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Cognitive Science Honors Thesis
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Parietal Cortex and Hippocampal Contributions to Rule-Based Spatial Fragmentation

Abstract

Humans are capable of the complex ability of thinking abstractly, and this allows us to easily and arbitrarily assign meaning to spaces, dividing them up mentally. Theses spaces can be divided by rules, such as learning the difference between infield and outfield in baseball; or social conventions, such as the personal space of a lecturer at a university and his students. These abstractions are made every day without a second thought -- but how do we encode and understand these abstract spatial boundaries? And is this a unique human ability? This paper aims to investigate whether animals, specifically rats, have the ability to learn an abstract spatial fragmentation. If from their behavior we conclude that they can, how do the cellular firing patterns of their brains reflect this? We will specifically be looking at the hippocampus and parietal cortex, for these are the two areas most strongly implicated in spatial navigation.

1. Introduction

1.1 A cognitive map

Spatial cognition, or navigating through the various environments you encounter daily, is a process which is taken for granted. Familiar routes can become almost second nature; for example, think of the exact route you take to get to work or school and how it has been maximized for time and efficiency. Roads, highways, walls, doors, and windows logically and unconsciously divide up our environment into spaces that we know and understand. In fact, you could say that humans are experts at spatial navigation: it is something we do every day, without without conscious thought of the process. But how exactly are we able to learn to navigate through space? How do we build up complex spatial representations in our minds? How do we even conceptualize space at all?

Before the advancement of technologies which allowed us to finally take a look inside the ever-elusive entity that is the human brain, psychologists studied all cognitive abilities, including spatial navigation, through behavior. Behaviorism was an ideology which was the dominant movement in Psychology for fifty years in the early 1900s. Proposed by psychologist John Watson, Behaviorism stated

that behaviors no longer allowed inference to an internal state. Instead, the behaviors themselves were the subject of interest. Psychologist B.F. Skinner took this ideology even further and added that all behaviors are shaped by rewards and punishments, and all that all behavior can be explained in terms of observable experience. Behaviorism rejected the existence of internal mental states and focused on what could be readily observed in an organism.

During this era, psychologist Edward Tolman was using behavior to study the ability of rats to navigate through their environment. However, his findings were contradictory to the foundation laid by Watson and Behaviorism. One of Tolman's famous experiments explains a key flaw in the study of Behaviorism. In his experiment, the rat was placed in an environment which contained a T maze (in a T maze, the rat is placed at the bottom of the T, runs up, and has the choice to either turn right or left). The rat was trained so that after many trials, he knew to run up and to the right in order to receive a food reward. However, after the rat learns this, Tolman turned the maze 180 degrees so it now faced the opposite direction. Then he placed the rat back down at the start of the maze to see what it would do. From a Behaviorist's perspective, the rat would undoubtedly turn right, since it had only learned "right turn" to receive a reward. Yet on the first trial, the rats performed a new behavior, turning left to correctly receive the food reward. Tolman took this to mean that rather than the rat's behavior solely influenced by positive reinforcement, it had actually formed a cognitive map of its environment. This was likely stored as a memory which allowed the rat to remember which way to go to retrieve the food. His proposal of an internal cognitive map was revolutionary because it challenged Behaviorism, and introduced the idea of spatial navigation as a mental process or ability.

1.2 Hippocampus: The universal map

In the present day, we have many more ways to study the brain than behavior on its own. With technological advances such as the MRI, fMRI, PET, MEG, EEG, and more, the discoveries we can now make about the brain are endless. In particular, one important electrophysiological technique is the single-unit recording. For this technique, bundles of electrodes are surgically inserted into the cortex. These wires pick up the electrical activity of cells in the brain known as action potentials. By analyzing the single unit firing as well as patterns of firing in population of neurons, we can start to learn more about how activity in the brain translates into our everyday thoughts, perceptions, and actions.

In particular, the invention of these advanced techniques led us to important discoveries which proved Tolman's hypothesis of a cognitive spatial map to be true. It is important to note that for many processes, including spatial navigation, experimental research has largely been performed on rats, not humans. While there are certainly precautions to be taken in generalizing findings from rats to human

brains, rats provide a useful model for many cognitive processes and abilities. Rats have excellent spatial navigation skills, and are ideal study subjects for experiments involving single cell recordings. In addition, rats and humans share many brain structures, including the hippocampus and parietal cortex, which are strongly implicated in spatial cognition.

The first major discovery of spatial mapping in the brain occurred in 1971, when John O'Keefe found a special cell with a unique firing pattern in a part of the brain called the hippocampus. These cells, later called place cells, were found to fire when a rat was in a particular place in its environment. Different cells have different place firing fields, such that the animal's entire environment is represented by these different "place fields." These place fields can also remap, changing which cells fire as well as rate of firing in new environments. In rats, these place fields were found to be about rat-sized. These cells are the neural basis of Tolman's hypothesized map, providing evidence that there does exist an internal spatial map, and it is manifested in our brains by specific cellular activity and their given firing patterns.

Decades later in 2005, Edvard and May-Britt Moser discovered another cell with a special firing pattern which was later named the grid cell. The Mosers recorded single cell activity in the rat's entorhinal cortex while the animal moved freely around in its environment, and found that some cells had multiple firing locations, unlike the place cell. The spatial firing fields were arranged at equal distances apart from one another, suggesting that these cells encode a cognitive representation of Euclidean space. Grid cells were named because their hexagonal firing pattern created a triangular grid of tessellated triangles. Grid cells can be thought of as the positioning system of the brain, because they encode the position of the animal as he traverses through an environment. Place cells and grid cells together can be thought of as an animal's universal map of its environment.

Another important discovery revealing how our brains map out space is the head direction cell. In 1984, James B. Ranck Jr discovered head direction cells in the rat subiculum, though they have also been found in areas including the entorhinal cortex, post-subiculum, retrosplenial cortex, anterior thalamus, lateral dorsal thalamus, and mammillary bodies. Head direction cells increase their firing rates when the animal's head is pointed in a specific direction. More specifically, the firing is closely tied to where the animal's head will be in 100ms from that moment. In other words, the activity of head direction cells predicts where the animal's head will be 100 ms in the future. Head direction cells are very tightly tuned, meaning that a head direction cell will fire only for its specific direction. In addition, when the animal is travelling in the direction preferred by the head direction cell, the firing rate increases as the animal's movement speed increases. In this way, the firing of head direction cells carries information about the direction of travel as well as how fast the animal is moving in that direction.

Though these different types of cells all encode a different part of your experience of space, they all have in one thing in common, which is that they all have spatially specific firing which carries the frame of reference of the boundaries of the observable environment. In the literature this is often referred to as allocentric space. Further discussion of frames of reference will be provided in later sections of this paper.

1.3 Parietal Cortex: Route space

A lesser known, but equally critical brain region implicated in spatial cognition is the parietal cortex. One finding which led to the discovery of the importance of the parietal cortex in spatial navigation is the phenomenon of visual hemineglect. Hemineglect is a neuropsychological condition which occurs after one damages one hemisphere of their brain. For example, a person with a stroke affecting their right parietal lobe will cause that person to neglect the left side of their visual field. This causes the person to act as if the left side of space no longer exists. Interestingly, this damage can even cause patients to ignore the left side of objects, even when those objects are in their right visual field. If a hemineglect patient is asked to draw a clock, they may only draw numbers 12 through 6. They will also ignore the left side of their own body. This fascinating condition shows how loss of function in the parietal cortex causes extreme deficits in perception of space, revealing how critical it is in maintaining the spatial abilities you use every single day.

Important initial findings about the parietal cortex were discovered by Vernon Mountcastle. Mountcastle studied monkeys, recording single neurons in their parietal cortex. He noticed special properties of parietal neuron activity. Parietal cortex neurons respond to visual stimuli, such that different neurons are tuned to different parts of the visual field. In addition, he found cells with different spatial tuning properties in the parietal cortex. He found cells that were tuned to the location of sensory stimuli, the memory for sensory stimuli, and spatial attention. Notably, all of these properties are mapped to the frame of reference of the individual. However, there are indications that the parietal cortex can map position in other frames of reference as well. For example, Crowe & Chaffee 2010 showed that the parietal cortex can map the position on an object no matter where it is oriented egocentrically.

While the hippocampus generally maps out the space of an environment such as a room, the parietal cortex maps out the space of a route. You can think of route space to the parietal cortex as allocentric space is to the hippocampus. Much of navigation is actually accomplished by routes: think back to my prior examples of remembering how you get to school, or home, or from class to class each day. But how does the brain encode routes? In Nitz 2006, animals were recorded running in the same route in different spaces in the room. Nitz found that parietal cortex neurons map the position in the route,

as previously described. When the firing rates of all the cells were analyzed together, Nitz found that they exhibited a different but reliable pattern which was specific to the route. For example, a cell would fire for a specific right turn in the route, not all right turns. If the track was moved to a new space, this same pattern would occur. Furthermore, if the dimensions of the track were actually extended such that the size of the route was doubled, the size of the pattern doubled as well. These findings provided evidence that parietal cortex neurons have flexible mapping properties, and that their activity is in the route-centered frame of reference. In other words, these neurons are mapped with and travel with the route.

In addition to mapping out the space of a route, the parietal cortex has another important and unique property. Approximately 25 percent of parietal cortex neurons are action specific. This means that these cells will fire when the animal performs a particular action, such as turning left. If you place an animal on a track while recording its 'left turn' specific cell, it will fire action potentials every time the animal makes a left turn, regardless of where the animal is on the track or in the room. This is just another aspect of spatial mapping that is accomplished by the parietal cortex.

Interestingly, there are many parallels between the hippocampus and parietal cortex, which show not only that the two are both highly implicated in spatial navigation, but suggests a potential interaction between these brain regions. First of all, route space is to the parietal cortex as allocentric space is to the hippocampus. In other words, these brain areas largely encode the same space with different frames of reference (although we will see exceptions to this). In addition, lesions to either of these areas will cause critical deficits in spatial cognition, providing evidence that these are both major structures involved in providing spatial orientation and navigation skills.

1.4 Frames of reference

When it comes to mapping space in the brain, there are actually many different ways this can be accomplished. In order to better understand the role of the hippocampus and parietal cortex in spatial navigation, it is necessary to have an understanding of the different frames of reference. While the standard assumption is that we map space based on the boundaries of our observable environment is true, there is more complexity to the story. There are many ways to perceive any given space. To name a few, think of personal space, building space, or classroom space. Frames of reference can roughly be divided into two categories, arbitrary frame of reference and egocentric frame of reference. Arbitrary frame of reference includes allocentric, object-centered, and route-centered frames of reference. Allocentric, or world-centered space, is where you are in relation to the world around you. The object-centered frame of reference is your place in the environment relative to an object. Route-centered space can be thought of as your position in any given route, regardless of the space of the overall room. On the other hand,

ego-centered, or self-centered space, is the way you map out space in relation to your own body. This can include things like retinal space, eye position, and hand position. These are all spaces that will vary for each individual; for example if I am looking at an object in a room, my retinal space and eye position will not be the same as someone who is next to me looking at the same object.

Once we have this understanding, we can make the distinction that the hippocampus generally maps allocentric space, while the parietal cortex generally maps egocentric space, as well as route space. Both play seemingly different, but equally critical roles in mapping out an individual's position in an environment as well as in a route.

1.5 Fragmentation

All of the studies and information up to this point have been concerning spatial fragmentation in relation to physical boundaries. For example, an animal navigating freely through a room, or running along a specific route. In these cases, the walls of the room, or the edges of the track, constitute the boundary which the animal encodes. One study investigated how place field mapping would change when a physical barrier was placed in a given cell's place field (Muller 1987). He found the place field for a cell of a rat, and then placed a small, clear plastic barrier in its environment where the place field would normally exhibit peak firing. Rather than dividing into two new place fields, he found that the spatial activity of the cell respected the fragmentation of the space when there was a physical barrier present.

However, very little is known about how animals map and encode abstract spatial boundaries. There is evidence that humans, and possibly other animals, can mentally fragment a space. As I previously discussed, there are many ways to perceive space, and in addition to physical boundaries, we can also arbitrarily assign meaning to spaces, which we can learn through rules, games, or social conventions. We will be using rats to investigate how the brain learns these abstract spatial relationships, because this type of ability happens at the cellular level.

There has not yet been a great deal of research on how animals understand abstract spatial rules, but one prior study investigating mental fragments was conducted by Freedman & Assad in 2006. By recording in the lateral intraparietal and and middle temporal areas, Freedman and Assad found that monkeys were able to mentally split a space into two categories. The monkeys were trained to group 12 directions of motion into two categories which were separated by a 'learned category boundary.' Their ability to learn this category boundary was assessed by their patterns of neural activity. Similarly, we aim to teach rats a categorical spatial boundary by implementing a rule. However, this will be a behavioral rule, and we will be looking at the neural activity in the areas most implicated in spatial cognition and navigation.

2. Methodology

2.1 Materials

We utilized a dimly lit room for all training and recording sessions, with various cues located in different areas such as a desk, table, computer, and chair. A T-maze was used in this experiment. The stem of the T maze was 48 inches long, 4.25 inches wide, and 1.5 inches above the ground. The side of the T was 26.38 inches long, 4 inches wide and 1.5 above ground. The purpose of the T-maze was to provide a simple way to divide the room into 2 spaces through a behavioral rule. We marked out 4 positions in the room with black tape, each position equally 8 inches apart and placed in all vertically on the same axis. Later on positions three more positions, 5, 6, and 7 were added which will be later described.

2.2 Training procedure

3 adult male Sprague Dawley rats were used in this experiment, 2 of which were surgically implanted with electrodes after training. Training consisted of first familiarizing the rats to the track environment. Animals were gently handled and taught to eat cheerios by hand for 2 weeks prior to training. They were trained by approximation to make ballistic runs from the bottom of the maze stem to the end of the T. Animals were then trained to perform the decision making task itself. The track was placed for blocks of 5 trials at one of 4 sites (see Figure 1) which were randomly assigned. While performing the task the animal has a clear view to his entire environment. The reward was contingent on the animal choosing the correct side to go to: running the length of the T and turning either left or right. Positions 1 and 2 demanded a left turn, while positions 3 and 4 demanded a right turn. There is no physical line or barrier dividing positions 1 and 2 from positions 3 and 4. Thus, the behavioral rule that determines the animal receiving the reward effectively splits the room into two fragments. This creates an invisible rule-determined borderline that lies directly between positions 2 and 3.

The number of trial blocks was slowly increased to 28, for a total of 140 trials per day. The 28 trial blocks were split into 7 sets of 4 blocks. Within each set, each of the 4 positions is utilized according to a random assignment. When the rat performed above chance at all positions for 5 consecutive days, assessed using the sign test, then a new position was introduced. These include positions 5, 6, and 7, experienced by all animals in that order. The reason for introducing new positions is due to the possibility that the animals, rather than mentally fragmenting the environment, have instead learned 4 independent simpler associations. By placing the animal in a novel location, we can assess if he is able to generalize the rule and effectively fragment the room in 2 separate spaces. Once the animal's performance reached criterion for positions 1-7, the animals were prepared for the electrophysiological component.
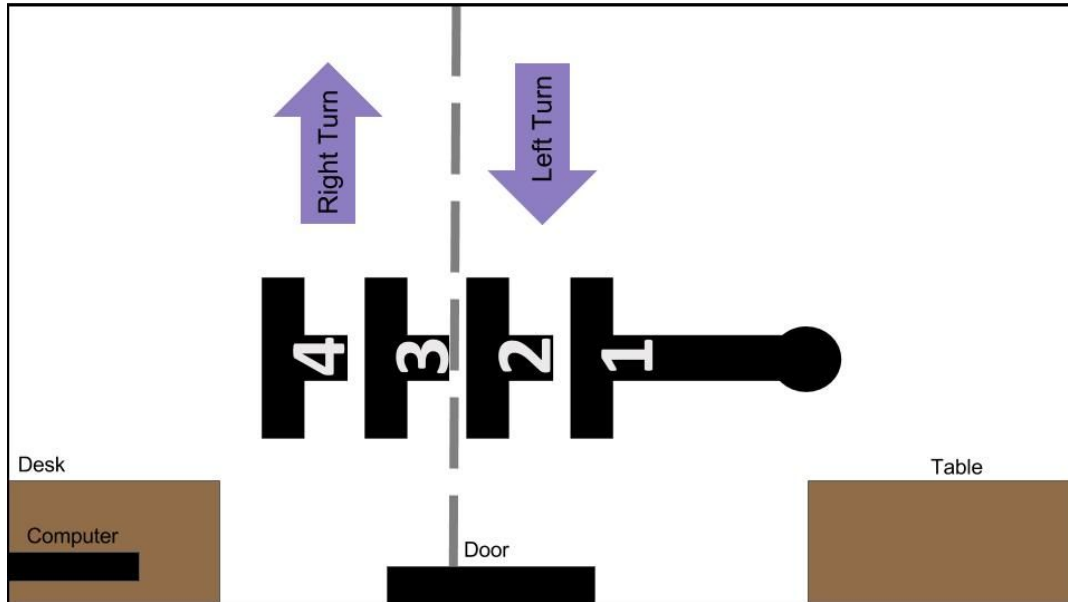
Figure 1: Setup of the recording room with visual cues and invisible boundary line. Positions 1 and 2 demand a left turn while positions 3 and 4 demand a right turn.

2.3 Electrophysiology

Tetrodes were placed in groups of 4 into a microdrive cannula. During surgery, electrodes were placed stereotaxically centered on posterior 3.8mm, lateral 2.2mm. The firing activity of individual neurons was recorded from the Posterior Parietal Cortex (PPC). Over the course of recording days, the electrodes are slowly turned down to gather recordings of single units in the PPC and later, the underlying hippocampus.

2.4 Recordings

Recordings typically occurred once per day for each rat. The electrodes were slowly lowered through the parietal cortex and into the hippocampus, collecting cells in each brain area. The rat was brought into the room, and connected to the recording device to record the cells' firing of action potentials. LED lights were also attached to the animal's head in order to track both its head position and body orientation, effectively tracking its movement through the room. The animal's activity was recorded by 3 separate cameras placed in different locations in the room, giving us a three-dimensional video recording of the task. During recording the room is dimly lit in order for the cameras to pick up the animal's position. A sheet was prepared beforehand, and Matlab was used to randomize each set of 4 blocks in the 4 different positions. These random sets of 4 were repeated 7 times for a total of 28 blocks. Animals were reinforced with half of a cheerio at the end of the T, and a quarter of a cheerio for running back to the start of the T.

2.5 Behavioral scoring

The behavior of the animal during each recording was scored using a GUI, or Graphical User Interface, in Matlab. The window plotted any specified number of given points in the window, each point representing each time the LED light was detected in the given pixel space of the camera, which translates to the space of the room. Scorers went through the tracking data from each recording, selecting the beginning and end of the outbound runs. Once these runs were scored, they were used to create a template for the rats' running trajectory at each position. The templates were used to create a basis for which to have an averaged position along the track for which to compare with the neural data.

2.6 Waveform discrimination & Rate maps

The neural data was acquired through Plexon Offline Sorter to identify the single units recorded in the animals. When the single units have been identified and the behavioral scoring was complete, the two sets of data were combined to create rate maps, which showed the amount of firing of each neuron each time the rat occupied a position on the track.

3. Behavioral results

In order to provide evidence that the animals have mentally fragmented the space based on a behavioral rule, we assessed the following:

3.1 General assessment of behavior

If the animals had not learned the abstract spatial fragmentation, then they should performance at chance, or 50%. However, all animals performed significantly above chance for all positions at all trials (see Figure 2), providing promising evidence that the animal's understand the behavioral rule.

3.2 Performance on all first trials

In particular, the first trial is the most important trial. For each block, the animal has 5 trials, or chances, to make the right choice (turning right or left). If the animal has not learned the abstract spatial rule, he could still perform above chance for all positions when averaged over all trials. For example, as long as he knew to switch his choice when he was incorrect, the rat could get the first trial wrong, then simply switch his behavior to the other direction for the next four trials. If this were the case, the rat's performance at first trials should be 50%. However, this is not the pattern that we see in the data (Figure 3). All animals still performed significantly above chance at all positions. Accuracy remained nearly perfect for positions 1 and 4. Accuracy for positions 2 and 3 was lower, averaging 84.92%.

3.3 Assessment of rate of error according to proximity to boundary line

As I stated previously, it is possible that the animals have learned 4 independent spatial associations rather than a categorical rule which splits the room into two fragments. If this were the case, the rats should have roughly equal performance and equal mistakes at each of the positions. However if the animals have learned the rule, then their performance should be impacted by how close they are to the invisible boundary line. If they are closer to the line (positions 2 and 3), they should perform worse as it is a more difficult decision. If they are further from the line (positions 1 and 4), they should perform better because this is an easier perceptual distinction. In our behavioral analysis, we find that this is the case (Figure 4). Their performance on positions 1 and 4 remains a high 99.735%, whereas their overall performance on positions 2 and 3 averages 84.96%. Additionally, performing a t-test resulted in statistical significance. This is further evidence that the animals have in fact learned the abstract spatial rule.
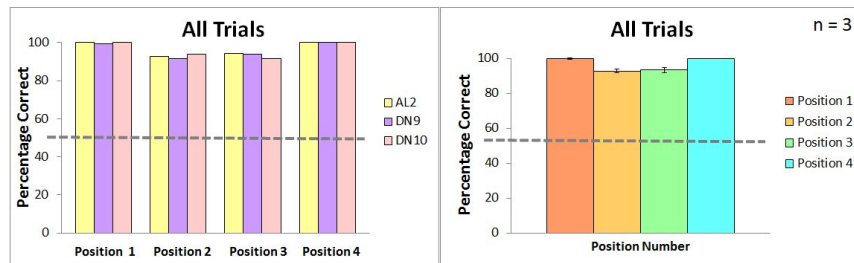
Figure 2: Performance for all positions across all trials
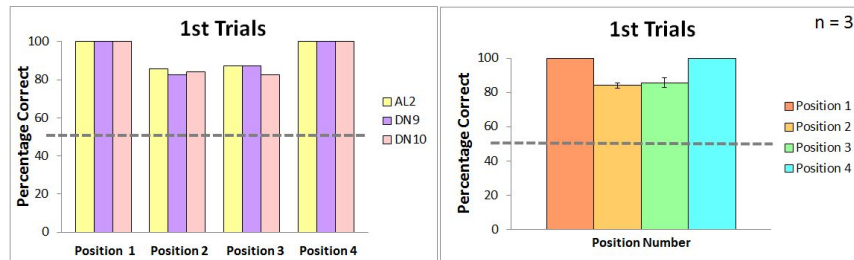
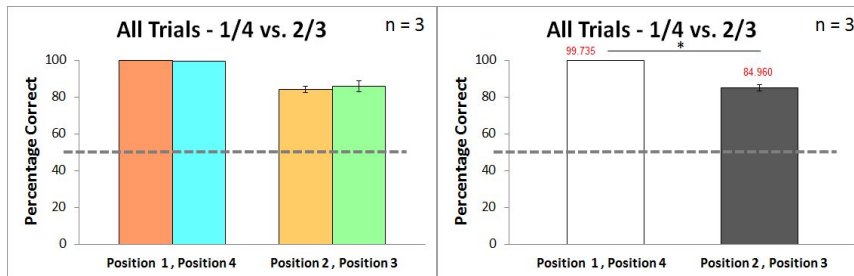*Figure 3: Performance for all positions, first trial only*

Figure 4: Performance on positions 1 and 4 versus positions 2 and 3

3.4 Behavior at new positions

       Finally, one last way we tested their understanding of the behavior rule was by introducing completely new positions. If the animals formed four separate associations, they should perform at chance level, 50%, the first time the track is placed in a new position. We recorded the first trial at the first introduction at each of these positions for all three animals (Figure 5). Position 5 was placed right above position 4, such that the correct response is a right turn. All animals got this correct on the first trial. Position 6 was placed laterally beside position 1, and turning left was the correct response. All animals got this correct on the first trial as well. Finally, position 7 was placed perpendicular to position 5, and turning right was the correct response. This position is arguably more difficult because it involves a change in position as well as a change in rotation of the room. Understandably, only 2 out of 3 animals got this correct on the first trial. This gives us an overall total of 8/9 for all performance at new positions, or 88.89%.
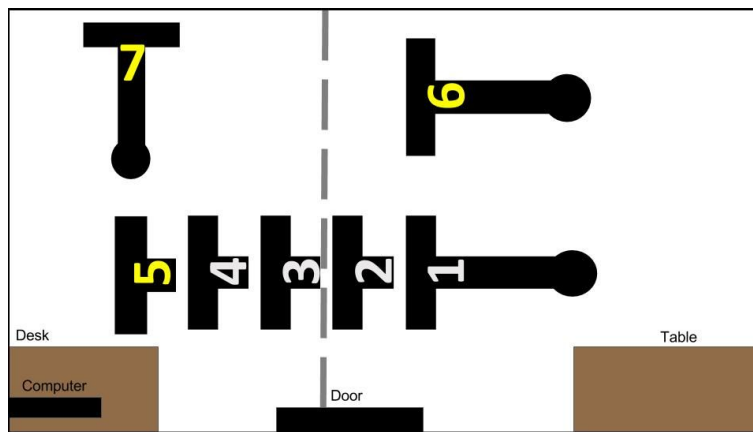
Figure 5: Introduction of new positions 5, 6, and 7

4. Neural results

       After completing the behavioral analyses, we have substantial evidence supporting that the animals have, in fact, learned an abstract spatial fragmentation based on a behavioral rule. Our next step is to look at the firing activity of the neurons in the hippocampus and the parietal cortex to see how their brains encode this information. To do this, we looked through the population of cells in each brain area and noted the patterns that we saw, or the characteristics of space that the cell seemed to map out. Then, we looked at the activity of the population of cells as a whole. The following is a preliminary analysis of both expected and unexpected findings of single unit activity in the hippocampus and parietal cortex. While further analysis is essential, the patterns we have seen so far have been reliable and consistent across cells and across brain regions.

4.1 Hippocampus: single units

We found the activity of individual neurons in the hippocampus to be surprising in many ways. We discovered that the hippocampus did not typically map out the allocentric space of the room as it normally does. Three examples of types of cell firing that we saw were place fields that moved with the track, change in in-field firing rates, and cells that fired differently for the first trial only.

Before analyzing the data, we predicted that the parietal cortex neurons would follow the space of the track and the hippocampus would map the space of the room, as that is what the previous research and literature has suggested. However, this was unexpectedly not the case. We noticed many cells which had firing fields in the same place on the track for each position, but a different position within the room (Figure 6). This finding is surprising and more analyses need to be done to better understand this phenomenon, but it suggests that the parietal cortex and hippocampus may be working together in some way, because they are using the same frame of reference. Given that the task itself is dependent on the animal knowing where he is in the space of the room, this finding is ironic because the area which would supposedly accomplish this is encoding a completely different aspect of space which is not explicitly relevant to the task.

Another pattern we noticed in the hippocampal firing activity may explain how the animal maps its space in the room as well as the track. Not only did we see place fields with travelled with the track, but within those place fields, many of the cells showed a reliable change in the in-field firing rates, either increasing or decreasing across positions (Figure 7). This means that these neurons are actually encoding two things simultaneously. First, by firing on the same part of the track in each position, he is mapping his place on the track. The second could be one of two options. Either the animal's position in the space of the room, which would be evidenced by a gradual and progressive change in firing from position 1 to position 4, or the animal's intent to turn either left or right, which would be evidenced by a similarity in rates for positions 1 and 2 and positions 3 and 4. Determining which of these is being employed will take further analysis which is not complete at this time. Regardless, this phenomenon provides evidence that the hippocampus supplies either the necessary information to make the right choice (position in room), or the choice itself (left or right).

Finally, we found that a number of cells showed higher mean firing rates for the first trial only, while trials 2-5 showed much lower mean firing rates (Figure 8). This is consistent both within and across the different track positions. The deviation from the mean is somewhat systematic, which implies that there is probably a reason behind this pattern, or some information it is encoding. Notably, the first trial is the most important trial because it determines if the animal knows which way he is supposed to turn, and

the hippocampal activity in this case is reflecting that. This is a novel finding of the study which we did not expect.
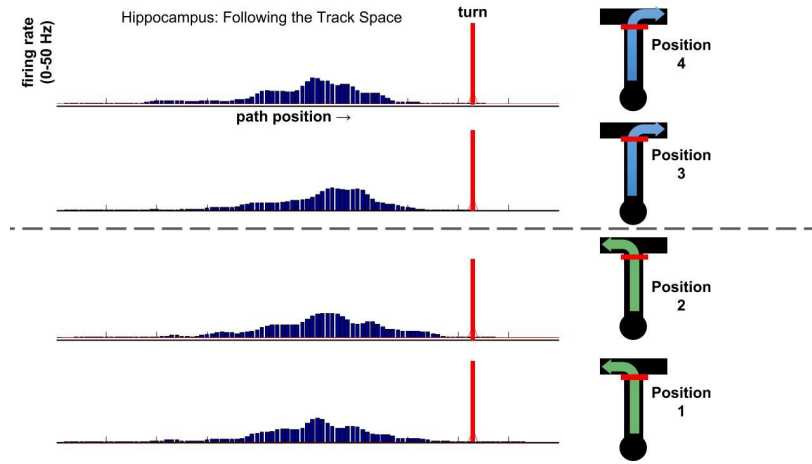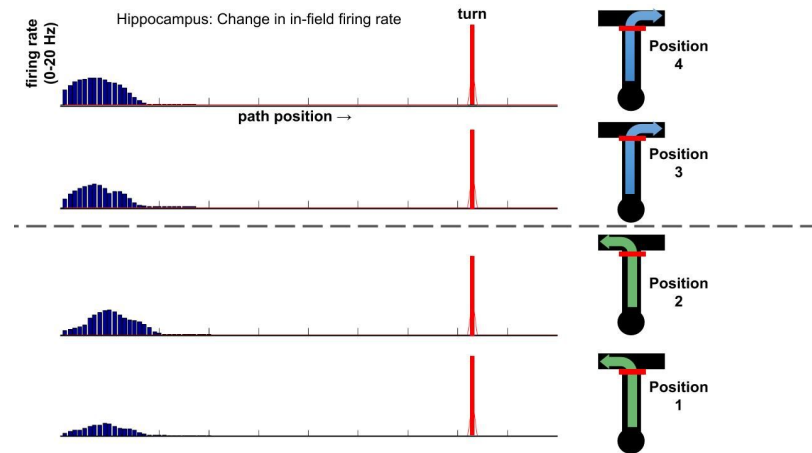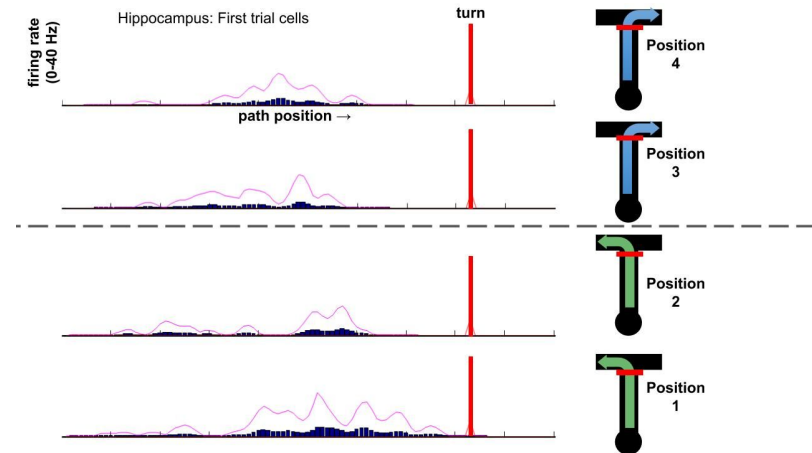

Figure 6

Figure 7

Figure 8

4.2 Parietal cortex: single units

Analysis of the parietal cortex single unit activity revealed a number of expected as well as unexpected findings that remained consistent across animals. Though these two brain areas are both highly implicated in spatial cognition, they have been shown to map out space with different frames of reference. However in this study, we surprisingly found this to be not the case. The hippocampus and parietal cortex actually both followed the same frame of reference, suggesting a possible interaction which will be discussed later in this paper. As for the parietal data, three of the consistent findings included cells which mapped out the route space, cells which fired for specific actions, and cells which seemed to plan out the action of the animal.

We noticed many cells which, as I described in the hippocampus, followed the space of the track (Figure 9). This finding is consistent with the literature and previous research in the parietal cortex, which has been known to map out the path along a route no matter where that route is in the larger environment. The particular cell in Figure 9 peaks when the rat takes off at the beginning of the stem of the T, and drops off after he runs about half of the straightaway. It is reasonable to believe that the rat has a population of cells like this, for example a cell that peaked in the middle of the stem, a cell that peaked at the end of the stem, and a cell that peaked at the turn. Then one could know where exactly the animal is along the path, just based on the full pattern of firing of these cells.

Another consistent and reliable finding in the parietal cortex is cells which fired only when the animal was executing a specific action (i.e. right turns only, not for any turn). These action specific cells are more informative of where the animal is in the route than where he is in the room (Figure 10). There could actually be two possibilities for the function of these cells. One, they could fire any time the rat makes a right turn no matter where he is in the space. In this case, the cell would fire when he makes the right at the choice point, but also when he makes a right to turn around and run back to the start of the T, and so on. The other possibility would be that the cell only fires when the rat is making the right turn relevant to the task. This would mean that the cell is identifying the choice of route, rather than the turn itself. As of now we don't know which is the case, so this would require further analysis.

The third type of cell has not been observed before, making it an original finding of the study. A subset of cells in the parietal cortex reliably fired not when the animal performed an action, but right before he executed an action (Figure 11). This activity leads us to believe that this cell is predicting, or planning, what the animal is about to do next; in a sense, an indication of when the animal has made its decision of which way it will turn. One might think the firing right before the right turn might indicate a 'right leaning' cell, if the rat had already been leaning into the turn. However, through analysis of the animal's head position and orientation, as well as the physical design of the maze, the data does not

support this. The rats lean very little if at all in the direction he is about to turn. Even if this were the case, if the cell was a 'right leaning' cell, it should increase firing when the animal actually executed the right turn. We see that instead, the firing stops for the actual turn. This provides strong evidence that these cells plan out the animal's future actions, predicting which way it will turn.
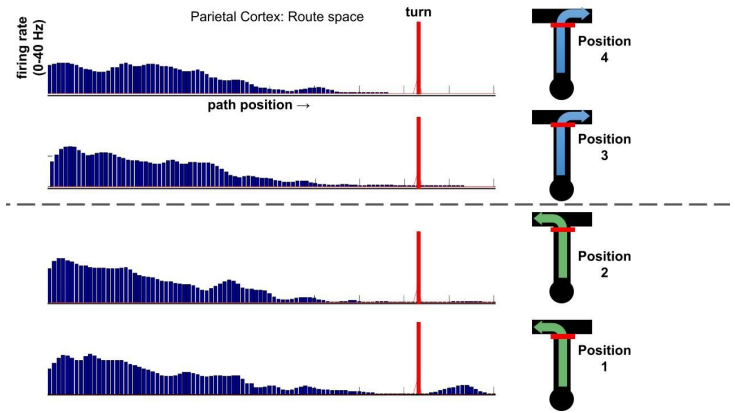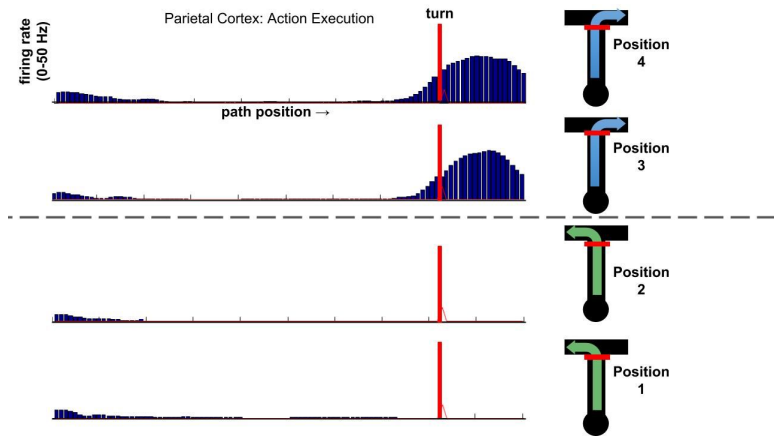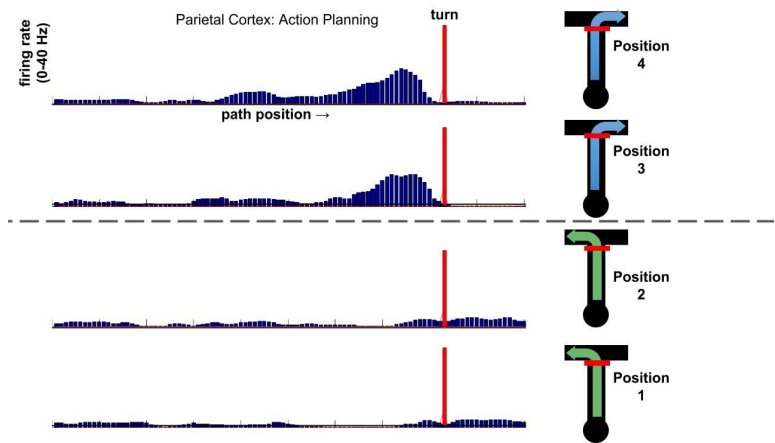

Figure 9

Figure 10

Figure 11

4.3 Population correlation matrices

While the analyses of firing activity of individual neurons is important to discern distinct and interesting patterns in both the hippocampus and parietal cortex, it is equally important to examine the firing activity of the population of cells as a whole. Not only is this a good way to characterize how the brain is encoding the spatial information in an efficient way, but it provides an opportunity to make comparisons between the parietal cortex and hippocampus. The brain works through patterns of activity, not individual firing of cells.

Our population data analysis was done through the creation of correlation matrices. The track space was divided into 100 sections, or bins. These 100 bins are the same for track positions 1, 2, 3, and 4. Then the mean firing activity for all of the cells in each brain region was found for each bin in each position. The Pearson correlation coefficient was calculated for the all the cells' activity at each bin in one position, to the cells' activity in each bin in another position, forming a matrix of correlations (Figure 12, 13). The diagonal of this matrix represents a comparison of correlation of the same bin for the different positions of that matrix.

Notably and unexpectedly, the hippocampus and parietal cortex both take the frame of reference of the track. This can be shown by the the strong correlation across the diagonals of the correlation matrices, revealing similar activity patterns for analogous positions on the track in different positions in the room. If the cells were mapping to the space of the room, the correlation would be very low, because the analogous bins on the different positions are different places in the room. However the correlation remains high for all possible position comparisons, until just before the turn, when the patterns diverge. Perhaps in solving this spatial problem, it is necessary that both brain areas maintain mapping relative to the track rather than the room. This suggests a possible important interaction between the parietal cortex and hippocampus.

Another important observation from the correlation matrices comes from looking at the correlation of the diagonal plotted as a line for each of the position combinations (Figure 14). By plotting the progression along the route against the correlation coefficient, you can once again see that the correlation remains high for all position combinations until before the turn. When the patterns diverge, the amount of correlation decreases for positions which are in different fragment, while positions in the same fragment (1/2, 3/4) retain high correlation. While both brain areas show this divergence, the decrease in correlation takes place earlier in the parietal cortex compared to the hippocampus. Based on the point of divergence, we can see when the animal is recognizing which choice he has to make. This is a very reliable pattern, as the lines represent the correlation of the mean firing rates of all of the recorded cells.
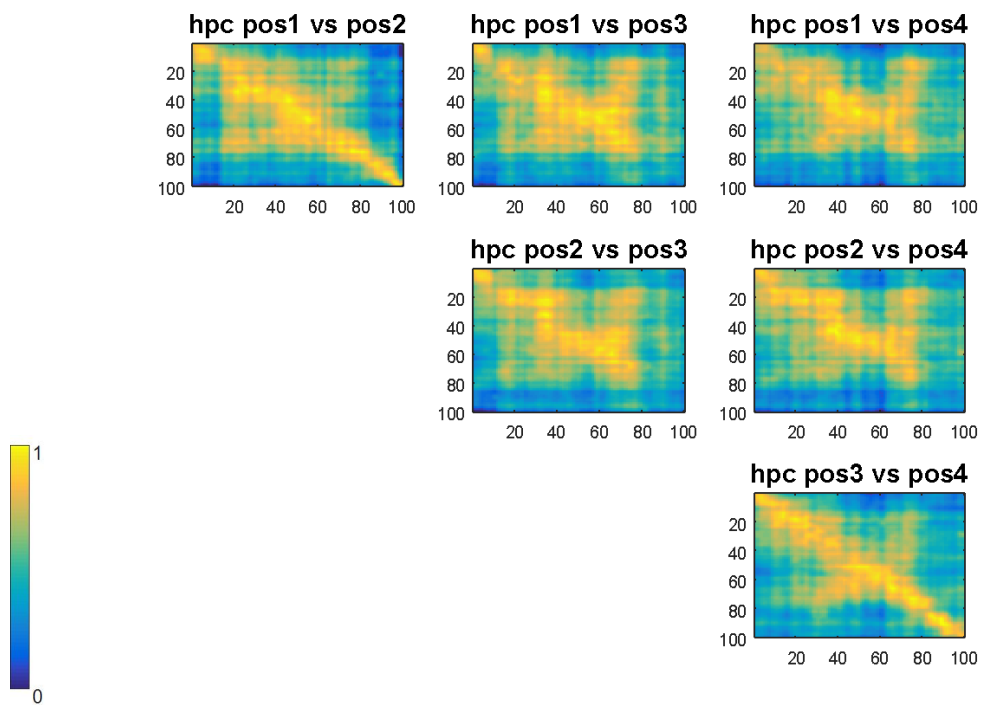
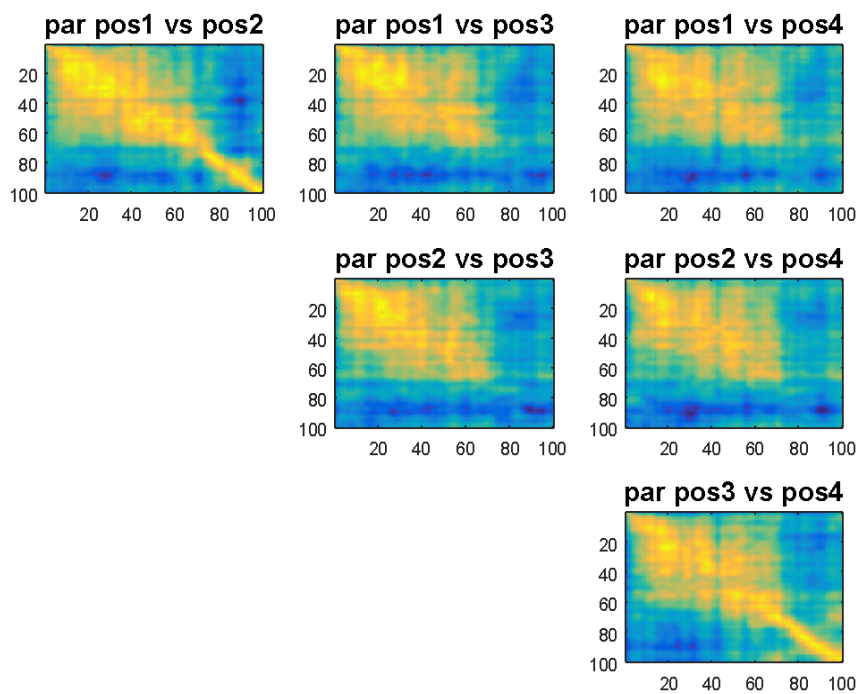hpc pos1 vs pos2   hpc pos1 vs pos3   hpc pos1 vs pos4

hpc pos2 vs pos3   hpc pos2 vs pos4

hpc pos3 vs pos4

Figure 12

par pos1 vs pos2   par pos1 vs pos3   par pos1 vs pos4

par pos2 vs pos3   par pos2 vs pos4

par pos3 vs pos4

Figure 13

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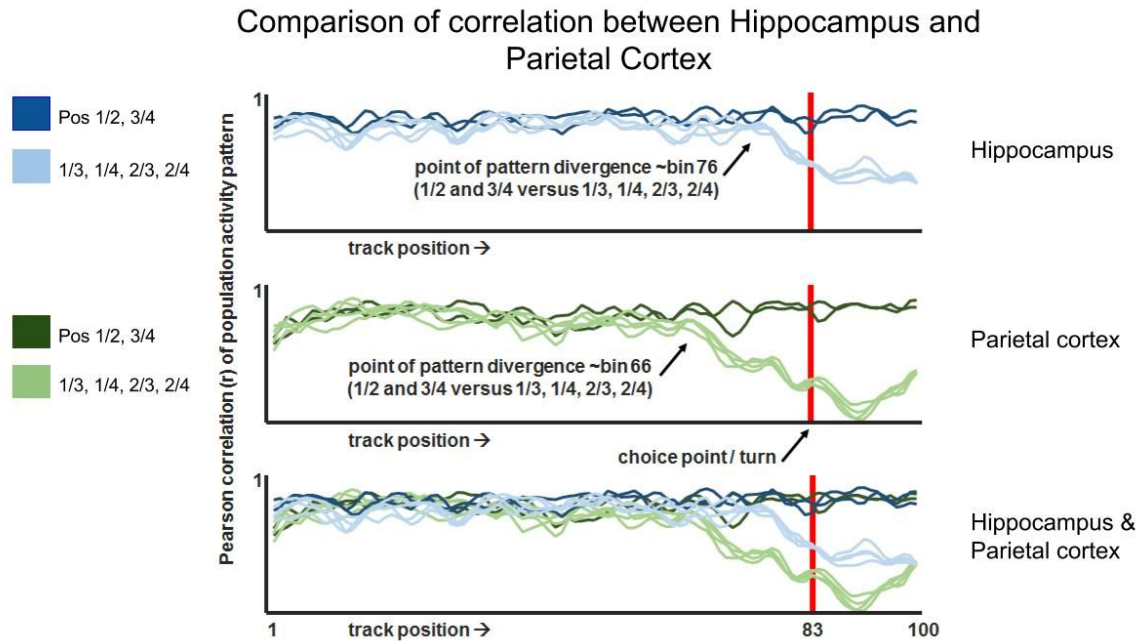**Comparison of correlation between Hippocampus and Parietal Cortex**

Figure 14

5. Discussion

From our behavioral analyses, it is highly probable that all 3 rats did, in fact, successfully learn an abstract spatial fragmentation based on a behavioral rule. This particular ability is not something that has been looked at before, and certainly was not a given before beginning this experiment. In fact, this experiment could have been run as a behavioral study on its own just to show this ability exists in rats. Thus, seeing such strong evidence that the rats have learned this, and perform very well, is an exciting finding on its own.

However, this was not all that we found. We found that certain cells in the hippocampus unexpectedly use the frame of reference of the track, when we fully expected them to use the frame of reference of the room. This is even more surprising considering that their ability to perform the task depends on their knowledge of where they are in the room. In the hippocampus, we also found that when cells moved with the track, they often changed in their in-field firing rates from position 1 to position 4. Though there are more analyses which need to be done to understand if the rat is encoding either position in the room or which fragment he is in, this shows that he is mapping two aspects of space at once, and that this occurs at the cellular level.

In the parietal cortex, we found cells which also moved with the track. We expected this, because the parietal cortex is known for mapping out routes. We also found action correlate cells which corresponded with the rat either turning left or right at the choice point in the T maze. However what we

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didn't expect to find were cells that predicted the actions of the animal, effectively planning out the animal's upcoming decision. This has not been observed before and is an original finding of the study.

Through analysis of population data, we found that the parietal cortex, and more surprisingly the hippocampus, both used the frame of reference of the track to map their position in the room. Though this is ironic because the critical aspect of the task is the rat's knowledge of where he is in the room, it implies there may be some important interaction between the brain areas. The relationship should be further investigated to see how shared pathways or mechanisms may influence their activity in a similar way.

There are many possibilities for further research in this study. First of all, our study so far consists of only 3 subjects, and only 2 of which participated in recording of action potential firing activity. It is essential to add more animals to the study to confirm the patterns of activity and types of cells that we have discovered. We encountered some issues when choosing statistical tests which would show significance for such a small sample size, so accumulation of more data for all animals is necessary for showing strong statistical significance. However despite this, although we have a small sample size, the results have been very promising so far, showing consistency and reliability across all animals. I believe that adding more animals to this study would confirm and strengthen our results.

In order to further confirm that the animals have learned the abstract spatial rule, more track positions could be added. For instance, we have seen a change in the in-field firing rates when the track moves from position 1 to position 4. However, in this case the track is only moving in one dimension. One could imagine a gradient in place, gradually altering the firing rate from low to high (or high to low) as the animal goes from one end of the room to the other. But does this gradient span across one dimension, or could it be two dimensional? One way to test this would be adding another position next to position 6, which is placed laterally beside position 1. If we saw the same change in in-field firing rates of this position with position 6 and 1, we would know that the gradient is two-dimensional, meaning the change in in-field firing rates occurs in both directions (up and down, and left and right).

I briefly discussed our finding that some cells in the hippocampus showed much higher average firing rates on the first trial than the average firing for trials 2-5. This is an interesting finding considering the first trial of each block is the most important, because it determines if the rat knows where he is in the room and if he understands the behavioral rule. The meaning behind these different first trial firing rates is not yet clear, and further analysis is needed to discover what information this may be providing to the rat.

Although we have not done this in the current study, a future direction could investigate how critical the hippocampus and parietal cortex are in the animal's ability to complete the task. This could be accomplished by lesioning either the hippocampus or parietal cortex, and seeing how the animal's

abilities are affected. This would be even more interesting considering the possible interaction between the two brain areas. Since both brain areas seem to use the same frame of reference to map out space, it would be interesting to lesion just one and then see which abilities would be affected compared to just lesioning the other. Another possibility for the future would be systematically moving around various cues in the room, to see if the animal is using specific spatial cues on which to base his decision.

6. Acknowledgements

7. References

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