# HOW DOES THE BRAIN REPRESENT SPACE?

INSIGHTS FROM DIRECT HUMAN BRAIN RECORDINGS

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### **SPACE IN THE BRAIN**

### **SPACE IN THE BRAIN**



### HUMAN NAVIGATION SYSTEMS





PLACE CELLS Wilson & McNaughton (1993)

**HIPPOCAMPUS** 

THETA OSCILLATION (~8 HZ)

K. Diba

#### ALLOCENTRIC MAP-LIKE REPRESENTATIONS





"STARTING AT THE LIBRARY. WALK NORTH 300', WALK 200' WEST."

#### EGOCENTRIC VIEWER-BASED REPRESENTATIONS





"STARTING AT THE LIBRARY. WALK TO THE CHURCH, TURN LEFT, GO 200'."

#### **A BROADER MEMORY NETWORK**



# **KEY QUESTIONS**

How does the human brain orient during navigation?

Is the neuronal coding of location a model of how the brain represents other cognitive information?

# **OVERVIEW**

Neuronal coding of location and direction: Place, grid, and path cells

Theta oscillations in navigation

Place cells in memory

Brain stimulation and memory reinstatement

### **DIRECT HUMAN BRAIN RECORDINGS**





MISRA, JACOBS, ET AL., IN PRESS

Electrodes implanted for 1–3 weeks.

Hybrid micro/macro electrodes in hippocampus and medial temporal lobe. Grids and strips.

#### **DIRECT HUMAN BRAIN RECORDINGS**









### NAVIGATION IN A NARROW CORRIDOR

Subjects navigate a virtual circular environment.

Deliver each passenger to their desired destination store.



**JACOBS ET AL., 2010, PNAS** 

#### **HIPPOCAMPAL PLACE CELL**

#### **CLOCKWISE**

#### COUNTERCLOCKWISE

#### PLACE







### **DIRECTION-ENCODING PATH CELLS**



### **COUNTERCLOCKWISE PATH CELL**

#### CLOCKWISE (CW)



#### **COUNTERCLOCKWISE (CCW)**







### PATH CELLS ACROSS THE BRAIN



DARK SHADING: CW & CCW PATH CELLS. LIGHT SHADING: COMPLEX PATH CELLS.

### PATH-CELL DEMONSTRATION



#### HOW ARE PLACE-CELL REPRESENTATIONS FORMED?



Hafting et al., 2005

### **OPEN FIELD NAVIGATION TASK**

Patients learn locations of four visible objects.

Navigate between the locations with the objects hidden.



JACOBS ET AL., 2013, NATURE NEUROSCIENCE

## **HIPPOCAMPAL PLACE CELLS**



# **IDENTIFYING GRID CELLS**

Measure the firing rate at each location in environment.

Compute each cell's gridness score, which measures six-way-symmetric activity (Hafting et al., 2005).

Assess significance using a shuffling procedure.

### HUMAN ENTORHINAL GRID CELL (1)



### HUMAN ENTORHINAL GRID CELL (2)



#### REGIONAL DISTRIBUTION OF GRID CELLS



REGION KEY: EC, ENTORHINAL CORTEX; PHG, PARAHIPPOCAMPAL GYRUS; CC, CINGULATE CORTEX.

### **EXAMPLE CINGULATE GRID-LIKE CELL**



### ANALYSIS OF ALTERNATE SYMMETRY PATTERNS



P VALUE FROM A BINOMIAL TEST COMPARING THE PREVALENCE OF SYMMETRIC CELLS TO CHANCE LEVELS

### DO ENTORHINAL NEURONS REPRESENT MULTIPLE LOCATIONS?



Identify neurons that activate at similar locations across an environment.

Work with my Ph.D. student Jonathan Miller

#### PATH INVARIANT CELL



#### PATH INVARIANT CELLS 2 & 3



#### **REGIONAL ANALYSIS**



# Hippocampal representations emerge from grid and path cells



Place

ENTORHINAL, PARAHIPP.



**Grid-like** 

**HIPPOCAMPUS** 



## IS PLACE CELL ACTIVITY REINSTATED DURING MEMORY RETRIEVAL?

MILLER, ET AL. (SCIENCE, 2013)



#### EPISODIC MEMORY TASK IN A SPATIAL ENVIRONMENT



#### PHASE 1

Navigate between stores.

Pick up an item at each store.

#### PHASE 2

Freely recall the items



#### EPISODIC MEMORY TASK IN A SPATIAL ENVIRONMENT



### **DIRECTIONAL PLACE CELLS**



### PLACE-CELL REINSTATEMENT

Measure neural activity during recall.

Compared recall activity to place cells from navigation.

Compute cosine similarity between recall vector and each location.



#### **EXCLUDED RECALLS LAST PRESENTED ITEM AND ITEMS RECALLED WITHIN 1.5S.**

#### PLACE-CELL REPRESENTATIONS OF ITEM PICKUP LOCATIONS ARE REINSTATED DURING RECALL



#### INDIVIDUAL PLACE CELLS SHOW REINSTATEMENT



# BRAIN STIMULATION AND MEMORY

### **BRAIN STIMULATION AND MEMORY**



Penfield (1938) found that temporal-lobe stimulation caused memory recall.



#### **OUTSTANDING QUESTIONS**

Which memory is recalled by stimulation?

Why does inhibition cause memory recall? (Logothetis, 2010).

#### Jacobs, Lega, & Anderson, 2012

#### twenty three, twenty four, twenty five, twenty six,



#### DOCTOR

"How do you feel? Does it feel like a seizure"

#### PATIENT

"No - but why am I, like remembering all these things from high school?"

**DOCTOR** "Is it bad?"

PATIENT "It's just weird."

### **HIGH-SCHOOL MEMORY TASK**

**VISUALIZE THE ANSWER** 

(3-SEC)

READ A QUESTION (1-SEC)

Who was your high school's football coach?



SPEAK THE ANSWER (1-SEC)



### **HIGH-SCHOOL MEMORY TASK**

Question group	Example
HS person	Who was your HS gym teacher?
HS nonperson	What were your HS colors?
non-HS person	Who is your current epilepsy doctor?
non-HS nonperson	What city has the Golden Gate bridge?

#### NEURAL ACTIVITY FOLLOWING QUESTION ONSET

Data from my lab showed that the "high gamma band" (65–128 Hz) positively correlates with neuronal spiking



MANNING, JACOBS, ET AL., 2009; JACOBS ET AL., 2010



#### HIGH SCHOOL-RELATED ECoG ACTIVITY



**GRAY SHADING DENOTES P<0.01; BLACK DENOTES P<10-6** 

### IMPLICATIONS

#### ILLUSTRATION OF A THEORIZED HIGH-SCHOOL BRAIN REGION.



SMALL CIRCLES, CORTICAL COLUMNS. LARGE CIRCLE, STIMULATING ELECTRODE. Stimulation recreates activity from normal cognition.

Stimulation inhibits local neurons and activates afferent networks (Logothetis et al., 2010).

Neocortex encodes memory attributes like "high school"-ness (e.g., Norman & O'Reilly, 2002).

## THE HUMAN NAVIGATIONAL SYSTEM

#### **SIMILARITIES TO RODENTS**

Hippocampus encodes specific locations.

Entorhinal cortex supports coarser representations.

#### **DISTINCTIVE FEATURES**

Links between allocentric and egocentric systems.

Path and grid cells represent position within corridors.

Grid cells in cingulate.

Slow traveling "theta" oscillations in hippocampus.



### Predicting memory encoding in Treasure Hunt

#### Item presentation





#### Retrieval



#### 100 memory encoding events per hour



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