Brain and Behavior Underlying Human Spatial Navigation

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Why Study Navigation?

Wayfinding and Guidance

Human Health
Approach

Cognition

Spatial Knowledge
Information
Cognitive Processes
Neural Substrates

Neuroscience

BOLD Signal vs Distance Traveled
BOLD Signal vs Distance Traveled
BOLD Signal vs Time
Questions

• What is the structure of spatial knowledge?
  • Cognitive graphs
• How can we learn new environments?
  • Active learning
• How does the human brain track locations during self-motion?
  • Path integration
• What sources of visual and body-based information contributes to human path integration?
• How do individuals differ in their spatial abilities?
• How does the brain process spatial information?
FROM COGNITIVE MAPS TO COGNITIVE GRAPHS
What is the structure of spatial knowledge?
Types of Spatial Knowledge

• Landmark
  • Salient objects or locations that provide navigational cues
Types of Spatial Knowledge

• Route
  • Series of place-action associations
Types of Spatial Knowledge

• **Graph**
  • A network of place nodes linked by path edges

• **Labeled Graph**
  • Local metric information
  • Coarse, contains biases

Types of Spatial Knowledge

- Survey
  - Maplike knowledge of metric distances and angles between locations
  - Enables shortcuts
## Cognitive Processes Involved

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HOW CAN WE LEARN NEW ENVIRONMENTS?

How does active navigation contribute to spatial learning?
What is “Active”? 

- Physical Activity
  - Proprioception
  - Vestibular information
  - Efferent motor commands

- Cognitive Activity
  - Allocation of attention
  - Cognitive decision-making
  - Mental manipulation

Maze Learning
Shortest Route Task
Decision Making and Individual Differences

Proportion Correct

Information

Walk
Video

Proportion Correct

Rank Order

Walking Groups

Free
Guided

Chrastil & Warren, JEP:LMC, 2015
Active Navigation – Next Experiments

- Does active decision making increase synchronous communication in the brain? – EEG
- Do better navigators have greater connectivity between different regions in the brain? – fMRI
How can we learn new environments?

- Specific components of active learning differentially contribute to particular forms of spatial knowledge
  - Active walking contributes to survey knowledge
  - Active decision making contributes to graph knowledge
- Individual differences in learning
SPATIAL LEARNING THROUGH SELF-MOTION

How does the brain track locations during human path integration?
What sources of visual and body-based information contribute to human path integration?
Path Integration

Continuous updating of position and orientation during movement in an environment

- Tracking a location
- Tracking translation and rotation

Chrastil & Warren, *in preparation*
Chrastil et al., *in preparation*
Vision and Path Integration

Egocentric
- Homing Representation
- Orientation (Bearing)
- Angular Velocity
- Head Direction

Allocentric
- Configural Representation
- Arc Length
- Reference Point
- Travel Direction

- Position Representation
- Metric Representation
- Velocity
- Time
- Linear Speed

Global Computations

Local Computations
Path Integration – Cognition

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Survey Knowledge

Labeled Graph Knowledge
Path Integration - Neuroscience

- Hippocampus, retrosplenial cortex, parahippocampal cortex, entorhinal cortex, precuneus, medial prefrontal cortex
Two Models of Path Integration

- **Configural/Accumulator Model**: Encode entire outbound path, then compute return trajectory (Fujita et al., 1993; Klatzky et al., 1999; Loomis et al., 1993)

- **Homing Vector Model**: Track the trajectory back to the home location during the entire outbound path (Fujita et al., 1990; Philbeck et al., 2001)

- Recent evidence suggests that humans can use either strategy when necessary (Wiener et al., 2011)
Loop Closure

- Difficult problem in robotics
- Eliminates execution step in triangle completion

Substantial execution errors have been found

Chrastil & Warren, Exp Brain Res, 2017
Loop Closure

Chrastil et al., *J Neurosci*, 2015
Loop Closure
Spatial Coding – Homing Vector

- Hippocampus, RSC, and PHC track Euclidean distance from the home location
- Consistent with a homing vector system
- New directions for computational and animal models

Chrastil et al., *J Neurosci*, 2015
Homing Vector – Individual Differences

Larger gray matter volume in better navigators

Resting state connectivity
- Hippocampus and entorhinal cortex with Central Executive Network

Chrastil et al., eNeuro, 2017
Izen, Chrastil et al., in revision
Spatial Coding – Translation and Rotation

Translation

Hippocampus, Parahippocampal Cortex, Retrosplenial Cortex

Rotation

Hippocampus, Parahippocampal Cortex, Retrosplenial Cortex

 Chrastil et al., *Human Brain Mapping*, 2016

Correct trials only

Encoding phase (1st video)
How does the brain track locations during human path integration?

- Path integration – the constant updating of position and orientation during movement through an environment
- Neural evidence for a homing vector system of path integration
- Neural evidence for encoding translation and rotation
Cues to Self-Motion

i. Optic Flow
   • Information from vision about how fast you are moving

ii. Proprioception
   • Information from muscles and joints about the location of the limbs

iii. Motor Efference
   • Commands coming from the brain used to predict the locations of the limbs

iv. Vestibular Information
   • Information from inner ear about balance and rotation
<table>
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<tr>
<th>Vision</th>
<th>Yes</th>
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<tr>
<td>Yes</td>
<td>Walk Vision</td>
<td>Wheelchair Vision</td>
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**Proprioception**
Loop Closure

1, 2, 3 meter radii
3 additional radii as fillers
12 of trials at each radius per condition
4 start quadrants in room
Alternating right and left turns
N = 23 healthy young adults (10 women)
Position Error

Position Error

Chrastil et al., in preparation
Absolute Angular Error

Means

Chrastil et al., in preparation
Absolute Angular Error

Angular Deviations

- Radius: $p = 0.001, \eta_p^2 = 0.280$
- Vision: $p = 0.017, \eta_p^2 = 0.233$
- Walking: $p = 0.004, \eta_p^2 = 0.320$

Means

- Radius: $p = 0.003, \eta_p^2 = 0.268$
- Vision: $p < 0.001, \eta_p^2 = 0.502$
- Walking: $p < 0.001, \eta_p^2 = 0.461$

Chrastil et al., in preparation
Difficulty Ratings

Vision: $p < 0.001$, $\eta_p^2 = 0.728$

Chrastil et al., in preparation
What sources of visual and body-based information contribute to human path integration?

- Visual information and proprioceptive information contribute equally to location tracking during path integration.

- Pure vestibular (Wheelchair No Vision) was no better than chance and was less accurate and precise than all other conditions.

- Results differ from previous work showing primary contribution from proprioception.

- Loop closure might differ from triangle completion in the contributions of different sources of information.
Conclusions

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Summary

• What is the structure of spatial knowledge?
  • Cognitive graphs

• How can we learn new environments?
  • Active learning

• How does the human brain track locations during self-motion?
  • Path integration – homing vector in hippocampus, retrosplenial cortex

• What sources of visual and body-based information contributes to human path integration?
  • Vision and proprioception make equal contributions

• How do individuals differ in their spatial abilities?
  • Large range of individual abilities, gray matter volume differences, functional connectivity differences
Thank you!

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