

**Title:** Characterizing the role of Posterior Parietal Cortex efferents during navigation

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**Abstract**

Successful organisms require the ability to efficiently traverse their environment for resources and to return home quickly whenever necessary. The complex computations integral to navigation necessitates a structure that can relate the activity of other structures that carry or produce spatial information to a common frame. Classically known as an association cortex, posterior parietal cortex is anatomically positioned to integrate the activity of several structures. The present study characterizes the spatial and action neural correlates of two PPC efferent targets, superior colliculus (SC) and dorsal subiculum (dS). Past studies have implicated SC's role in orienting attention. As such, it is conceivable that SC may contribute to fluid navigation by orienting attention to known sensory stimuli along a path. Alternatively, dS is part of the hippocampal network whose activity as a whole provides a cognitive map of the environment. dS may contribute to navigation through the episodic encoding of spaces visited.

We found that an appreciable amount of neurons in both areas perform path discrimination in the form of differentiating their activity as a function of the upcoming or current turn. Pearson's correlation analyses show that both SC and dS differentiate their activity when the upcoming turn is a forced or choice turn. Additionally, population analysis show that both structures differentially fire at all points along a route. Head-direction analysis show that some dS neurons are also sensitive to head-direction.

## **INTRODUCTION**

Successful organisms require the ability to efficiently traverse their environment for resources and to return home quickly whenever necessary. Quick, fluid, and efficient behavior along a predetermined route demands the integration of several factors that each contribute to the behavior of the animal. Among the factors needed for successful and fluid navigation, the organism requires knowledge of: where one is in space, one's orientation to the world, start position, goal position, available pathways, and current best action. In conjunction, other factors such as planning movements, enacting movements, specifying muscle activation, shifting attention, working memory, and recognizing relevant sensory stimuli all must work concurrently to shape optimal behavior of the animal.

Neural correlates of some of these factors have been found in various regions of the brain. The discovery of place cells in the hippocampus (Dostrovsky & O'Keefe 1971) brought attention to the spatial navigation field by providing a neural correlate that supports the idea of a cognitive map of the environment. Subsequently, other crucial spatial representations were found to have neural correlates in nearby regions. Primarily, head direction cells in the postsubiculum (Taube & Ranck 1990) and grid cells of the entorhinal cortex (Moser, 2006). However navigation requires more than these spatial representations, factors such as planning the route and activating muscles required for movement are also necessary. As such spatial navigation is most likely unrestricted to the hippocampal proper, but may require the integrated functioning of multiple widespread structures. The complex computations integral to navigation necessitates a structure that can relate the activity of other structures that carry or produce spatial information to a common frame.

A primary candidate for such a structure is the posterior parietal cortex (PPC).

Classically known as an association cortex, parietal cortex is heavily interconnected with structures in primary and secondary sensory cortices, retrosplenial cortex, hippocampus, superior colliculus, entorhinal cortex, medial precentral, zona incerta, reticular nucleus, neo-cortex, lateral dorsal thalamus, lateral posterior thalamus, and other structures that have been found to have spatial and action correlates (Nitz 2009, Reep&Corwin 1994). Additionally, the population of PPC neurons robustly maps the position of the animal in a route, regardless of where the route is in space (Nitz 2006). This information may be crucial in the coordination of other structures at specific points along a route. For example, organisms may use sensory information along a well learned route in order to plan and execute the upcoming turn, leading to swift and fluid behavior along the route. The organism is no longer tasked with learning the specific actions it must execute along the route, but is more coordinated in what it must do at specific points along the route. PPC may be transmitting this information to its efferent targets to create a cohesive integration of spatial and action behaviors.

The superior colliculus (SC) receives dense reciprocal projections from PPC (Clower&Strick 2001) and is most regarded in terms of orienting behavior (Krauzlis&Zenon, 2013). Many of PPC's efferent target structures have been studied in terms of spatial navigation, but there are few studies involving SC in spatial navigation. Due to literature involving SC in orienting behavior towards a stimulus, the SC may contribute to the spatial network by biasing attention to specific sensory cues that can help guide behavior of the current or upcoming action (Krauzlis&Lovejoy, 2013). While there has been evidence of action and spatial correlates in SC, many of these studies were done on anesthetized animals and even

fewer had recorded from awake animals performing a spatial task. Due to the animals' lack of free movement and the limited variation of spatial apparatus used in the spatial task, these studies are unable to accurately characterize the complete role of SC in active navigation.

PPC also innervates parts of the hippocampus proper, namely the dorsal subiculum (dS). The hippocampus as a whole provides a cognitive map of the environment (O'Keefe&Dostrovsky 1971), where at specific time-points, the hippocampus maps out the prior position of the animal, the current position, and future position. The dS is considered one of the output areas of the hippocampus. As such, dS may contribute to the spatial network by episodically encoding the places visited and projecting this information to other structures.

The focus of the current experiment is to begin to characterize PPC's less studied efferent target structures, SC and dS. Questions of interest include discerning factors the SC and dS might contribute to the spatial navigation network. Specifically, we want to determine if both the SC and dS contain action or spatial correlates. We questioned whether SC and dS perform path discrimination in the form of differentiating their activity depending on the upcoming and current action. Additionally, we questioned whether both structures contain cells that are sensitive to head-direction relative to the room.

## **SPATIAL LITERATURE**

When determining the location of an organism in space, the answer to the question depends on which frame of reference is used. In theory, an object's location can be described in multiple ways. An allocentric frame of reference provides information about the spatial relationship between the organism and its external environment. For example, an organism can be in a specific place in relation to the walls of the room or in contrast, that same spatial

location would be encoded differently in relation to an object in the room. In contrast, the egocentric frame of reference refers to the relationship of stimuli compared to the self. For example, an eye-centered frame provides information about where a stimulus is in retina-space, or compared to your eye. Egocentric reference frames encompass your entire body, such as head space, limb space, or both. Both egocentric, allocentric, and a conjunction of these frames are crucial factors for spatial navigation, as it sets the basis for fluid execution of planned trajectories from an initial location to a goal site (Anderson 1997). As we will see, the neural correlates of spatial navigation encode their information based on these frames of reference.

One of the major hypothesis of spatial navigation is the idea of path integration. Path integration is the continuous updating of egocentric position displacement with a direction, and makes use of information such as optic flow, combinations of muscle synergies, and vestibular orientation to move from one place to the next. Path integration is subject to errors in displacement calculations, and therefore must be corrected with external cues that provide known relationships about the environment. Place cells, head orientation cells, and grid cells are hypothesized to play a part in path integration (Navratilova et al 2014, Samu et al 2009, McNaughton et al 1996)

The hippocampus and surrounding cortices have provided the literature with pertinent spatial neural correlates. Place cells found in CA1, CA3, and subiculum (Lee&Knierim, 2004) fire in a specific location within the observable environment and provide an allocentric view. These 'place fields' are further modulated with context, such as whether the organism is moving in a directed path or free-foraging. Additionally, place fields are modulated by direction of

movement of the animal. Importantly, place cells provide information about where the organism is within a certain environment.

However, place cells do not provide enough information about how to move to a different location. Other factors that encode orientation and movement velocities are needed to complete the calculation (McNaughton et al 1996). The discovery of head-orientation (HD) cells provided one such answer. HD cells fire when an animal is facing a certain orientation in the room. HD cells map out the environment in a manner similar to polar coordinates, where each of the degrees of orientation is encoded by a different HD cell (Taube&Ranck). Altogether, the population of HD neurons provide allocentric information about the orientation of the animals' head compared to the environment.

The discovery of grid cells in the EC provide another allocentric spatial correlate necessary for calculating movement velocities inherent to navigation. Grid cells map out the environment in Euclidian space, where each grid cell has multiple firing fields spaced out as tessellated triangles. These grid cells are topographically mapped out and retain their orientation to each other in different environments. Grid cells are anchored to the external environment and shift in accordance to a distal stimulus. Movement through different grid fields may contribute to spatial navigation by calculating the movement velocities of the animal through space (Sargolini&Moser 2006).

Place cells, grid cells, and head-direction cells encode key factors for spatial navigation. However, these cells and the structures they reside in are widespread throughout the brain. An open question then is how information from these various regions are integrated to form fluid spatial behavior. Classically known as an association cortex, PPC has the ability to coordinate

the activity of other structures to a common frame. Its sub-regions can be characterized by which reference frames are encoded and what effector muscles are used for activation. For example, the lateral intraparietal cortex (LIP) has neurons that encode the direction of eye saccades and responds to visual and auditory cues (Hamed 2002). This is done through gain field properties, where the firing rate of a neuron will be dependent on more than one factor (Brotchie&Anderson, 2005). Neurons with a certain preferred direction fire more robustly in response to that direction if the organism is also gazing contralaterally. In this case, not only is the neuron responding to preferred direction relative to the environment, but the egocentric muscle synergies necessary for conducting a contralateral gaze. Gain fields provide PPC with the ability to encode more than one reference frame at a time, an important factor for the coordination of swift and fluid movement.

A growing body of literature also suggests PPC's role in active navigation. Single-unit studies of PPC neurons while rats traversed a hairpin maze show that neurons in this area are responsive to acceleration and self-motion variables (Whitlock&Moser 2012). Some neurons have been shown to integrate three variables including: position within an environment, the specific action, and direction of movement (Nitz 2006). Rats with PPC damage have trouble locating changes in spatial arrangement of known objects (Save&Buhot 1992). PPC ablation studies of rats traversing the Morris water maze also show that damage impairs active navigation. In this study, rats showed increases in error for initial heading as well as swim latencies to reach the platform (Kolb&Wishaw 1983, Kolb&Walkey 1987, DiMattia&Kesner 1988). Finally, when the lights were turned off during this task, rats with PPC damage failed to

use self-motion cues to find the platform (Commins et al, 1999). These studies suggest PPC's importance for integrating the spatial relationships of objects.

Possible functional roles of PPC in active navigation include biasing sensory modalities into detecting relevant stimuli for upcoming actions, a possible form of attention (Corwin&Reep 1998). In addition, PPC may be important for the integration of sensory and motor systems for execution of behavior (Nitz 09). Due to the associative nature of PPC and its projection to sites that are pertinent for spatial cognition, PPC may be the integrative structure relating the activity of other structures to a common reference frame to produce swift and fluid movements through a well-learned route. This notion leads to the question of whether PPC's less studied efferent target structures, might also contain spatial representation that contribute to the behavior of the animal.

### **Superior Colliculus**

Studies of SC, a structure with dense reciprocal connections with PPC, have promoted this region for orienting behavior. The superficial layers of SC primarily respond to visual stimuli and contain a topographic eye-centered frame corresponding to the contralateral visual field with an enlarged representation of the central visual field. The intermediate (ISC) and deep (DSC) layers are known to orient the eyes and head with regards to multiple sensory modalities including audition (Druga&Syka, 1984) and somatosensation (McHaffie et al., 1989). The ISC and DSC contain motor maps that roughly align with sensory maps of the superficial layers (Sparks&Nelson 1987). Microstimulation of this area produce eye and head gazes relative to the frequency of stimulation (Stanford&Sparks, 1996). Additionally, ablation studies of ISC and DSC produce neglect of contralateral stimuli and disrupt saccades (Hikosaka&Wurtz, 1985). SC



has implications for covert attention shifting. When microstimulated, thresholds decrease at the location of visual space represented by the stimulated site (Muller&Newsome, 2004). The importance of SC in orienting to stimuli is coupled by the finding of spatially sensitive cells. Neurons encoding forward movement, stopping, and turning have been found in the SC. Additionally neurons discharged when animals traversed around particular points within an eight arm maze and during directional movement (Mizumori, 1998). An odor-guided spatial task conducted by Felsen and Mainen (2008) showed that SC neurons appear to be prospectively selective for the upcoming movement. Some cells also maintained their direction selectivity only during locomotion while others persisted until the end of the trial. Additionally, inactivation of SC caused a bias for rats to enter the contralateral reward port. These data show the orienting, action, and spatial correlates encoded by neurons in the SC. However the spatial apparatus used in these studies have been largely limited, such that many studies of SC have been confined to the eight arm maze or to a non-spatial task. As such, these studies may not be sufficient in characterizing the complete role of SC in spatial navigation.

### **Dorsal Subiculum**

The dS is one of the output regions of the hippocampus and projects to areas that are important for spatial learning. These areas include the retrosplenial cortex, posterior cingulate cortex, prefrontal cortex, nucleus accumbens, and perirhinal cortex (sharp&green 1994). Hippocampal place field sizes are organized in an incremental fashion along the dorsal-ventral axis, that is dorsal place fields are smaller and increase to as long as 18 meters at the ventral pole (Kjelstrup et al 2015). As stated, place cell firing rate is also modulated by context. Different forms of context can arise as direction of motion, prior turn, and upcoming turn.

When moving through a planned trajectory, a specific pattern of place cells are activated with regards to the context of movement. In the rat, this pattern of firing is carried in the locomotion induced theta rhythm that travels in phase but not in sync through the dorsal-ventral axis of the hippocampus. In a phenomenon known as phase precession, as an animal moves through a space, the pattern of place cell firing precesses to earlier parts of the theta cycle (Skaggs et al 1996). Due to the traveling theta rhythm and notion of phase precession, at any given moment in time the hippocampus as a whole has the ability to encode the position of the animal as a small field in the future, a medium field at present, and a large field in the past.

Only a limited number of studies have been conducted on the dS. Studies of dS neurons show that in contrast with place cells in CA1 and CA3 region, dS place fields seem to have more flexibility in their firing fields. For example, while foraging in an open arena, one dS place cell can have two firing fields in the apparatus (Sharp&Green 1994). This differs from the classic view of CA1 and CA3 place cells, whose firing rate is modulated by only one place in the apparatus (Sharp&Green 1994). Additionally, dS place cells seem to be more reliable in their firing rate across different environments (Sharp 1997, O'Mara et al 2009). For example, dS place cells may not rate remap between environments of different geometric configurations. As an output region of the hippocampus, the dS may contribute to spatial cognition by providing its efferent target structures with information about the animals' position in space. The observation that differences in spatial representations reside within dS, CA1, and CA3 regions of the hippocampus necessitates characterization of neurons in these areas. Due to the limited number of studies on dS, we chose to characterize neurons in dS during a navigational task.

## **METHODS:**

Subjects: All experimental protocols adhered to the AALAC guidelines. Male Sprague-dawleys (n=4) served as behavioral subjects. Animals were housed individually and sustained on a 12 hour light/dark cycle. Animals were free-fed and acclimated to the environment by daily handling for a period of 2~3 weeks. After this period rats were placed on a food-restricted diet until they reached 90% of their free-fed weight. Water was available continuously. Rats were operated on when they reached a minimum weight of 350g and when performance on the maze was deemed sufficiently fluid.

Triple T navigational task: Behavioral tasks are performed on a triple T-Maze (8cm-wide pathways, overall 1.6m x 1.25m, painted black), (see fig 4 in figures). The track is situated .25m above the floor in a black recording room containing distal cues painted on the walls.

Blockades were inserted to constrain the maze to four main routes and two return routes. Each of these routes differed in their left right turn sequences (see figure 5 in figures). Animals were trained to run to each of these four paths with a honey nut cheerio serving as the reward when the animal reached an endpoint. Two consecutive runs to the same endpoint were not rewarded, incentivizing the animal to visit all four locations. Animals were trained until behavior was swift, fluid, and contained no backtracks when progression onto the route began.

Surgery: Animals were anesthetized using isoflurane gas. Each animal was implanted with 12 micrometer tetrodes housed in a custom built Microdrive system to allow slow movement in the dorsal-ventral axis towards the target region. Each of the four rats were implanted with

three microdrives: two animals had two microdrives implanted over bilateral SC and one over right PPC, the other two animals had two microdrives implanted over bilateral MPC and one over right SC. Each rat was allowed 1~2 weeks of recovery and given antibiotics for possible infections.

Recordings: Electrodes were allowed movement (40 $\mu$ m) through the dorsal-ventral axis to allow for maximum unique unit recordings. Signals were amplified at the level of the headstage connection (20x), again at the pre-amp stage (50x) and lastly at the amplifier stage (15x). Signals that reached amplitude threshold were recorded using SortClient (Plexon). Waveform discrimination into individual units was manually performed using Plexon's Offline Sorter software. An overhead camera monitored the behavior and position of the animal by recording two different LED lights situated on the animal's headstage.

Analysis: Position tracking was analyzed using a custom built MATLAB user guided interface.

Only ballistic runs were used for analysis. Neural data was discretized by creating a template of bins covering all routes taken. Each bin corresponded to approximately 1cm of the maze. Each trial in a session was fitted to the template, allowing for the calculation of firing rates for each position on each route. Firing rates of each neuron are calculated by summing the number of spikes in each bin and dividing by the total time the bin was occupied. Mean firing rates for each neuron are calculated by summing the firing rates for a bin and dividing by the amount of trials.

-Head Direction Analysis: Firing rates as a function of head direction was calculated by taking the time-points at which an animal was facing each direction (1-360) and determining whether

a spike occurred within the range of half a millisecond before and after each time-point. Spikes were summed to provide a spike count for each direction. Average rate was calculated by binning directions into twelve partitions, with each partition containing thirty degrees of head-orientation. All spikes within a given partition was summed and divided by the number of times the animal occupied those orientations within a given partition. To test whether each neuron's firing rate was modulated by head direction, we applied Rayleigh's test for non-uniformity to the average firing rate for each partition of head directions.

-Path Discrimination Analysis: To determine whether SC or dS neurons differentially fired as a function of the upcoming turn or current action, t-tests were performed over specific maze segments. Each bin corresponds to a position within a route. The path with corresponding bins 1-40 and 93-112 represent the areas in the maze where the animal is preceding a choice turn. The path with corresponding bins 46-56 and 113-123 represent the areas within the maze where the animal is making the choice turn. Bins 57-81 corresponded to maze segments preceding a forced turn, while bins 82-92 corresponded to maze segments when making a forced turn. Additionally, to reduce the signal to noise ratio only recording sessions where the animal ran at least three times to each route were included in the analysis.

Predictive first turn analysis was conducted by grouping routes 1 and 2 together and routes 3 and 4 together. Since routes 1 and 2 both have a left as the first turn, they were categorized as left first turn predictor routes. Conversely, routes 3 and 4 have a right as a first turn and were categorized as right first turn predictor routes. Summation of firing rates across positional bins 1-40 for each run in the left turn predictor routes was compared against

summation of firing rates across positional bins 1-40 for each run in the right turn predictor routes.

Analysis of first turn utilized the same route categorization as the predictive first turn analysis, with the exception that bins 46-56 were analyzed. Summation of firing rates across positional bins 46-56 for each run in the left first turn routes was compared against summation of firing rates across positional bins 46-56 for each run in the right first turn routes.

Predictive third turn analysis was conducted by grouping routes 1 and 3 together and routes 2 and 4 together. Routes 1 and 3 both have a left as the third turn, and was categorized as left third turn predictor routes. Conversely, routes 2 and 4 contained a right as the third turn and were categorized as right third turn predictor routes. Summation of firing rates across positional bins 93-112 for each run in the left third turn predictor routes was compared against summation of firing rates across positional bins 93-112 for each run in the right third turn predictor routes.

Analysis of third turn utilized the same route categorization as the predictive third turn analysis, with the exception that bins 113-123 were analyzed. Summation of firing rates across positional bins 113-123 for each run in the left third turn routes was compared against summation of firing rates across positional bins 113-123 for each run in the left third turn routes.

Population firing correlation matrix: We compared the population firing rate vector for each position to itself and with every other position for each route. For route 1, the firing rate vector for each cell was averaged across bins of the same position to form one vector, called the population firing rate vector for route 1. Pearson's correlation was performed for each position

against itself and with every other position along the route. This analysis was also conducted for routes 2, 3, and 4 for both SC and dS neurons.

-Pre-choice turn versus pre-forced turn: Average r-value was calculated for two conditions. First condition was pre-turn 1 segment (choice) averaged with pre-turn 2 segment (forced). The second condition was pre-turn 1 (choice) segment averaged with pre-turn 3 (choice) segment. This was done for all four routes, for both SC and dS.

-Ranking: Additional analysis of pre-turn choice segments against pre-turn forced segments involved ranking r-values, utilizing condition categorization in the same manner as the pre-choice turn versus pre-forced turn analysis. SC route 1 R-values for each condition was mixed together and ranked in a decremental fashion. Each number was stripped of its actual numerical value and retained as their value, their position in the list. Each number was returned to their original condition and t-tests were performed against these two conditions. This analysis was done for all routes for both SC and dS.

## **RESULTS:**

Head Direction: When firing rates are organized by the associated head direction of the animal they can be exposed to the Rayleigh test for non-uniformity. SC neurons do not seem to be modulated by head direction. We found that 26/77 dS neurons yielded significant results. However, as stated several of the dS neurons had very obvious bi-directional tuning. As such, further analysis of data will demand application of circular statistic that assesses bi-directional firing.

Path Discrimination: Only recording sessions where the animal ran at least three times to each route was included in this analysis. We analyzed a total of 30 SC neurons across four animals. Population analysis of the four segments of the route corresponding to predictive activity of both first and third turn and current action on the first and third turn was conducted. We found that 12/30 neurons fired significantly different when the upcoming first turn was a left versus a right. 10/30 neurons fired significantly different when the current action for the first turn was a left or a right. 7/30 neurons were predictive of the third turn, firing differentially when the upcoming turn was a left or a right. Lastly, 8/30 discriminated the third turn by firing significantly different when the turn was a left or a right.

We analyzed a total of 55 dS neurons. Population analysis for dS was conducted in the same manner as SC analysis. We found that 30/55 neurons discriminated their activity during the pre-turn 1 segment when the animal was going to make a left versus a right. 26/55 fired significantly different during the first turn, when the action was a left versus a right. 10/55 neurons fired discriminately during the pre-turn 3 segment when the animal was going to make a left versus a right. Lastly, 22/55 fired significantly different during turn 3, when the animal was making a right versus a left.

From such a group of tests, one would expect 5% of results to appear significant simply due to variation, but we see in all cases four times as many neurons each with p-value less than .05. We therefore conclude that an appreciable number of neurons in both dS and SC are sufficiently impacted by the upcoming and current action.



Population Correlation Matrix: The correlation matrix yields that the highest correlations are along the main diagonal. These correspond to position points on the route that are closest to each other.

-Pre-choice turn versus pre-forced turn: SC population analysis observed lower average correlation values for pre-turn 1 and pre-turn 2 segments (condition 1) than for pre-turn 1 and pre-turn 3 segments (condition 2), for routes 1, 2, and 3. Route 4 yielded similar results between both conditions. Alternatively, dS population analysis observed higher average r-values for condition 2 across all four routes.

Route	SC condition 1 mean	SC condition 1 std dev	SC condition 2 mean	SC condition 2 std dev
1	.2252	.0228	.4454	.0217
2	.3089	.0204	.4872	.0074
3	.5422	.0180	.5757	.0135
4	.5702	.0211	.5752	.0116

Figure 1: SC mean and std dev of r-values for all routes. Condition 1: pre-turn 1(choice) correlated with pre-turn 2 (forced). Condition 2: pre-turn 1 (choice) correlated with pre-turn 3 (choice)

Route	dS condition 1 mean	dS condition 1 std dev	dS condition 2 mean	dS condition 2 std dev
1	-.0647	.0136	.3266	.0190
2	-.0756	.0143	.1874	.0153
3	-.0534	.0209	.3665	.0149
4	-.0063	.0164	.3527	.0167

Figure 2: dS mean and std of r-values for all routes. Condition 1: pre-turn 1(choice) correlated with pre-turn 2 (forced). Condition 2: pre-turn 1 (choice) correlated with pre-turn 3 (choice)

-Ranking: Additional analysis of pre-turn choice segments against pre-turn forced segments utilized the same categorization of conditions in the pre-choice turn versus pre-forced turn analysis. Results show that most routes for both SC and dS had significantly different r-values for condition 1 versus condition 2.

Route	SC significance (1=yes, 0=no)	SC p-value	dS significance (1=yes, 0=no)	dS p-value
1	1	<.001	1	<.001
2	1	<.001	1	<.001
3	1	<.001	1	<.001
4	0	.20	1	<.001

Figure 3: t-test results for ranked r-values of condition 1 vs. condition 2 for both SC and dS for all routes.

## **DISCUSSION**

**Head-Direction:** Head direction analysis showed that some dS and no SC cells were modulated by the head direction of the animal. We did observe dS cells that fired bi-directionally, with their preferred directions as 180 degrees apart. The preferred directions of these cells also persisted across reorientations of the triple-t maze and in the open field arena. This is a novel and unexpected finding since past literature has no mention of cells encoding two directions at once. This finding brings up several questions. First, what cues do these cells use to anchor to their preferred directions? Second, what types of environment would be conducive to producing such preferred directions? Third, what type of information do these cells provide for spatial cognition?

**Path Discrimination:** Most neurons in the dS were influenced by action, that is the upcoming and current action often modulated the firing rate of the neurons in this area. This is congruent with the hypothesis that hippocampal cells are modulated by contextual information regarding the trajectory of the animal. Additionally, a lower but significant proportion of SC cells were also influenced by the action of the animal. The observation that both of these structures contain action cells is supportive of the notion of their role in active navigation. However, further analysis is required to ascertain their exact role in spatial cognition. For example, SC and dS cells are modulated by the upcoming and current action, but the modulation of firing

rate according to these variables is not as robust as would be seen in structures such as medial precentral. Thus, how these action correlates are utilized by the wider spatial network still remains an open question. Additionally, further analysis is required to dissociate the exact variables that modulate the firing rate of both of these regions. Although both structures encode action variables, it is clear by their mean firing rates across routes that this is not the only variable that modulates their firing rate. Further analysis is needed to quantify all variables modulating the firing rate of neurons in both of these structures.

Population Correlation Matrix: Observation of the correlation matrix of both structures for all routes show that the highest correlations are along the main diagonal. This means that adjacent position points along a route are most alike. Of importance, this means that both dS and SC discriminate their activity along the length of the route. However, a full determination of whether dS and SC are sensitive to position along a route demands future analysis.

-pre-choice turn vs pre-forced turn analysis: Population analysis of neurons in both the dS and SC showed that for most routes, activity over segments of the maze corresponding to a pre-turn forced choice (pre-turn 2) was less correlated with segments of the maze corresponding to a pre-turn choice (pre-turn 1) than when two maze segments corresponding to a pre-turn choice (pre-turn 1 and 3) was correlated with each other.

-Rank: Because neural data does not often follow a normal distribution, we did further ranking analyses to determine whether SC and dS discriminated between upcoming choice or forced turns. Ranking analysis of dS neurons shows that in all routes, pre-turn 1 activity was more correlated with pre-turn 3 activity than pre-turn 1 correlated with pre-turn 2. SC neurons showed the same pattern of activity for all routes except for route 4. The present data suggest

the both SC and dS neurons are modulated by whether the upcoming action requires a choice or whether the action has been predetermined.

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## FIGURES

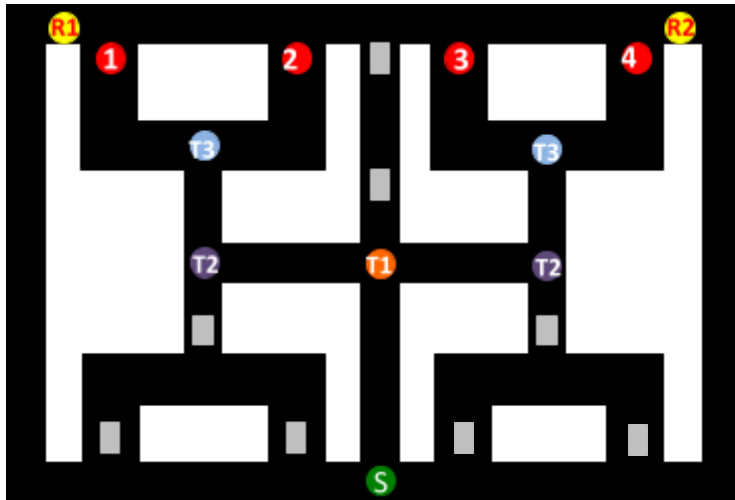


Figure 4: A schematic of the triple-t maze used as the navigation task. Gray blocks inserted was used to constrain the maze into 4 main routes and 2 return routes. The 4 main routes always started at the same start position indicated by a green circle. The goal site of each route differs and is indicated by the red circles. The orange circle indicates the first turn, purple circle indicates the second turn, and blue circle indicates the third turn for each route. The return routes start at positions indicated by the yellow circle and ends at the start position (green circle) of the four main paths.

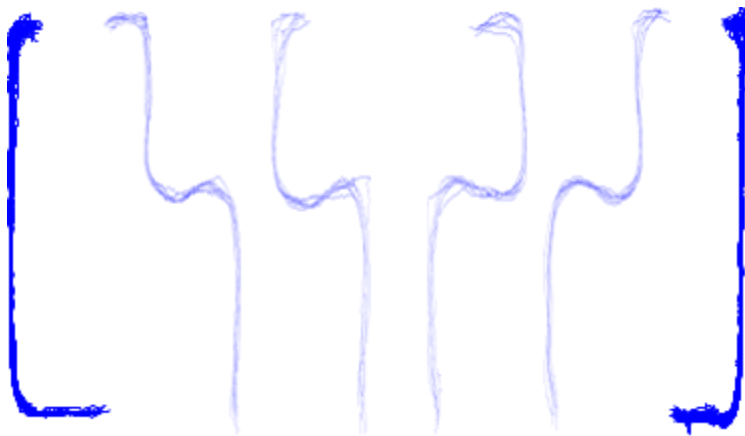
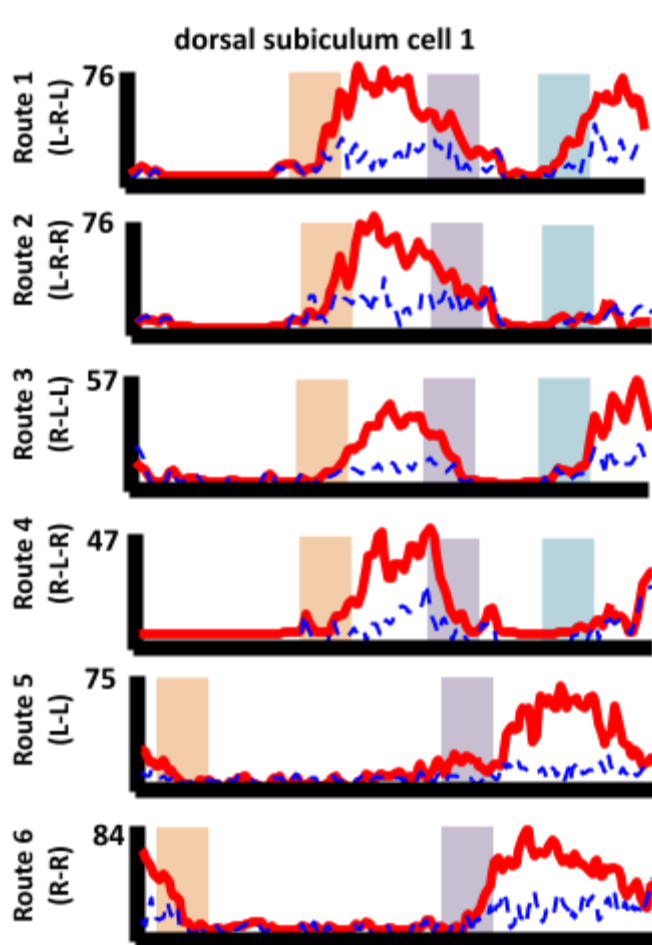
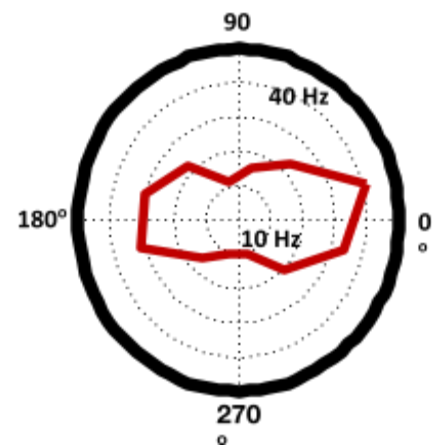


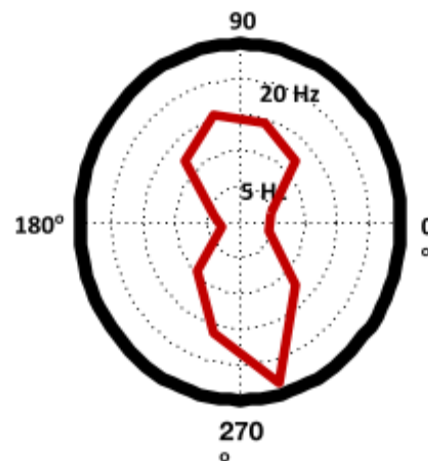
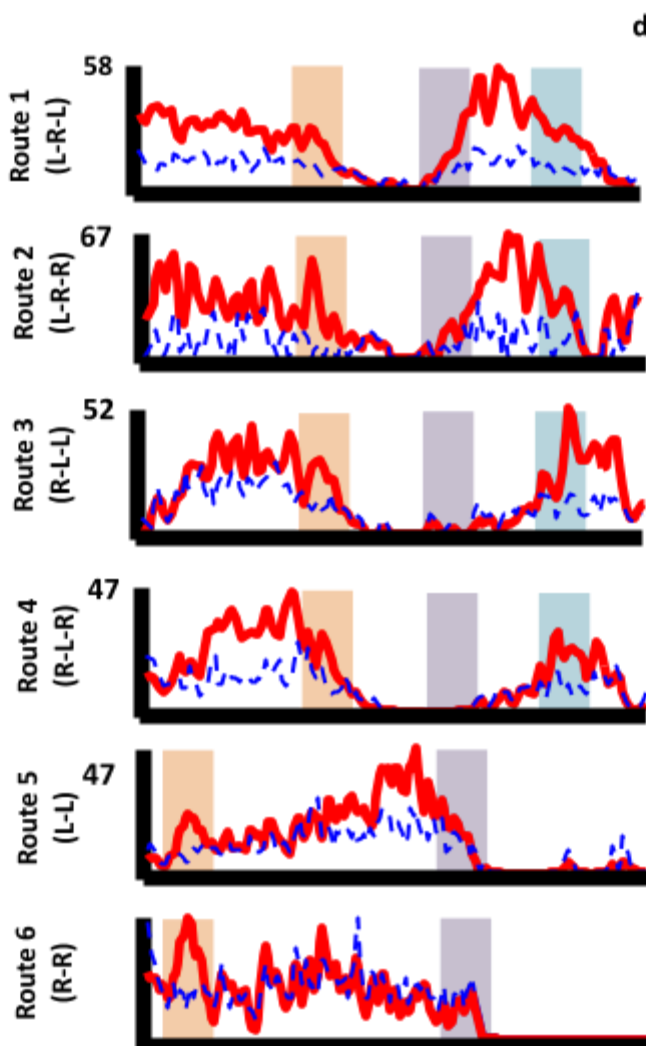
Figure 5: Representative tracking data for multiple runs across each of the six paths



— Mean  
- - Std. dev



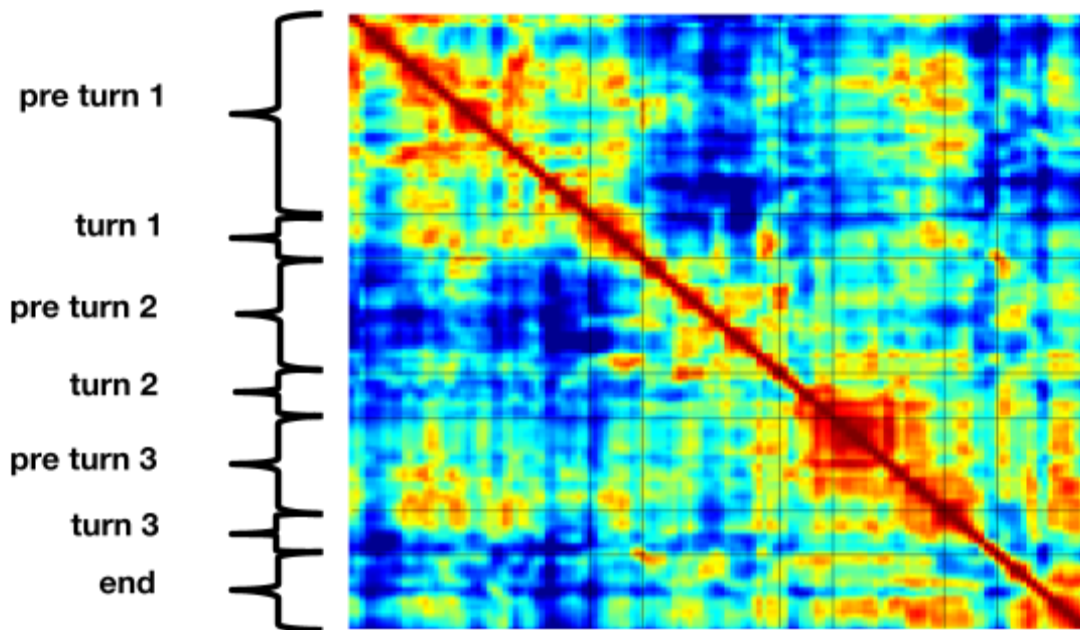
Left figure shows the mean firing rate of a dS bi-directional neuron along all 6 routes (4 main, 2 returns). X-axis is the position along the route, y-axis is firing rate in Hz. Colored blocks indicate turns on the path. The specific sequences of turns for each route are located on the left of each route. Linear rates show that this neuron fires more on maze segments when the animal is heading in an east/west direction compared to any other direction. Above figure shows directional tuning of the neuron corresponding to east/west axis.



Left figure shows the mean firing rate of a second dS bi-directional neuron along all 6 routes (4 main, 2 returns). X-axis is the position along the route, y-axis is firing rate in Hz. Colored blocks indicate turns on the path. The specific sequences of turns for each route are located on the left of each route. Linear rates show that this neuron fires more on maze segments when the animal is heading in a north/south direction compared to any other direction. Above figure shows directional tuning of the neuron corresponding to the north/south axis.



23

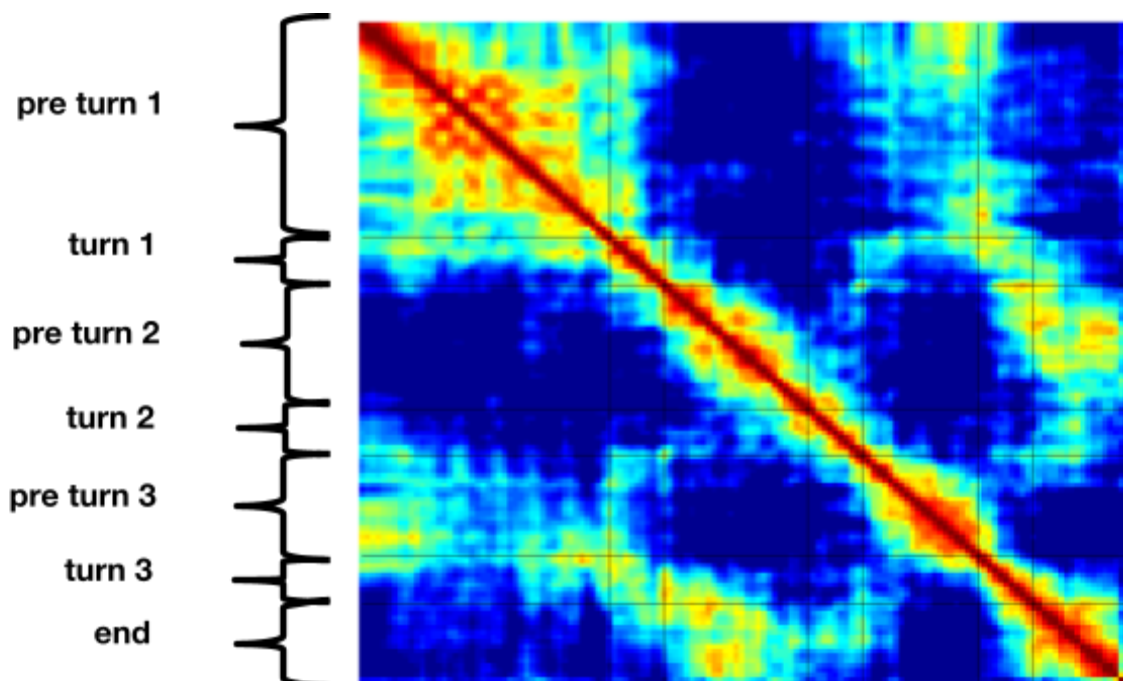


Top figure: SC, bottom figure: dS

Each image depicts the Pearson correlation (blue=0, red=1) between the population rate vector at each position and that at all other positions for route 1. High values (red) indicate that similar patterns are seen for any combination of positions.

The highest correlations are along the diagonal (adjacent points are most alike) indicating that SC and subiculum produce distinct firing patterns across all path positions (similar observations were made for paths 2,3,4) as is seen in posterior parietal cortex.

In both neuron populations, there is high similarity between the pre-turn 1 and pre-turn 3 sections which share the same movement direction and which both demand an upcoming L/R decision.



— Mean  
— Std. dev

SC cell 1

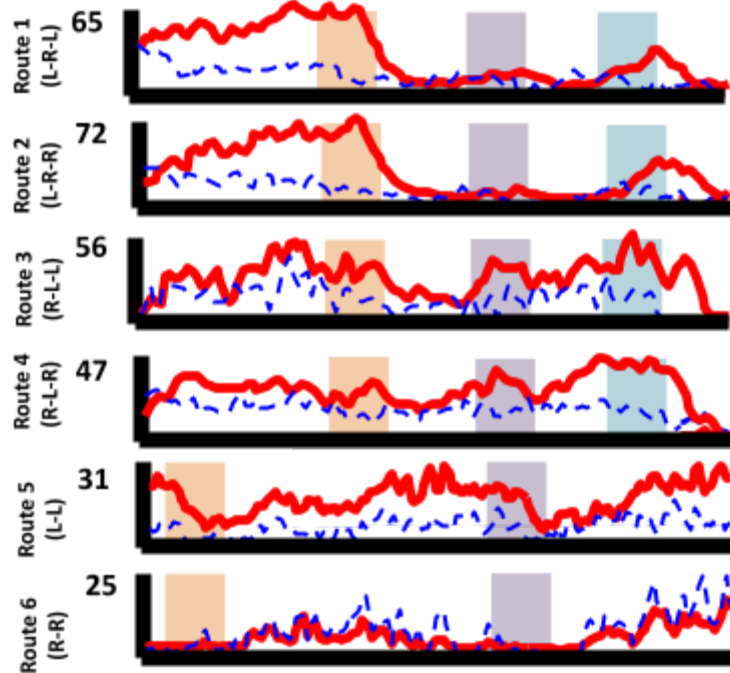


Figure 2: This figure shows the mean firing rate of a SC neuron along all 6 routes (4 main, 2 returns). X-axis is the position along the route, y-axis is firing rate in Hz. Colored blocks indicate turns on the path. The specific sequences of turns for each route are located on the left of each route.

Path discrimination analysis determined that this neuron fired significantly different on all path segments of interest, depending on the upcoming or current left right action. pre-turn 1 segment ( $p < .001$ ). Turn 1 segment ( $p < .001$ ). Pre-turn 3 segment ( $p < .001$ ). Turn 3 segment ( $p < .001$ ).

SC cell 2

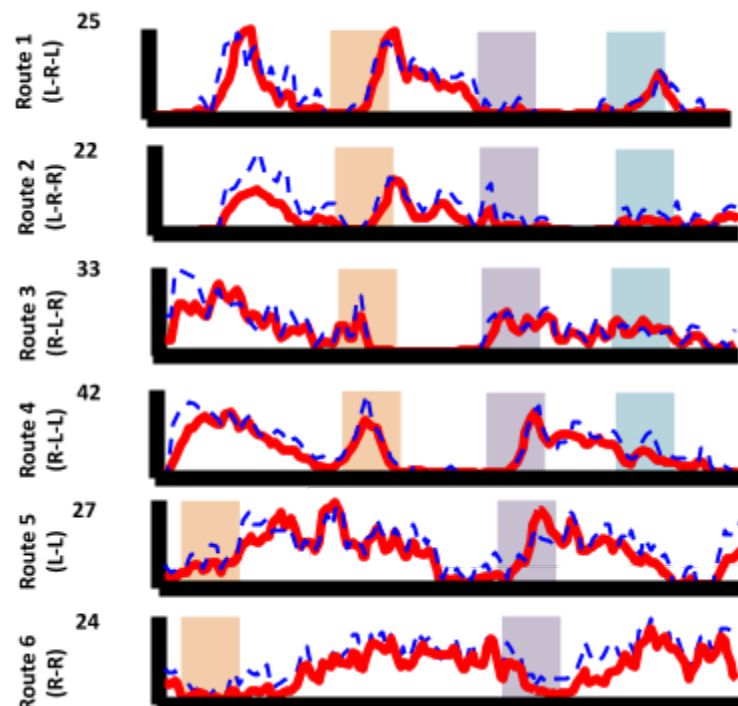


Figure N: This figure shows the mean firing rate of a second SC neuron along all 6 routes (4 main, 2 returns). X-axis is the position along the route, y-axis is firing rate in Hz. Colored blocks indicate turns on the path. The specific sequences of turns for each route are located on the left of each route.

Path discrimination analysis determined that this neuron fired significantly different on 3/4 path segments of interest, depending on the upcoming or current left right action. pre-turn 1 segment ( $p < .001$ ). Turn 1 segment ( $p = .001$ ). Pre-turn 3 segment ( $p = .31$ ). Turn 3 segment ( $p = .001$ ).