structural abstraction and behavioral flexibility

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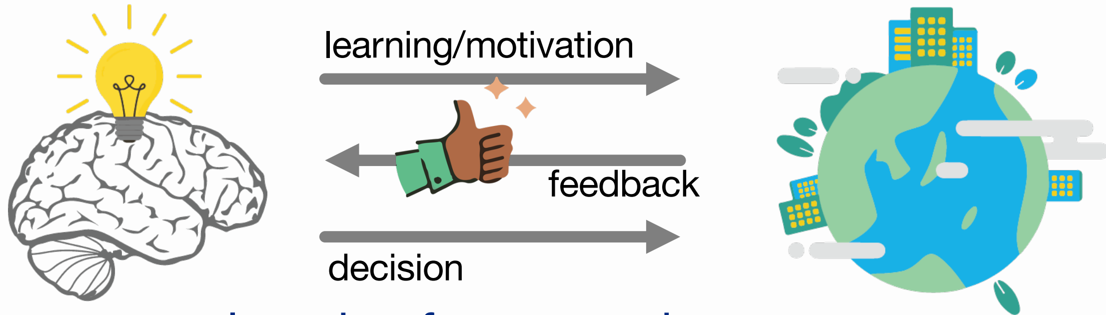
how do we make decisions that have never been made before?

lunch menu?

reinforcement learning (RL)



learning from experiences

Park et al., 2020

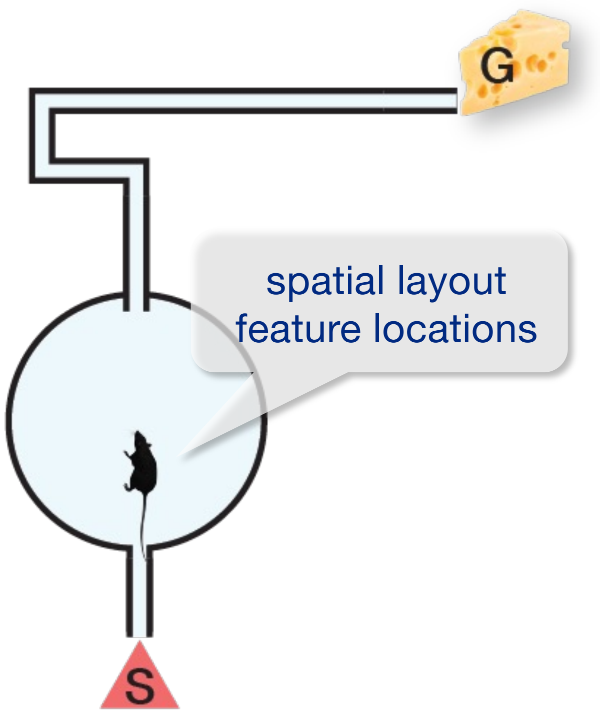
future colleague?

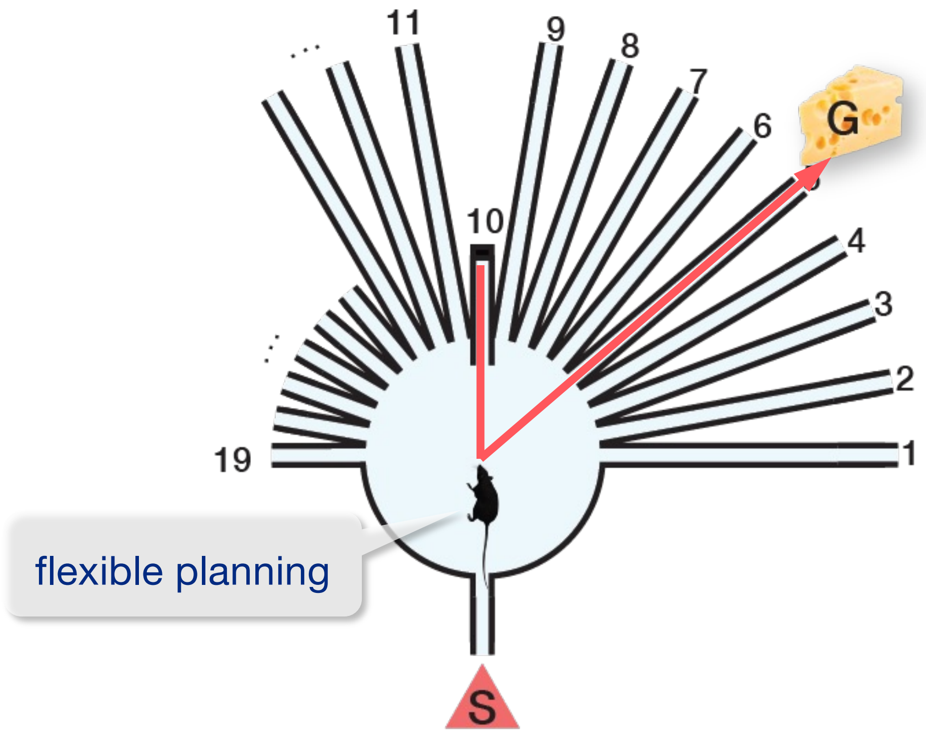
limits in standard reinforcement learning models

where do values come from in novel decisions?

how can we find an optimal route without prior experiences?

cognitive map

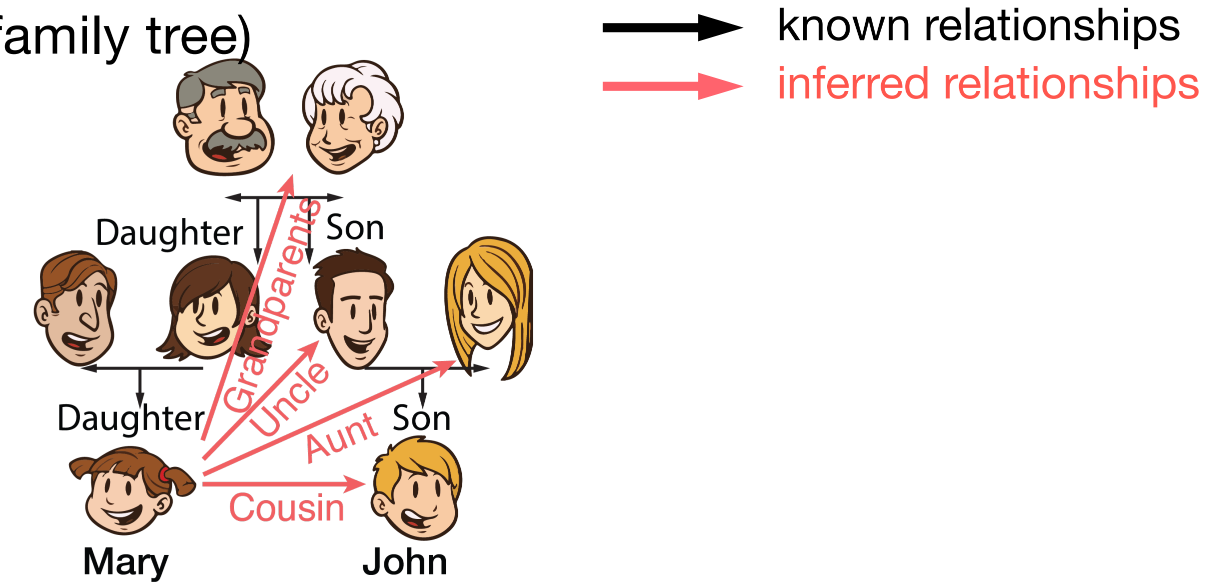




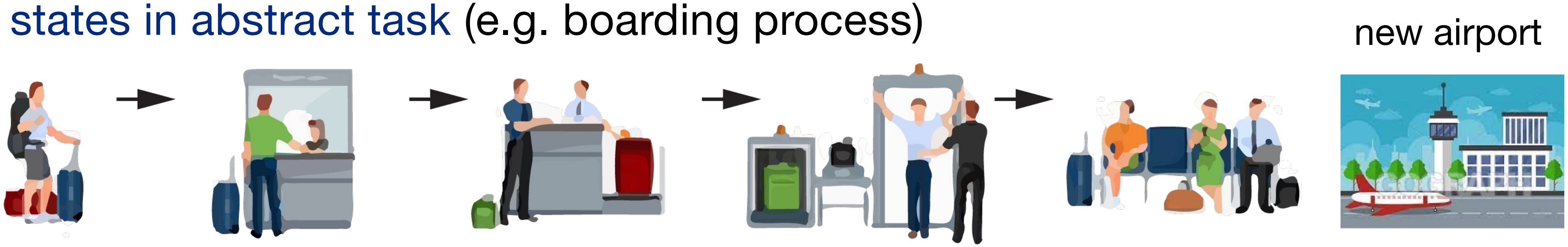
Tolman 1948

our cognitive map is not limited to relating physical locations

objects and people (e.g. family tree)



states in abstract task (e.g. boarding process)



Boorman, Sweigart, and Park, 2021
Behrens et al., 2018, Bellmund et al., 2018

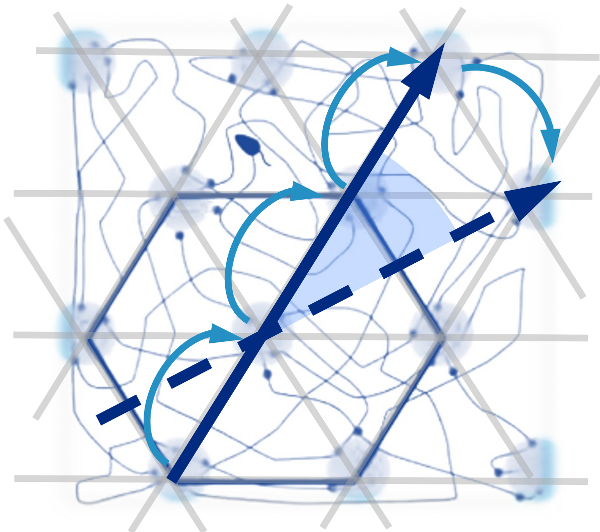
how does the brain build the cognitive map?

hippocampus (HC)

place cell

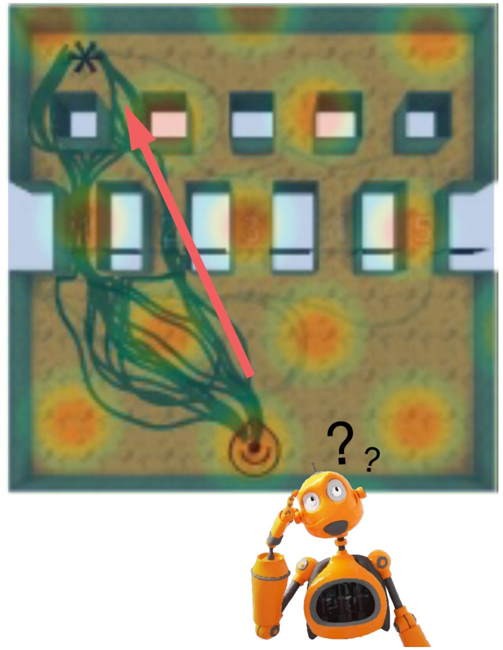
entorhinal cortex (EC)

grid cell



generalization

finding shortcuts



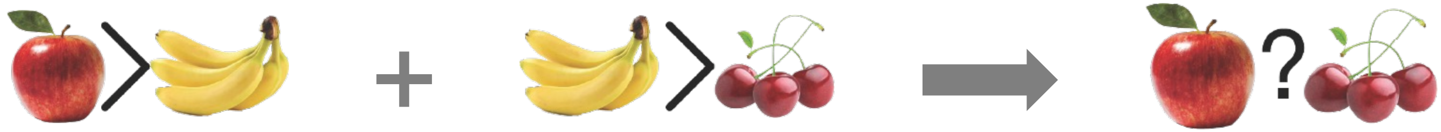
Hafting et al., 2005; Bush, Barry, and Burgess, 2014

Banino et al., 2018, Sorscher et al., 2020

behavioral flexibility in learning and decision making

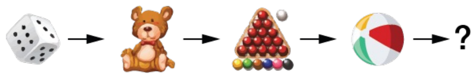
orbitofrontal cortex (OFC)

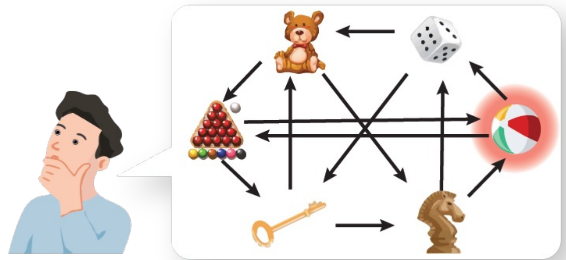
- *associated inferences*

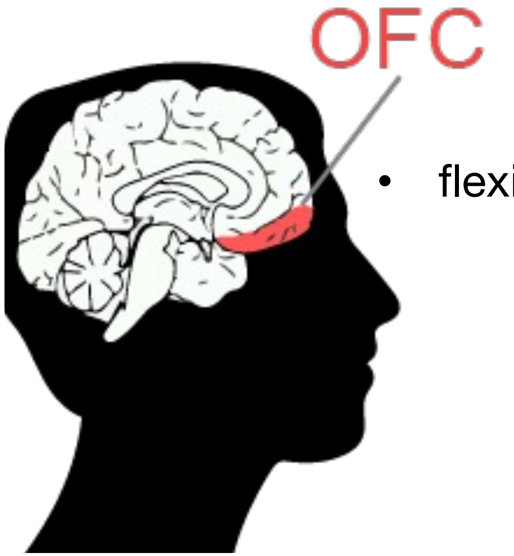


Spalding et al, 2018, Jones et al., 2012

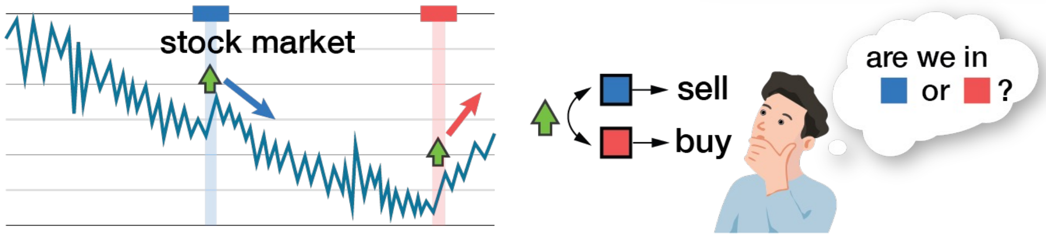
- current state in a *hidden task structure*







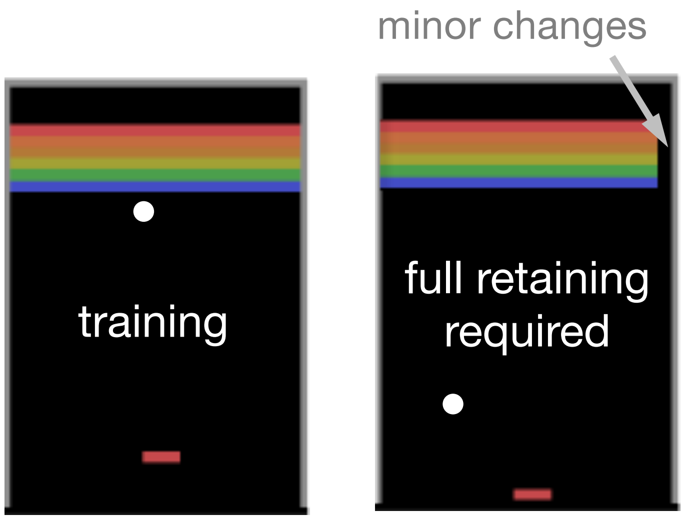
- flexible decision making



Boorman, Witkowski, Zhang, and Park, 2021
Schuck et al., 2016, Zhou et al, 2021, Basu et al., 2021

generalization and flexible decision making, a hallmark of human intelligence

- easy for humans but hard for AI
- the lack of behavioral flexibility in people with mental health disorders
- EC is the earliest to degenerate and the most damaged in Alzheimer’s disease
- potential applications for translational research and human-like AI



e,g., brick breaker game
Kansky et al., 2017

Uddin et al., 2021 *Hoesen et al., 1991, Igarashi, 2022*

questions

1. what is the *architecture* of the cognitive map of non-spatial abstract relationships in the brain?

   Park et al., 2020 Neuron

2. how does the brain use the cognitive map to make *flexible decisions* according to changing task goals?

   Park et al., 2023 BioRxiv

3. how does the brain use the cognitive map to *generalize* previous experiences and to find solutions to novel problems?

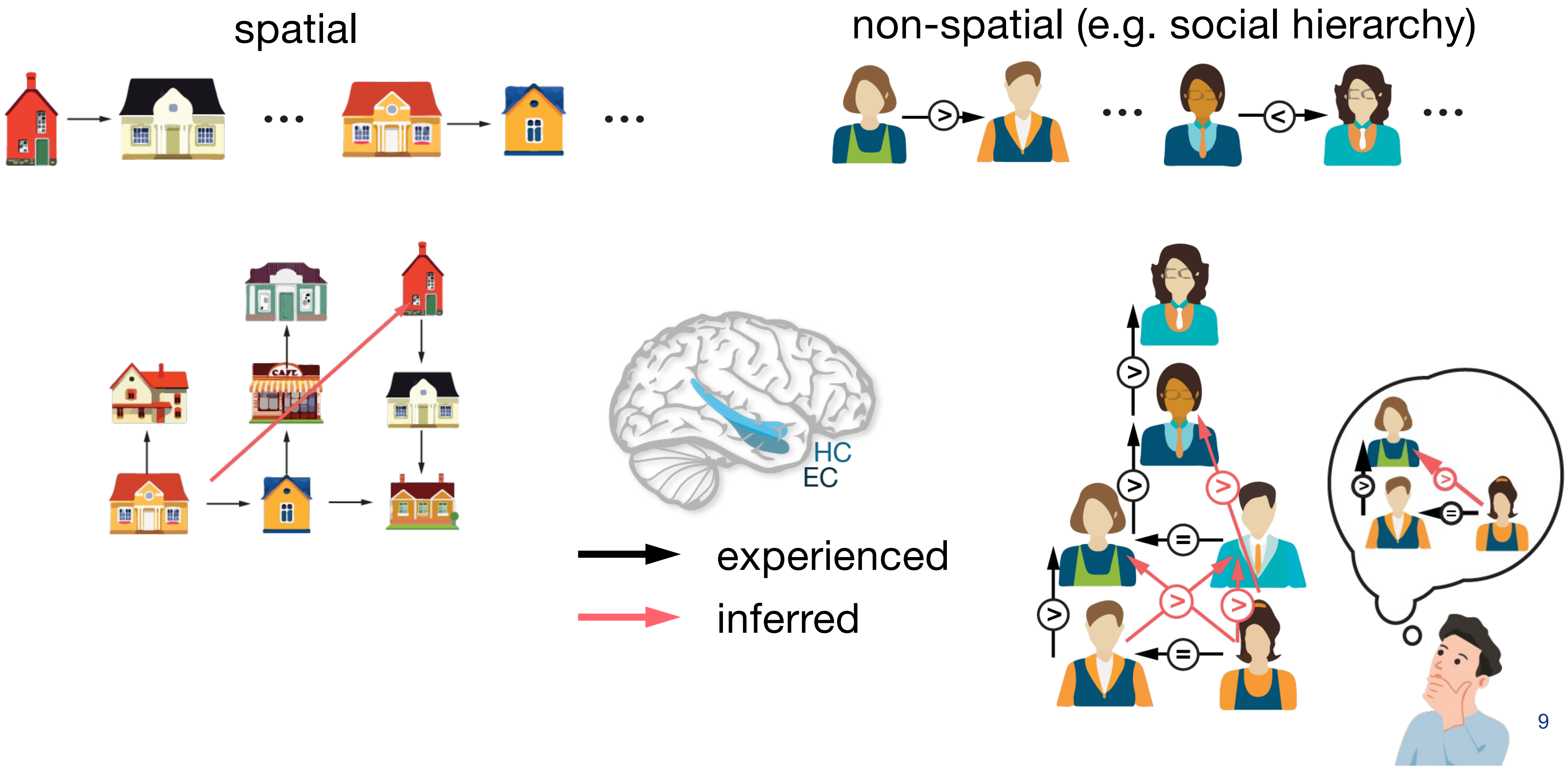
   Park et al., 2021 Nature neuroscience

architecture of the cognitive map

how does the brain represent and use the non-spatial relational structures for novel inferences?

Park et al., 2020 Neuron

representations of relational structures and novel inferences



what geometry does our brain use to represent a social hierarchy?

...

competence ↑

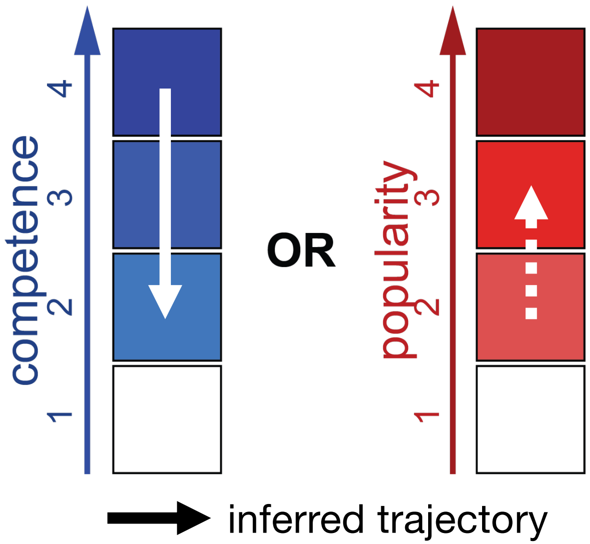
...

warmth / popularity ↑

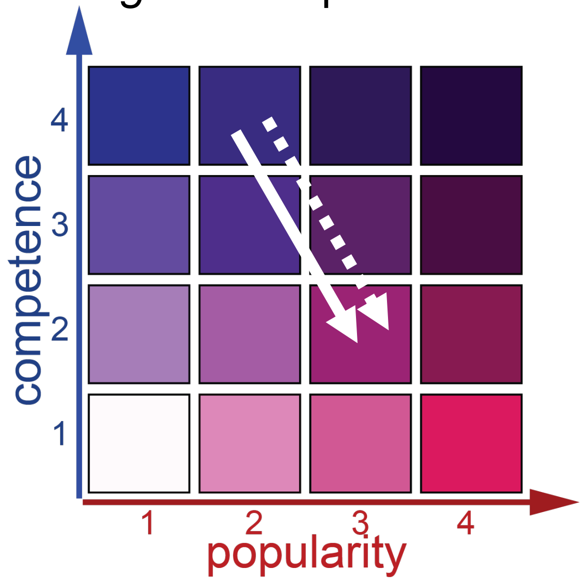
...

Fiske et al., 2007, 2018

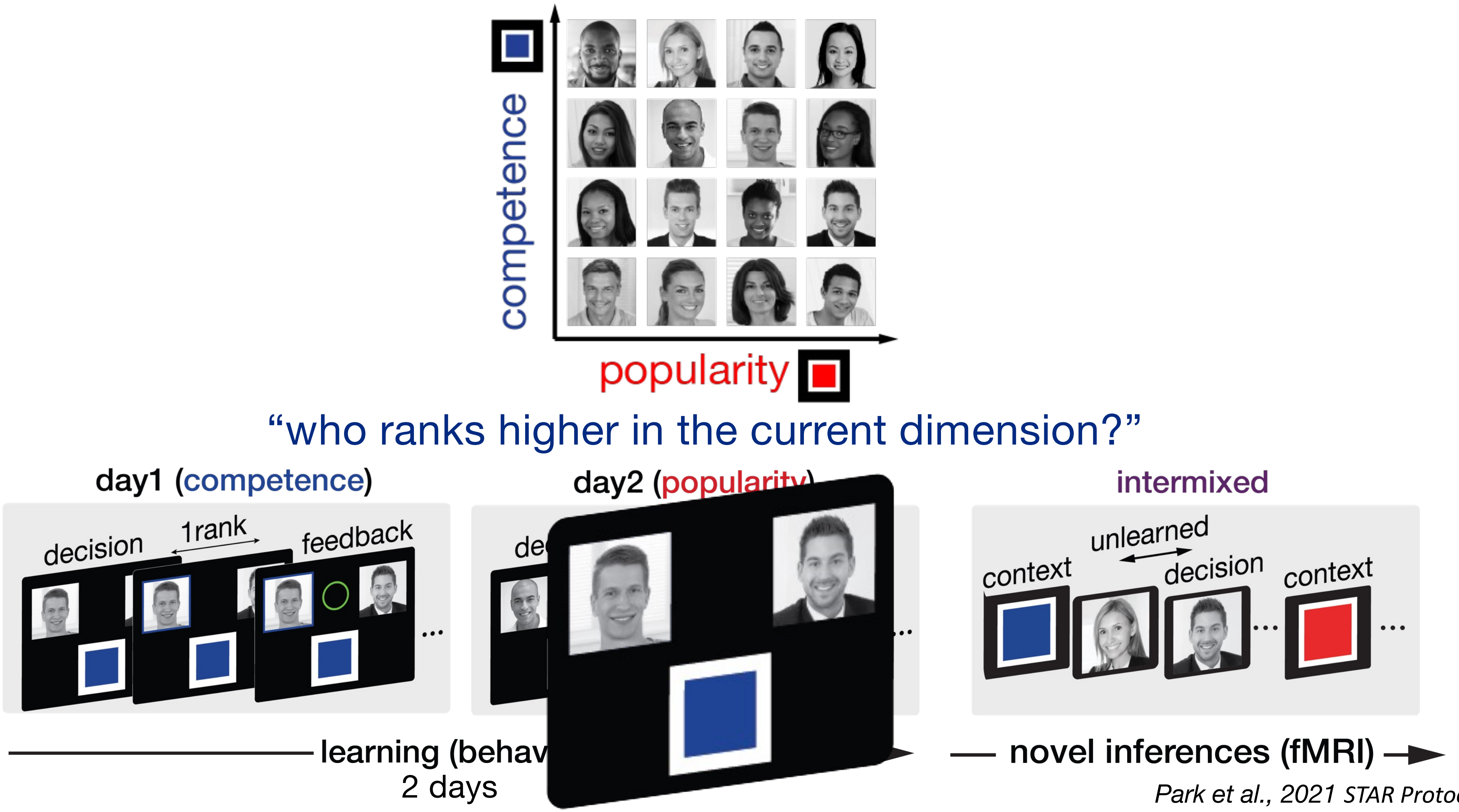
multiple 1-D representations



a single 2-D representation



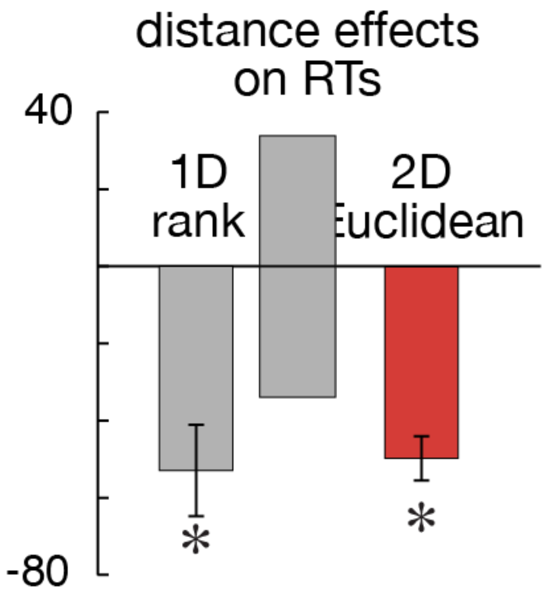
novel inference task in fMRI and behavioral training

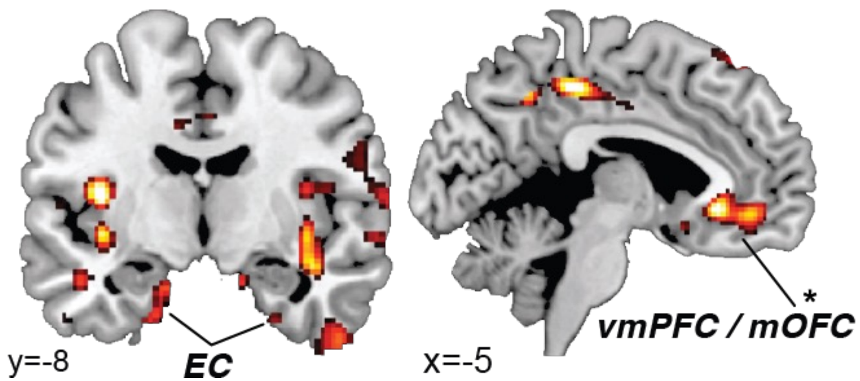


Park et al., 2021 STAR Protocols

evidence of using cognitive map for novel inferences

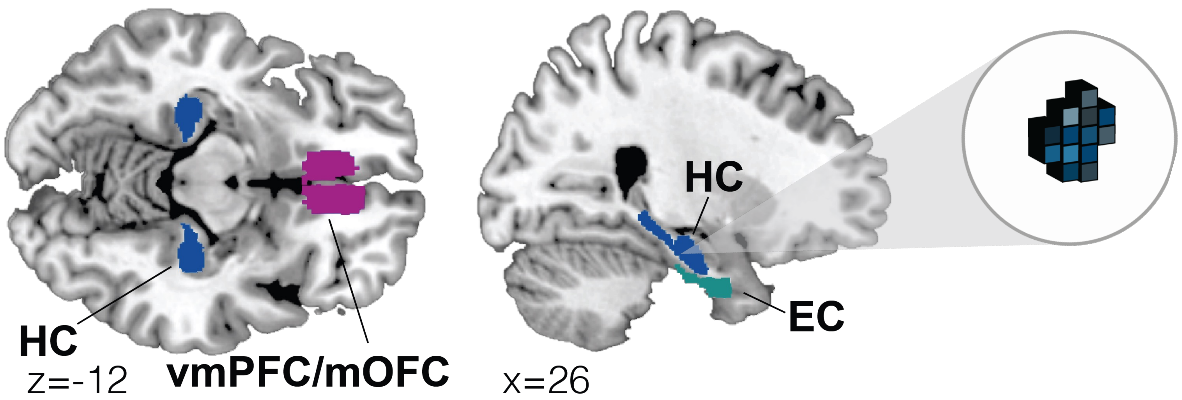
- a high level of accuracy in novel inferences (93.6%)
- on-the-fly computation or using the cognitive map for novel inferences?
- neural encoding of *2-D Euclidean distances* of inference trajectory

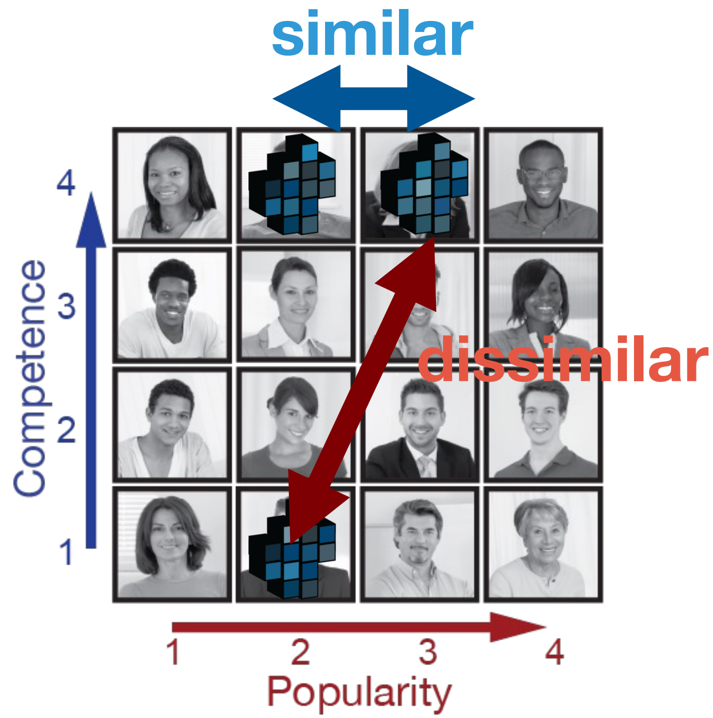




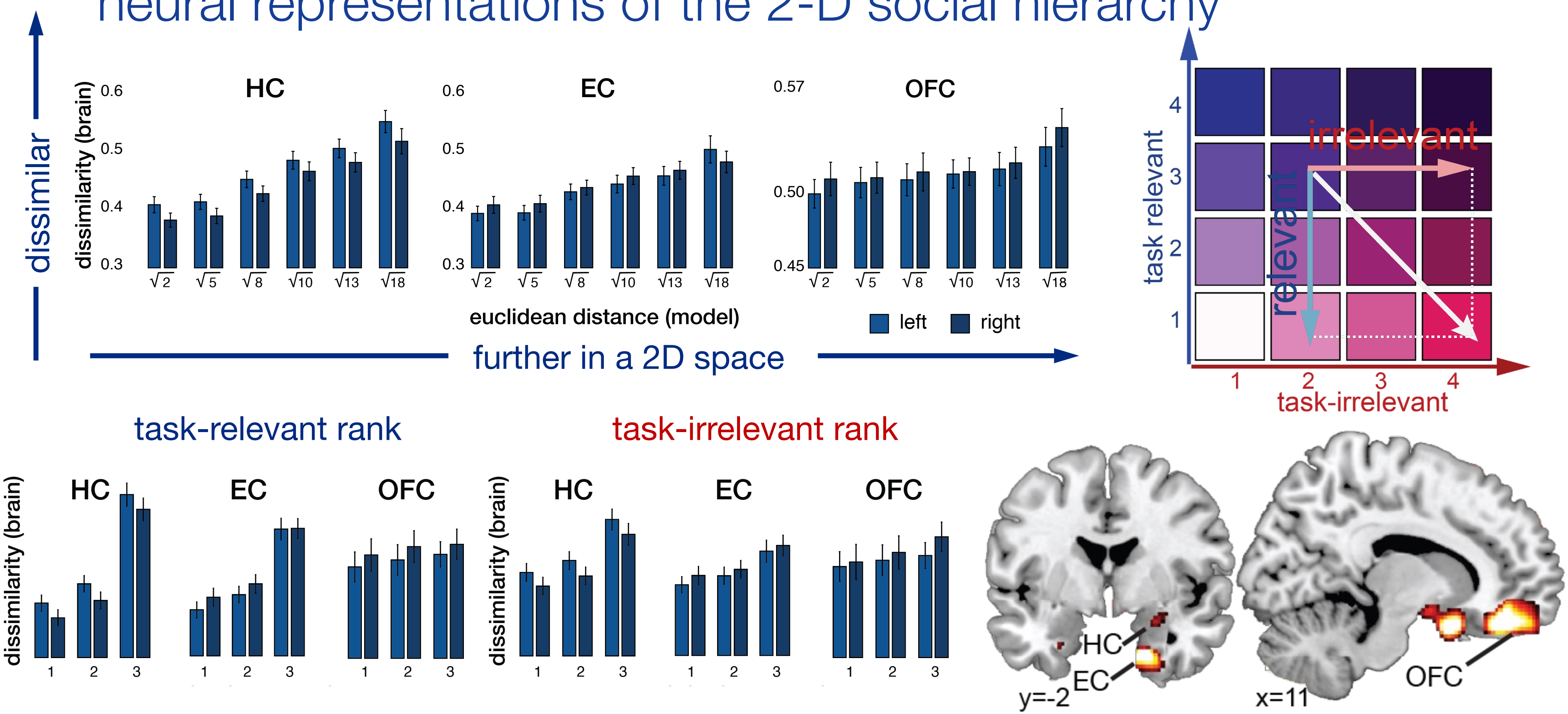
testing the 2-D representational geometry in the brain

representational similarity analysis (RSA)





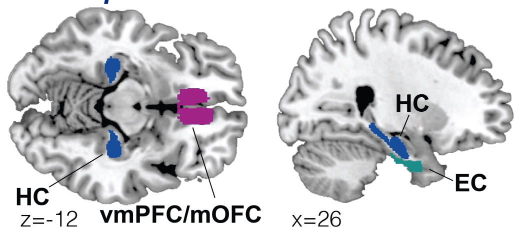
neural representations of the 2-D social hierarchy



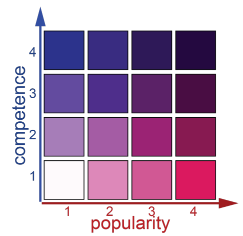
suggesting spontaneous combination (even when it is not necessary)

interim summary

- the same system to represent *non-spatial abstract relationships* among discrete entities

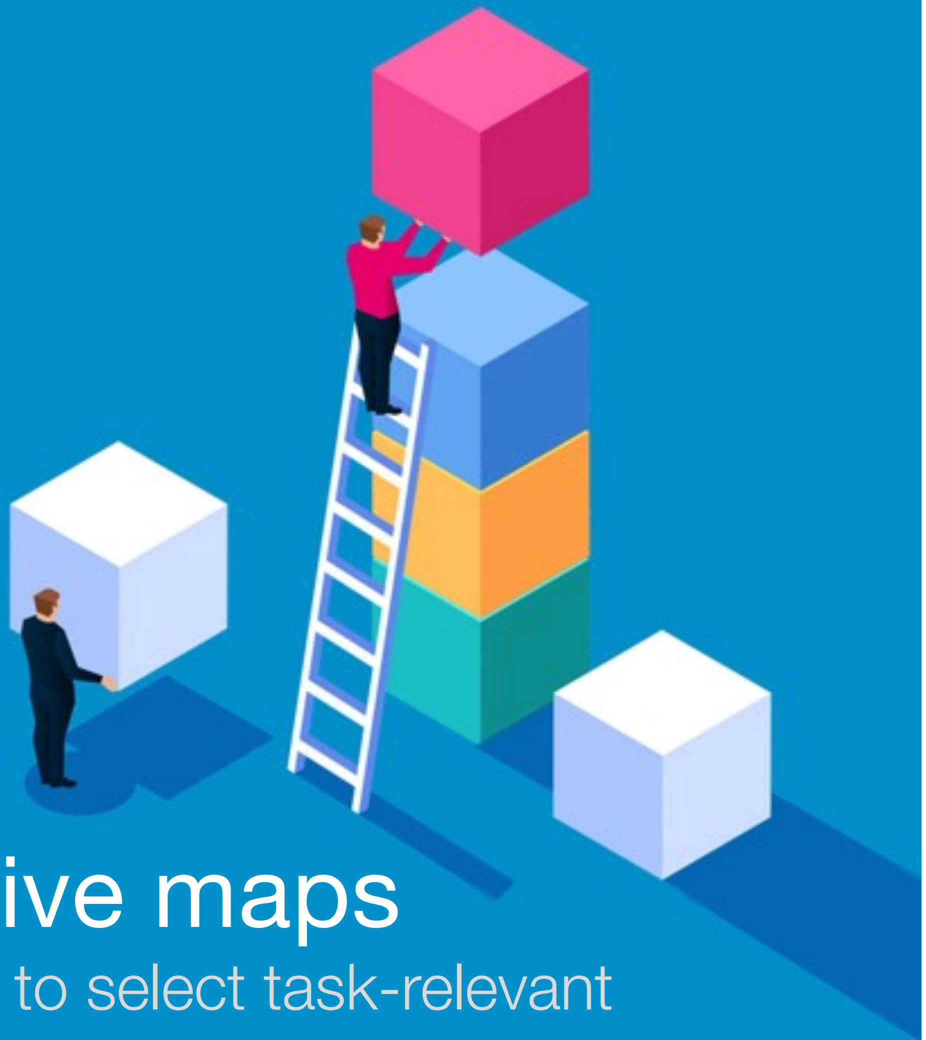


- the brain *combines* dimensions learned piecemeal on separate days into a unitary *multidimensional representation* in a 2-D space



- using the 2-D cognitive map, the EC and OFC encode *Euclidean distances* of inferred vectors between entities to afford *novel inferences*

- novel inferences depend on the ability to *find a direct route* through a multidimensional, abstract cognitive space



cognitive control in cognitive maps

how does cognitive control allow the brain to select task-relevant information from the multidimensional cognitive map?

Park et al., 2023 BioRxiv

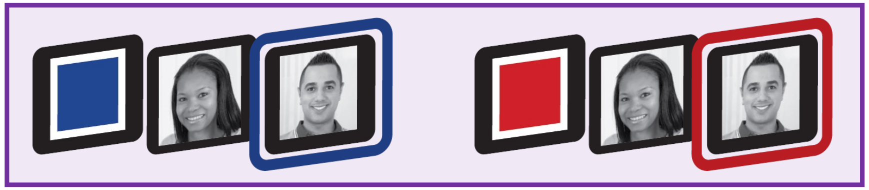
cognitive control for flexible decision making

external
"name the font color (don't read the word)"

internal
"who ranks higher in the given dimension?"

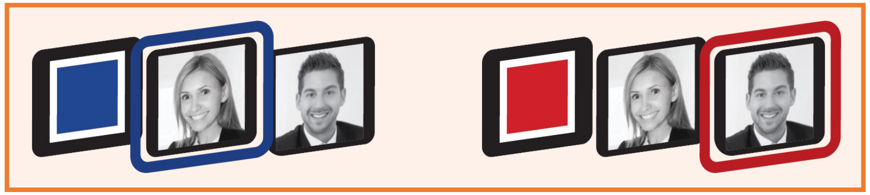
congruent

green yellow
red black red



incongruent

green yellow
red black red

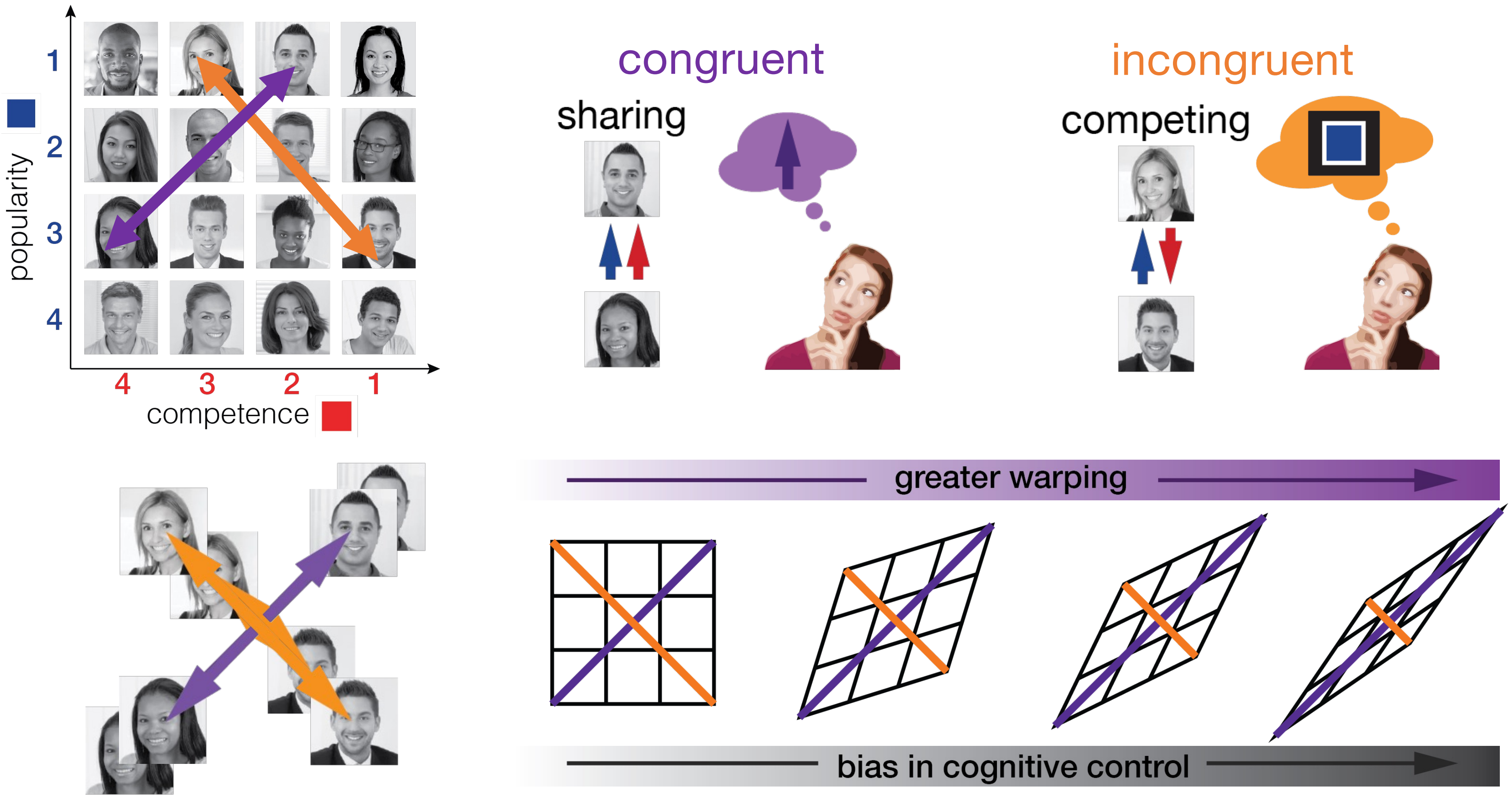


- incongruence → *control demands* ↑
- *context-dependent computation*
- same principles for inferences over the *cognitive map*?
- how does the representational geometry interact with changing task goals?

congruent
incongruent

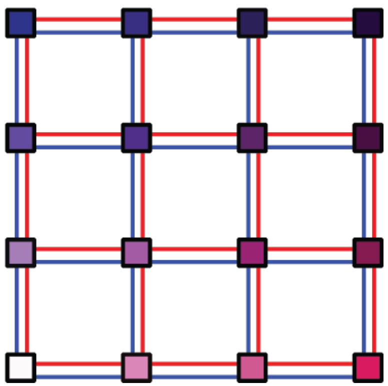
Mante et al., 2013, Aoi et al, 2020, Takagi et al., 2021

H1 effects of congruence on representational geometry

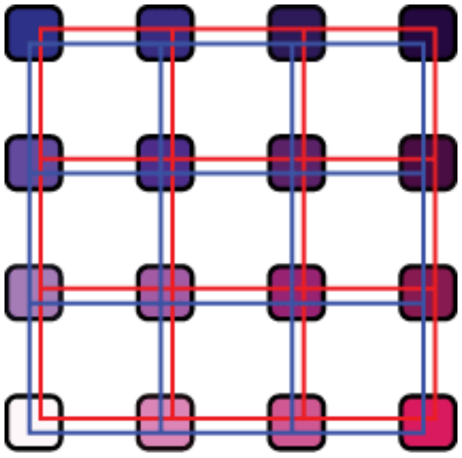


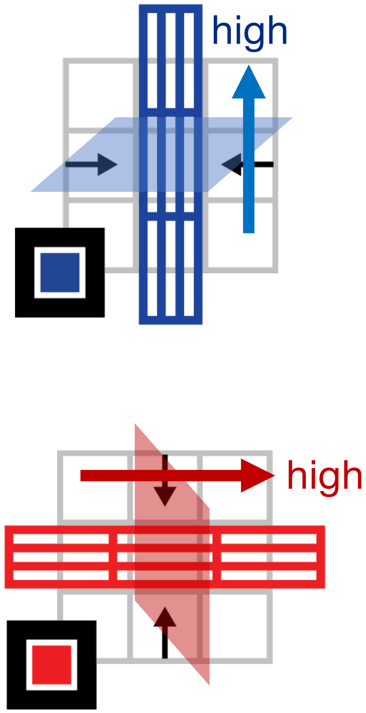
H2 task-dependent representation to support context-dependent computations

2-D task-independent



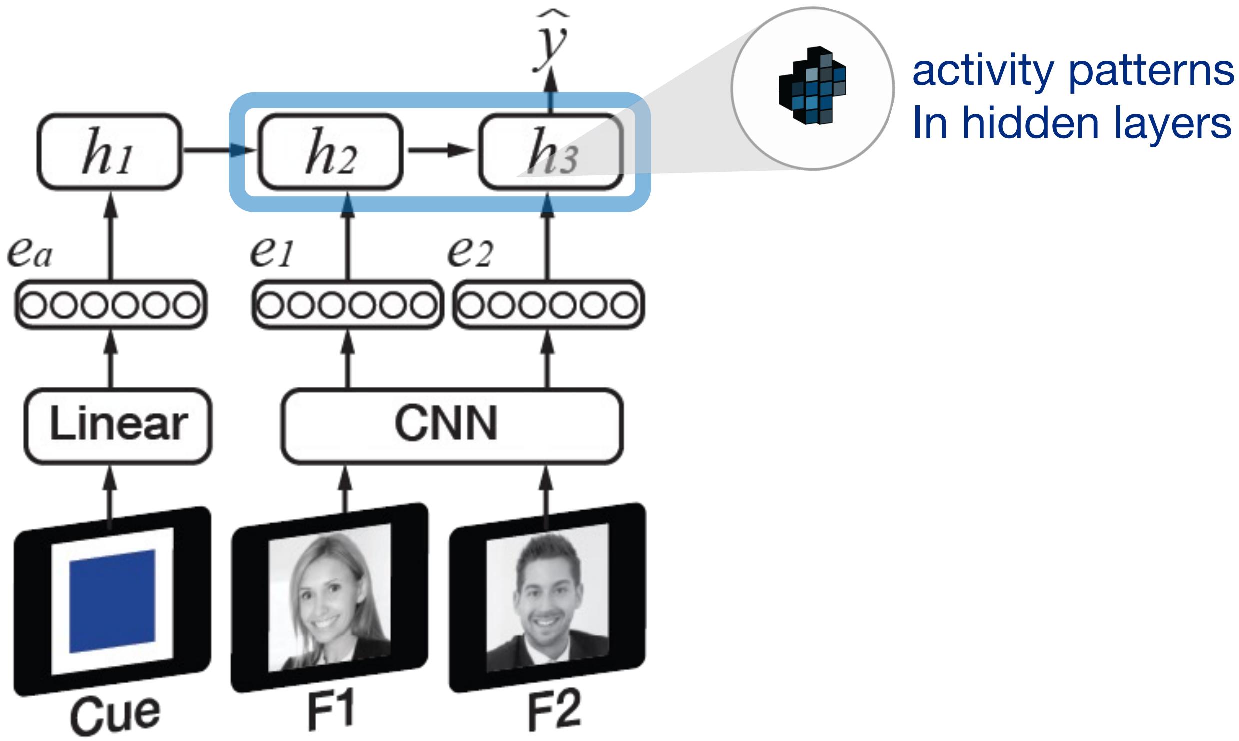
1-D task-dependent





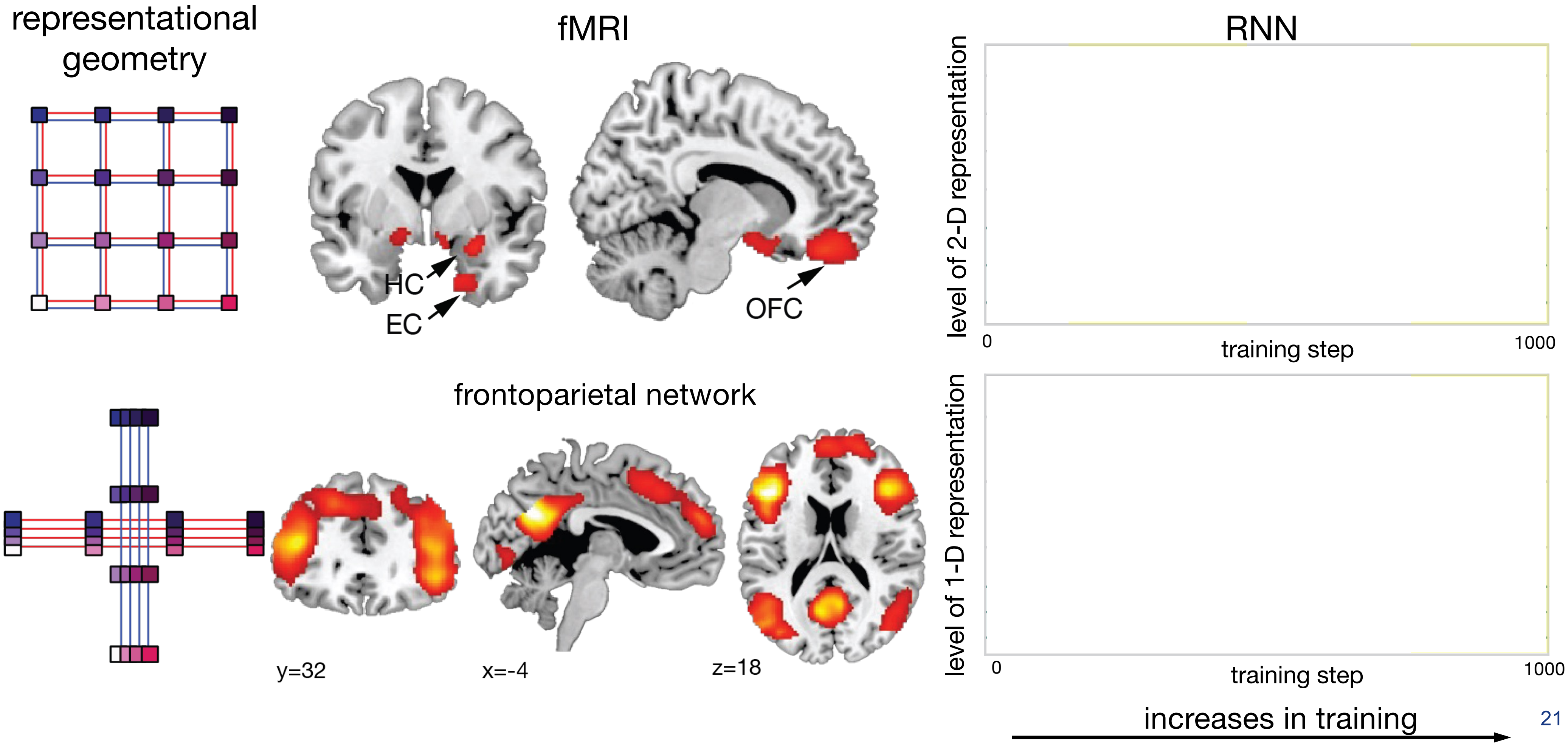
parallel analyses of recurrent neural network (RNN) and fMRI

Park et al., 2020

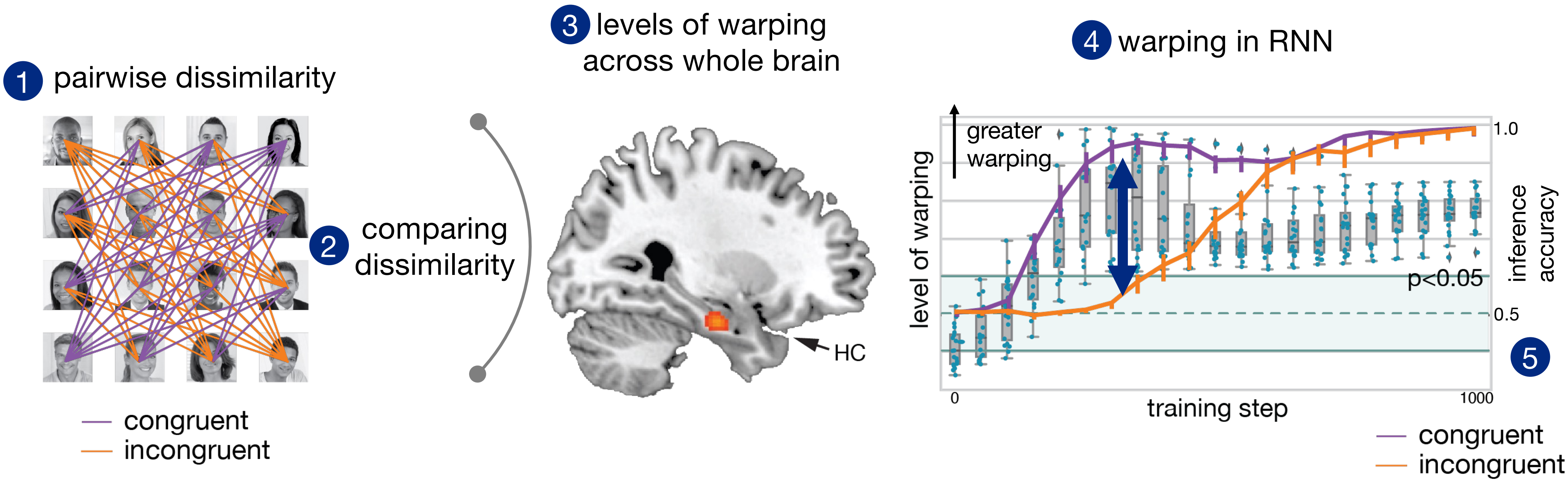


- *tracking changes* in the representational geometry in a course of training
- relating representational geometry to the *inference performance*

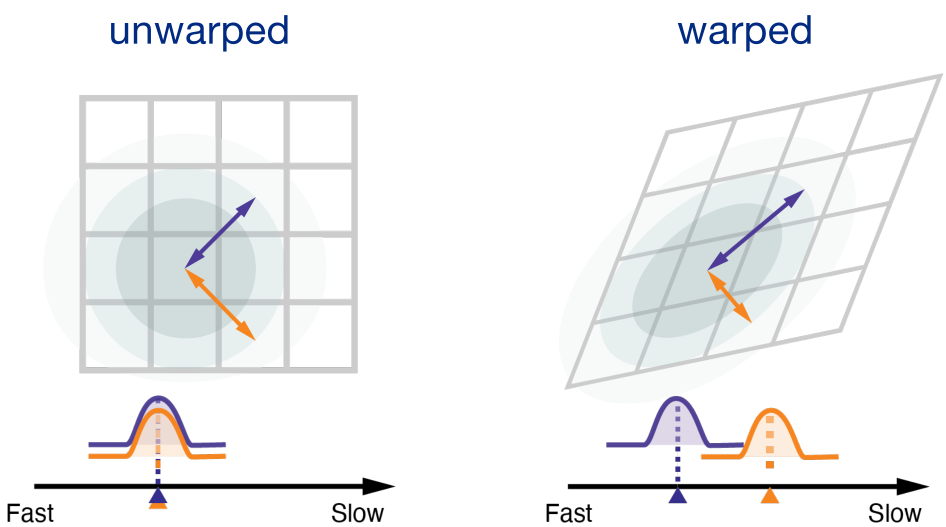
simultaneous representations of the cognitive map

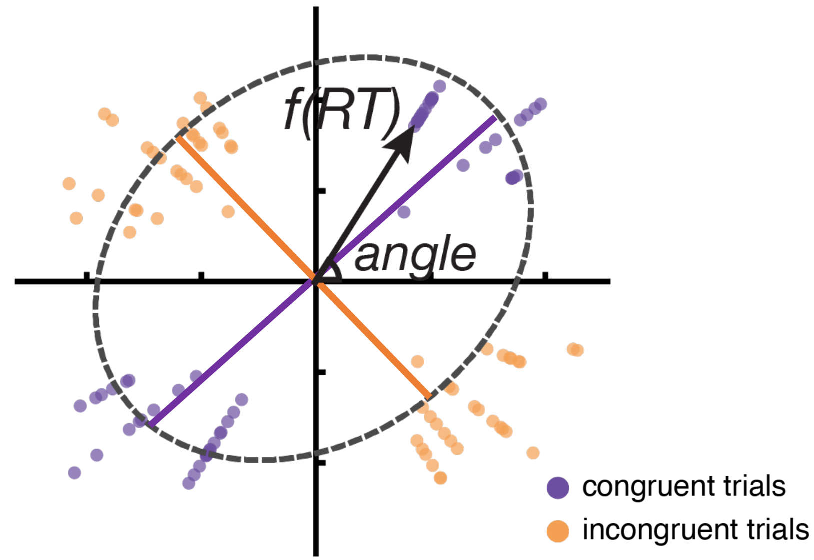


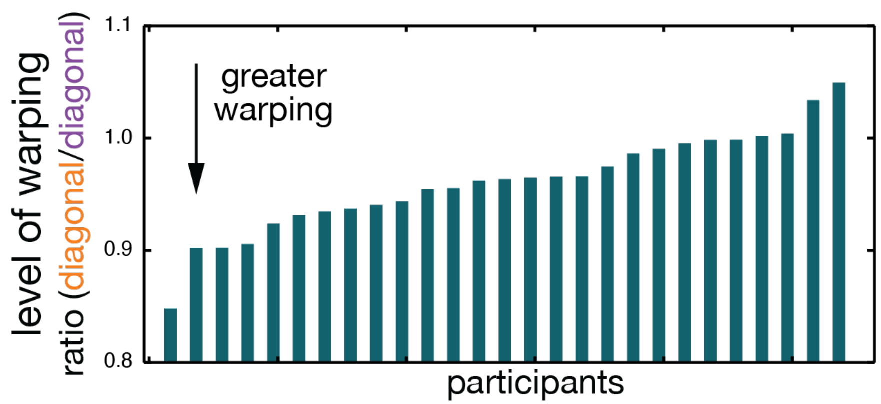
testing warping in 2-D representations of the cognitive map

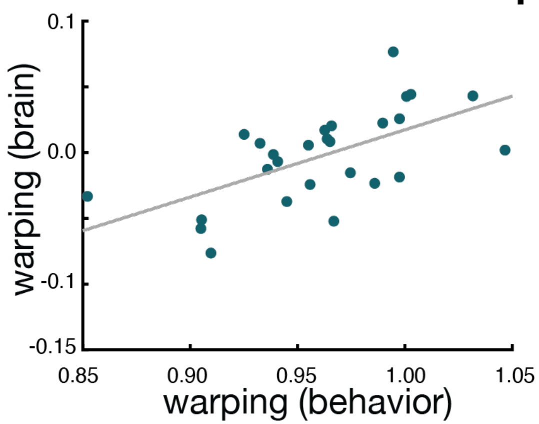


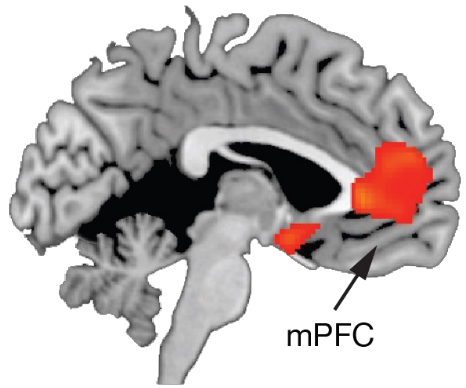
subjective levels of warping estimated from reaction times



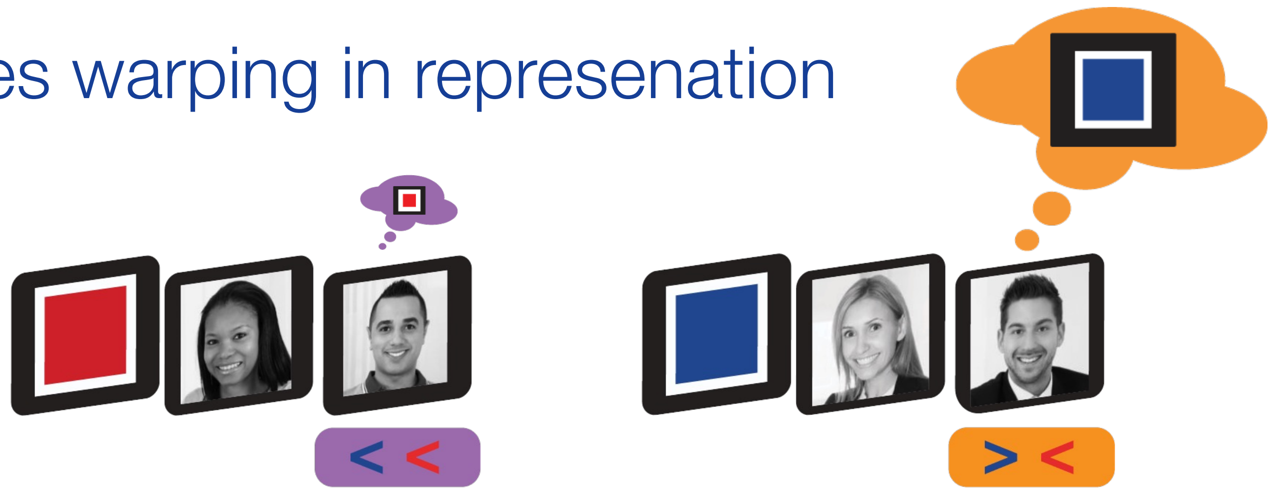


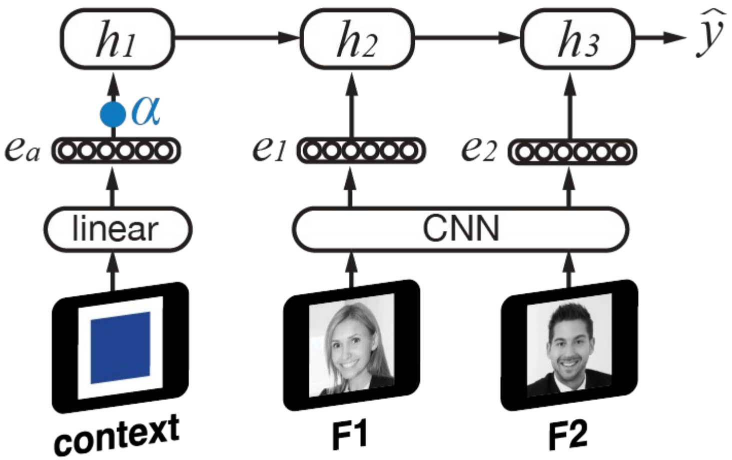


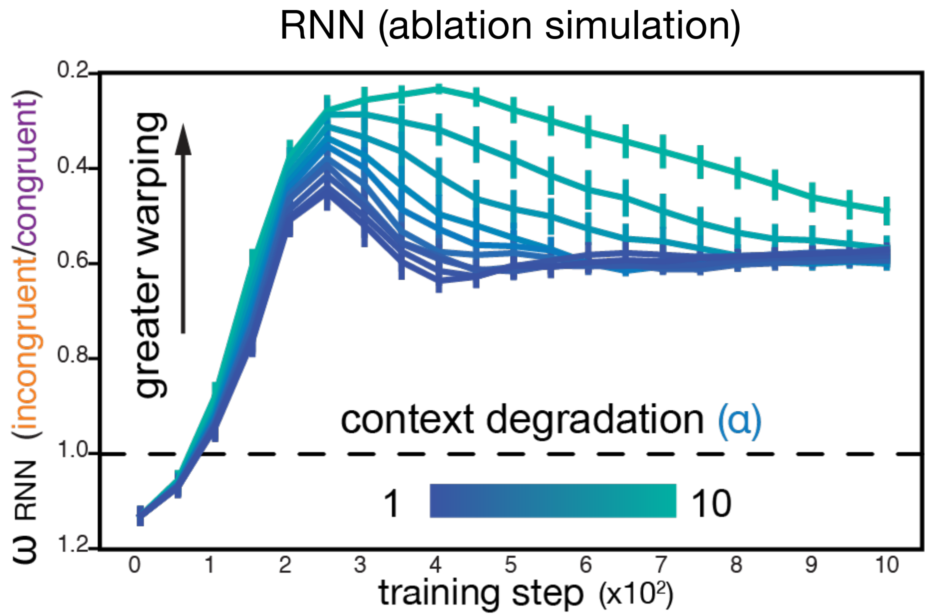




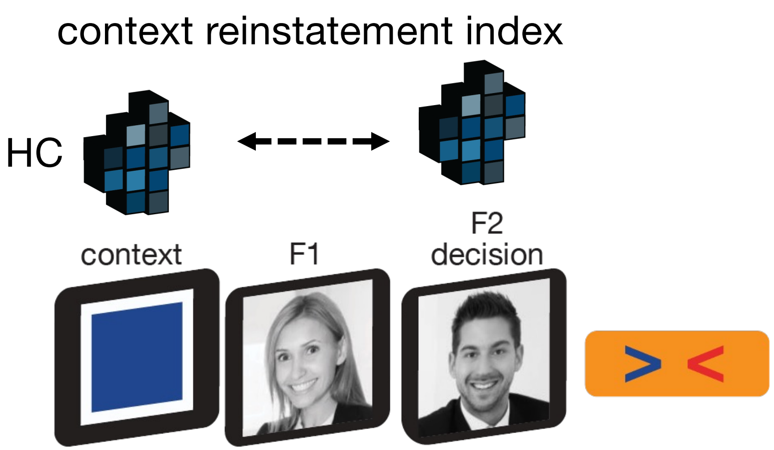
what causes warping in represenation

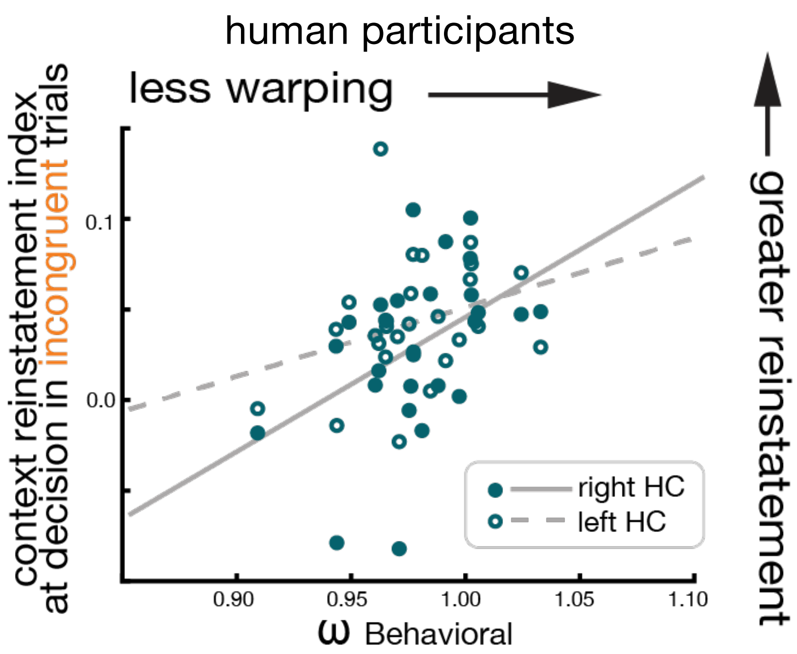






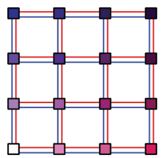
effective uses of context reinstatements decrease the influence of congruence on reaction times

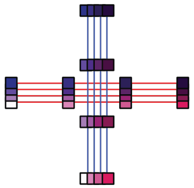




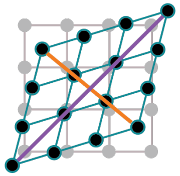
interim summary

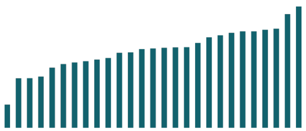
- cognitive control for flexible top-down selection of goal-relevant information from *multidimensional* cognitive maps retrieved from memory
- *parallel* analyses of fMRI and RNN that was trained to perform the same task
- *simultaneous* 2-D and 1-D representations supporting representational stability and flexibility, respectively

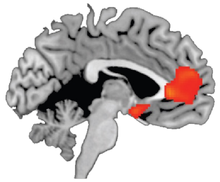




- ↑ control demands due to incongruence → *warping* representational geometry → *individual differences* in cognitive control







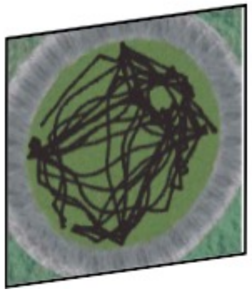
- intricate *bidirectional relationships* between cognitive control and the representational geometry of the cognitive map

generalization in novel problem solving

does the brain use grid like representations to make novel inferences of non-spatial relationships?

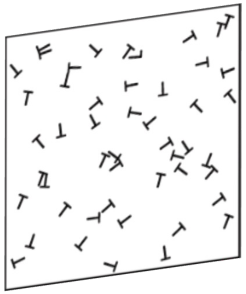
Park et al., 2021 Nature neuroscience

grid-like representations in EC as a general mechanism to navigate continuous spaces



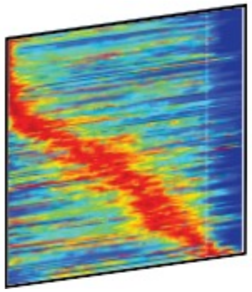
navigation

Doeller et al, 2010



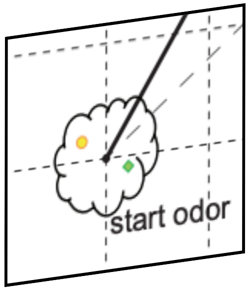
visual/memory search

Julian et al, 2018, Nau et al., 2018, Killan et al., 2012



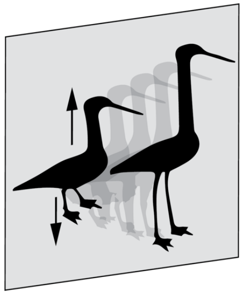
sound frequency

Aronov et al, 2017



odor intensity

Bao et al, 2019



conceptual

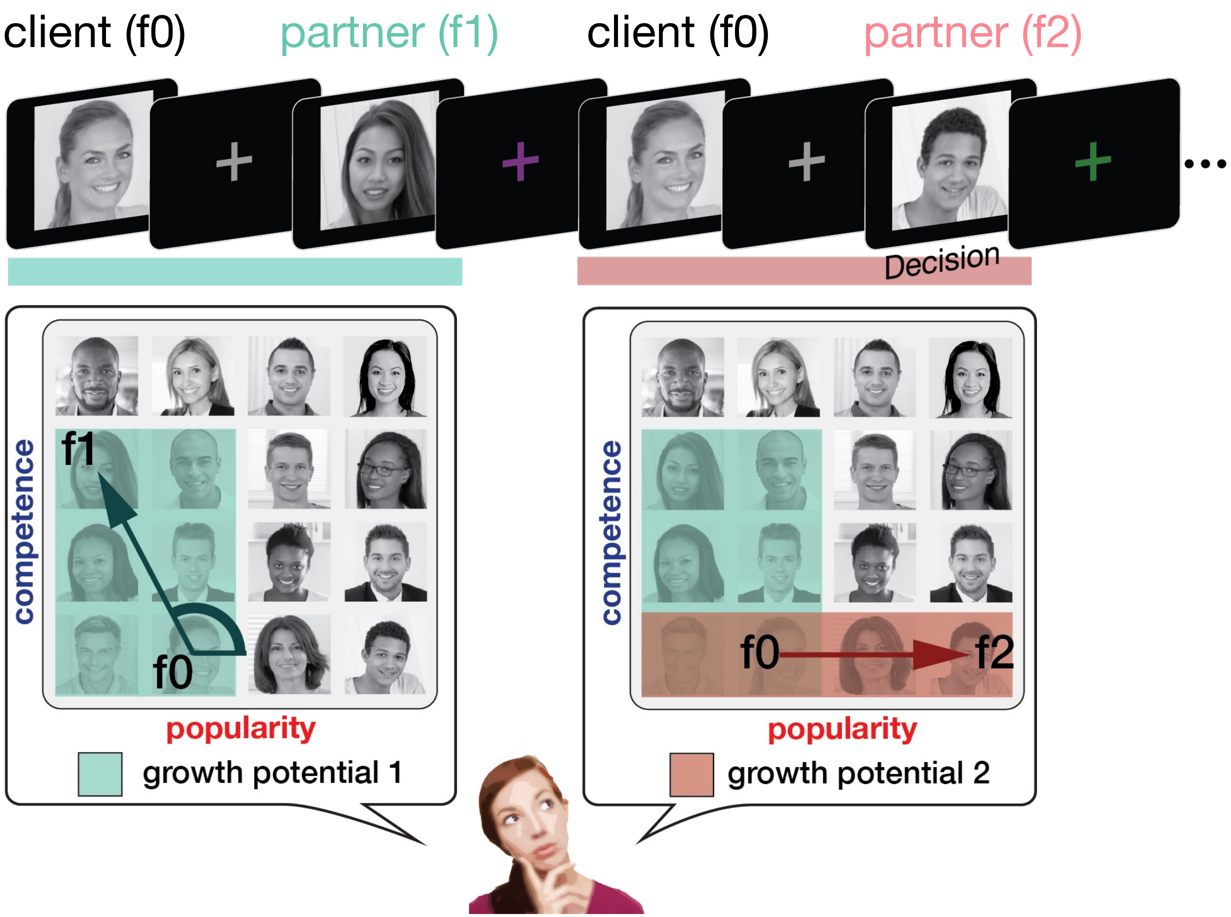
Constantinescu et al, 2016

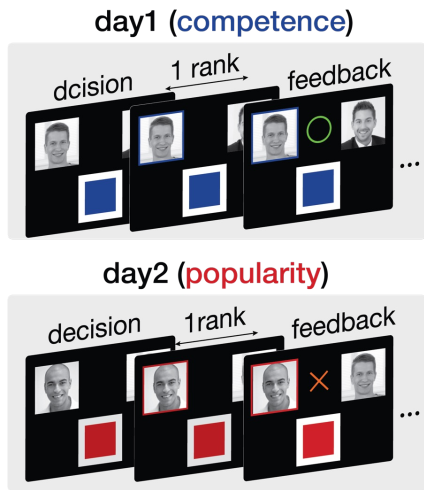
does the brain use grid-like representations

- to uncover *unexperienced trajectories* for novel inferences?
- to encode decision trajectory between *discrete options* in knowledge spaces?

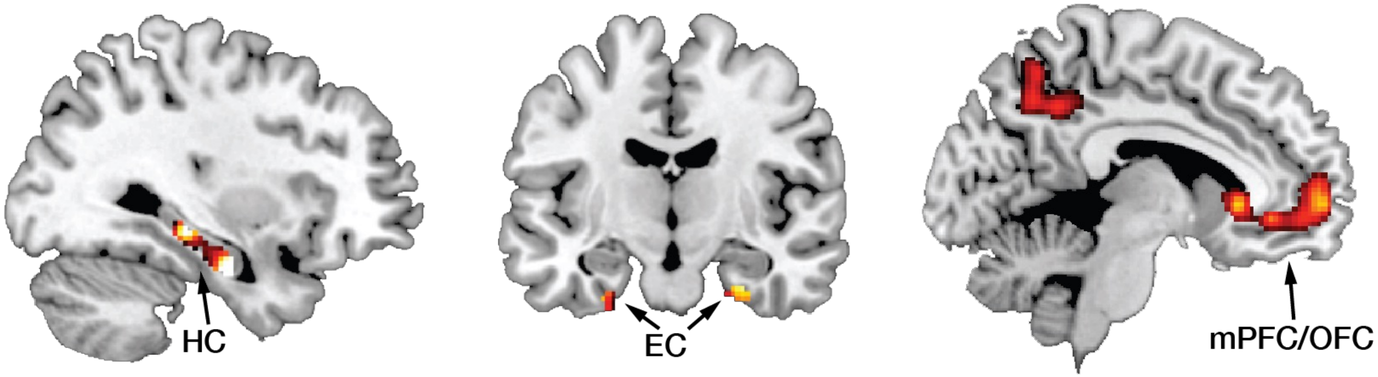
grid-like representation for generalization in novel problems

“select a better business partner for a given entrepreneur (f0)”

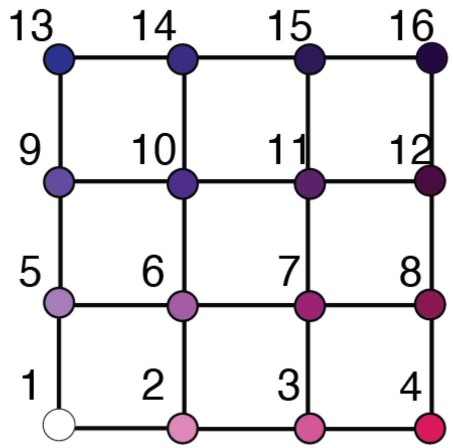




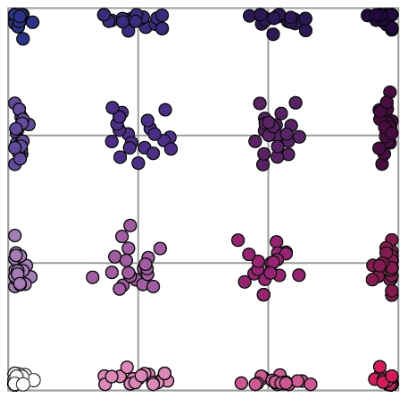
confirming 2-D representations of the cognitive-map



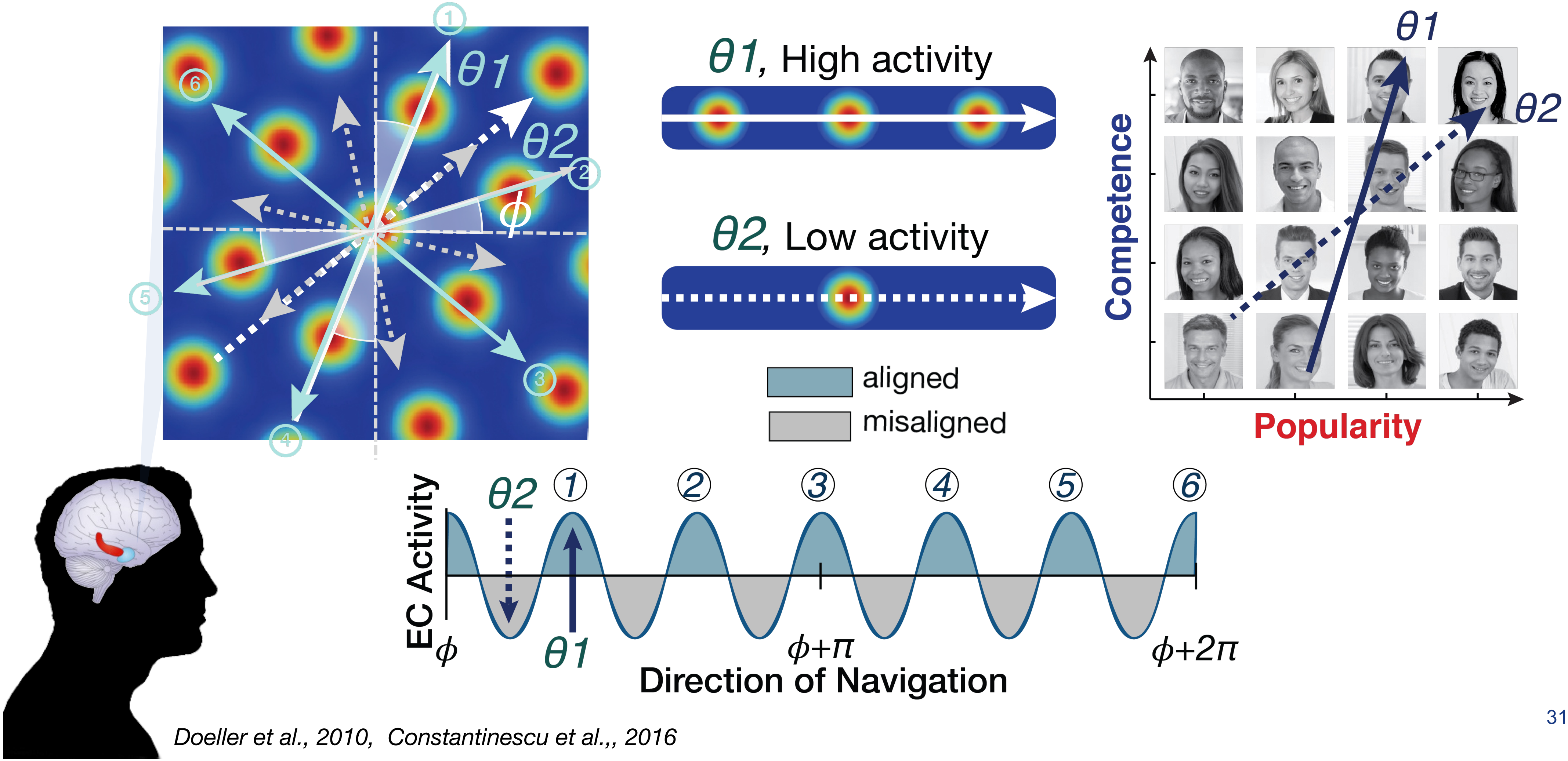
ideal representation



post-scanning (placement task)

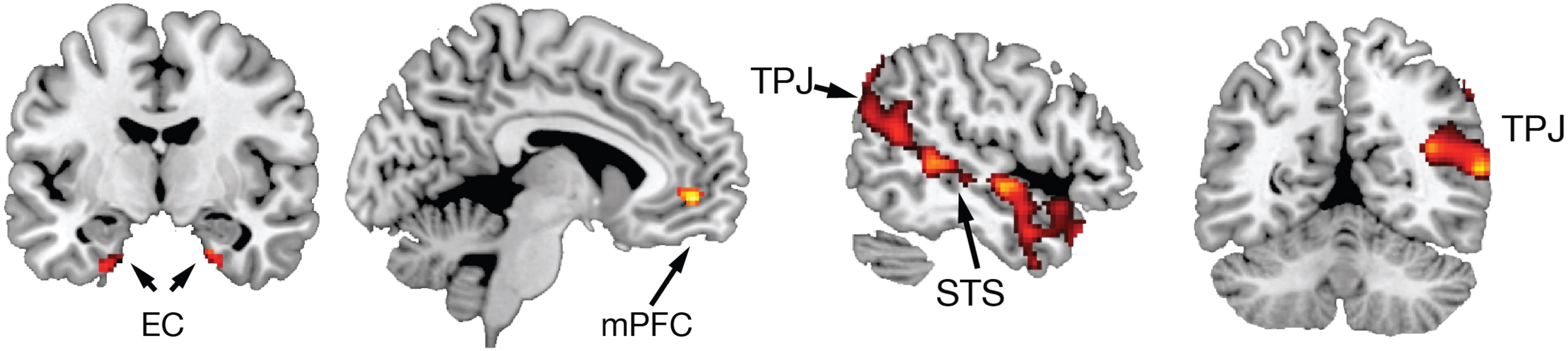


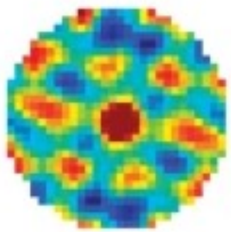
how can we measure the grid-like representations with fMRI?

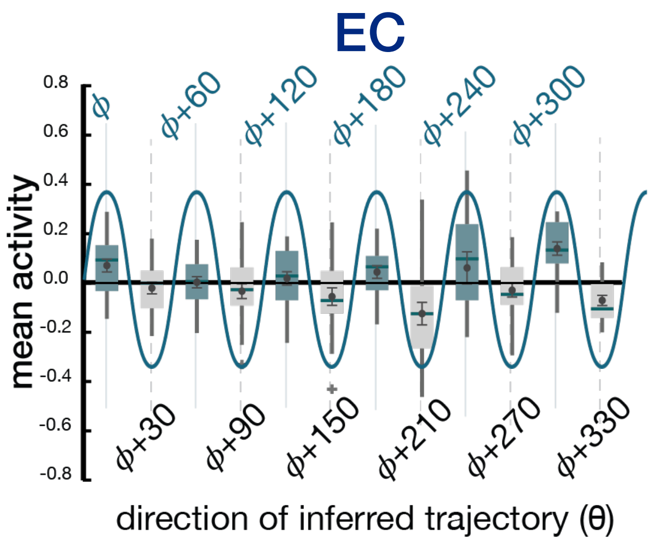


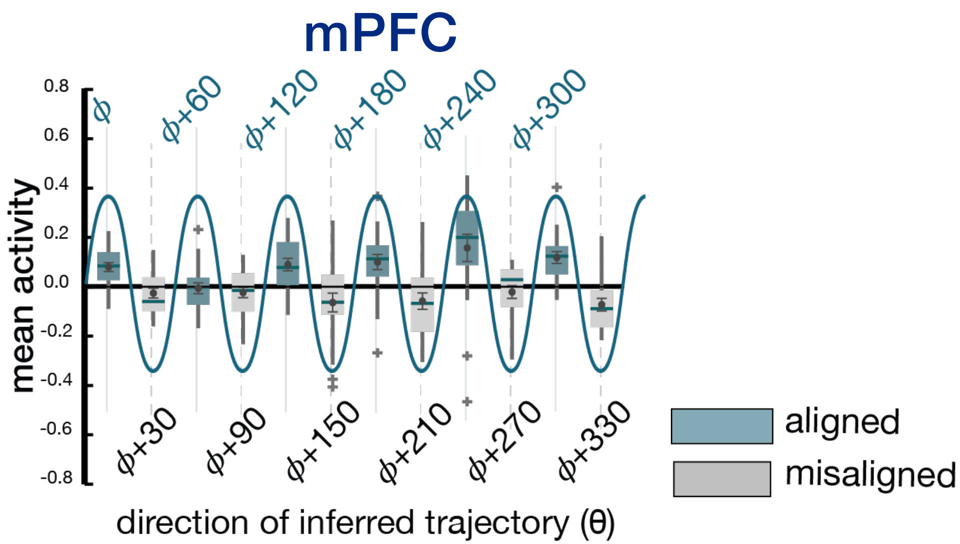
Doeller et al., 2010, Constantinescu et al.,, 2016

hexa-directional grid-like representations in the brain

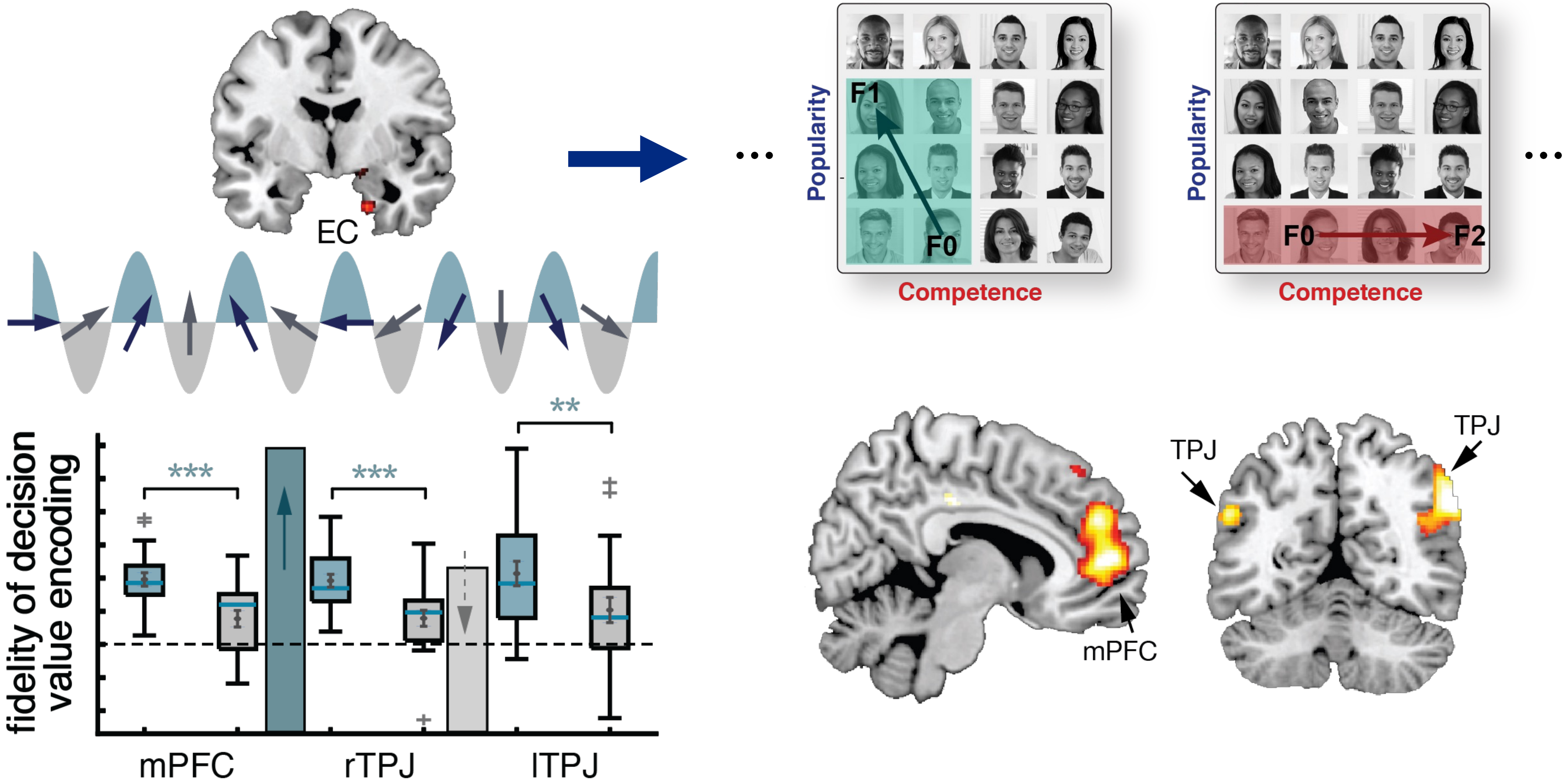



Jacobs et al., 2013



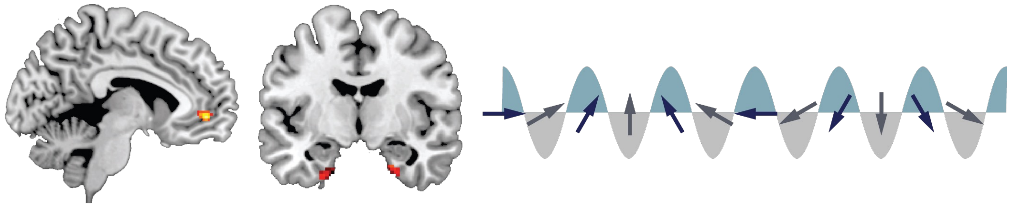


neural encoding of decision values to guide novel decisions

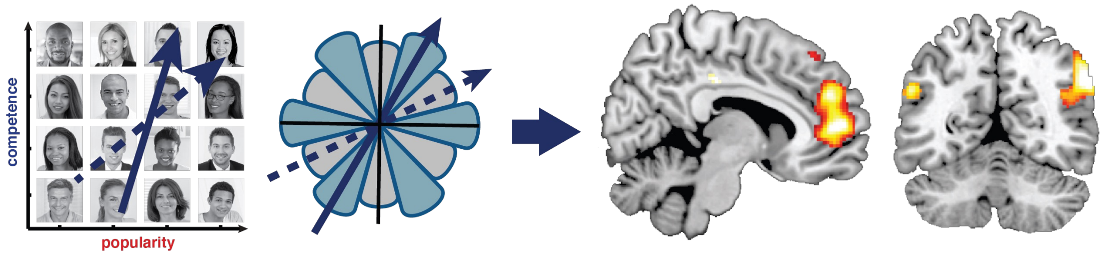


interim summary

- the grid-like representations map the non-spatial relationships between *discrete decision* options in the *absence* of continuous sensory feedback
- this effect was specific for *six-fold* – a corollary to hexagonal firing fields in the grid cells



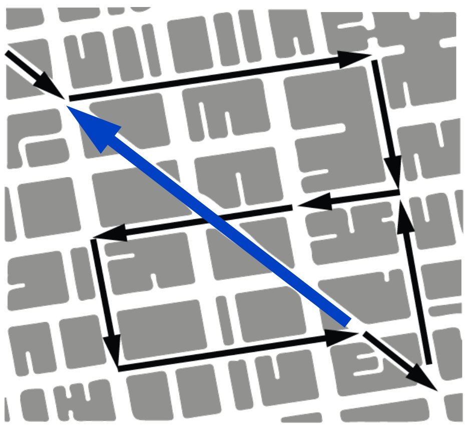
- allowing integration of multidimensional information to construct values for *novel decisions*



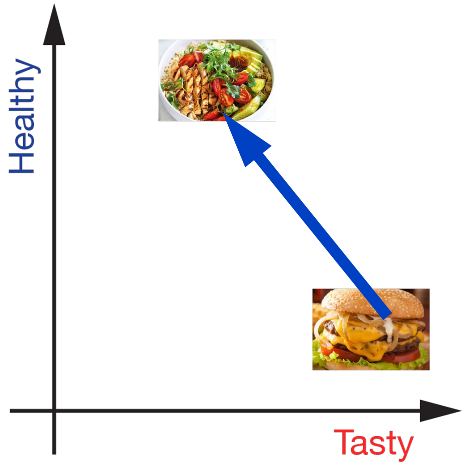
- enabling *generalization* of the cognitive map learned from different tasks

the cognitive map acts as a general mechanism to encode the relational structure

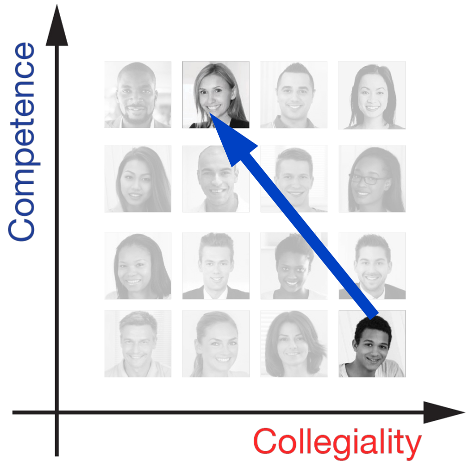
finding a shortcut



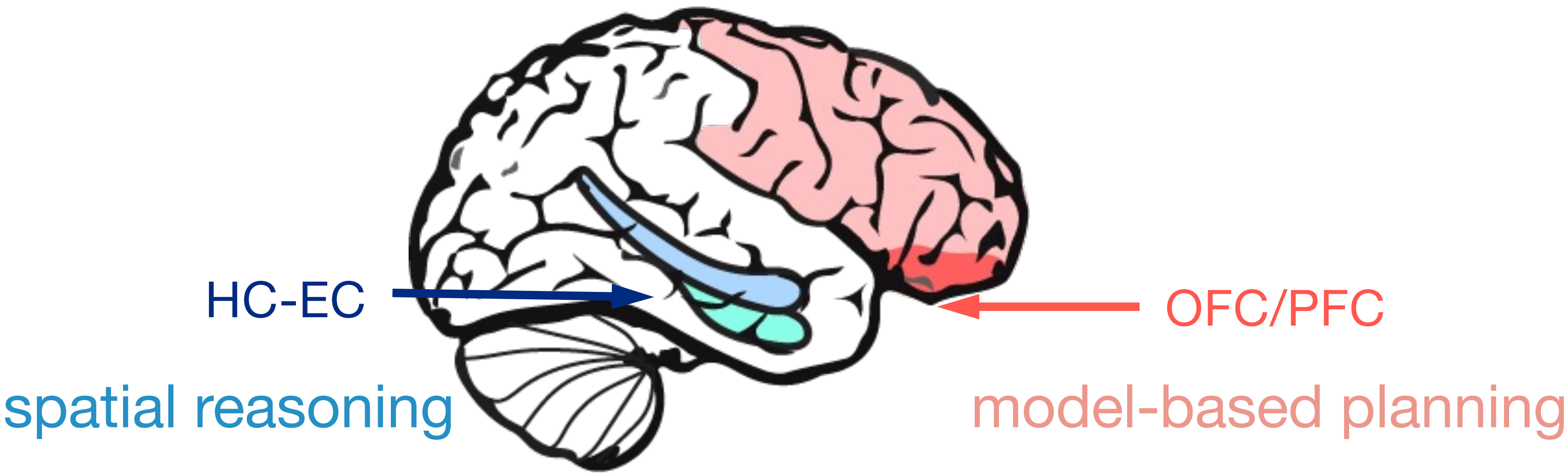
flexible decisions



solutions to novel tasks



interaction between OFC/PFC and HC-EC to afford behavioral flexibility



what representations and computations can bridge these seemingly distinct functions in the brain?

acknowledgement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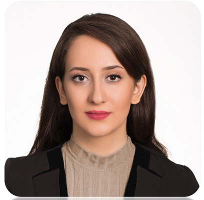
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NIH National Institute of Mental Health

NSF

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anr

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Thank you!