from different fragments. The six graphs represent the six different combinations we can have when we make comparisons for positions 1, 2, 3, and 4. For each graph, the position listed first is on the x axis, and the second listed position is on the y axis. The red line represents the bin at which the animal turns on the track. The color bar represents the strength of the correlation between two positions, where the color blue at 0 means no correlation and the color yellow at 1 means a perfect or very high correlation. For the graphs by same fragments, we see that there is high correlation on the same point of the route or track, indicated by the diagonal line. The bottom graph shows the plotted diagonals of the correlations. The y-axis is the same as the color map values, ranging from 0-1 where a higher number means a higher correlation. The x-axis is the point on the track. Here, the dark blue lines show that place specific activity follows the track and the pattern remains high. This means that he is mapping out the space of the track. The graphs comparing positions by different fragments show that the correlation drops earlier. We see that the point of pattern divergence happens just before he turns left or right.

The dark green color highlights the comparisons of two positions of the same fragments, and the lighter green color highlights the comparisons of two positions of different fragments. Now when we look at the neurons for the parietal cortex, we see that there are similar patterns in the color maps as we saw in the hippocampus. Jumping down to the graph on the bottom, we see that the point of pattern divergence happens earlier in the parietal than it does in the
hippocampus. This is insight for when the animal is recognizing when he is making a choice and this shows that the rat seems to know which side of the boundary line he is occupying.

**Discussion**

This study’s objective was to find a measure for generating a behavior that would satisfy the conditions for the rule, as well as to find which brain areas map out these fragmented spaces.

In the hippocampal first trial cells, we believe this suggests the animal is processing what he needs to do on the first trial as he performs the task, and that allows him to subsequently perform the same behavior on trials 2-5. However, we are still unclear about this finding and its relationship to this study. For hippocampal cells that were mapping out the space of the track, the evidence suggests that the parietal cortex and hippocampus are interacting together in some way because the hippocampus is being influenced by what the parietal cortex is doing. The changes in in-field firings rates show that the animal is mapping out both the route and the room simultaneously, which suggests there is some kind of interaction between the parietal cortex and hippocampus.
References


Figures

Figure 1

(A) 2.5”

(B) 26.38”  4”

1.5”

1.75”  4.25”

1.75”

1.75”

48”

7.25”
Figure 2
Figure 3
Figure 4

The figure shows the percentage correct across different positions for two different conditions: AL2, DN9, and DN10. The bars represent the percentage correct for each position (1 to 4) for each condition. The data is presented for two different trials: AL2 and DN9, with a total of n = 3 participants.
Figure 5
Figure 6
Figure 7
Figure 9

Population correlation matrices: Hippocampus

Parietal Cortex
Figure 10

Comparison of correlation between Hippocampus and Parietal Cortex

- **Hippocampus**
  - Pos 1/2, 3/4
  - 1/3, 1/4, 2/3, 2/4

- **Parietal cortex**
  - Pos 1/2, 3/4
  - 1/3, 1/4, 2/3, 2/4

- **Hippocampus & Parietal cortex**

Point of pattern divergence ~bin 76 (1/2 and 3/4 versus 1/3, 1/4, 2/3, 2/4)

Point of pattern divergence ~bin 66 (1/2 and 3/4 versus 1/3, 1/4, 2/3, 2/4)

Track position → Choice point / turn

Track position →

1 track position → 83 100
**Figure Captions**

*Figure 1.* The dimensions of the maze are shown, which include (A) the L-shaped blockers or barrers and (B) the stem and side of the T-maze.

*Figure 2.* The layout of the room where the animal has a clear view of the visual cues on the walls that serves as the boundary of the environment. The four different positions (Pos1, Pos2, Pos3, and Pos4) are shown where they are placed in the training room and how distant they are from the other positions.

*Figure 3.* The introduction of three new positions: Pos 5 (up from Pos4), Pos 6 (right laterally to Pos 1), and Pos 7 (right perpendicularly to Pos5). The original four positions are also shown to visually demonstrate the distances between all 7 positions.

*Figure 4.* Performance for all trials

*Figure 5.* Performance for first trials only.

*Figure 6.* Performance for Pos1 and Pos4 vs. Pos2 and Pos 3.