Learning and using generalized attentional templates in the frontoparietal cortex

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Attentional template

Feature-based attention allows us to focus on the stimuli with task-relevant features (e.g. color, shape, motion).

An **attentional template** encapsulates the set of stimulus features that are relevant for the current situation.

Attentional templates are represented in the frontoparietal cortex

Attentional templates are represented in prefrontal and parietal cortex:

- Both regions are active when attention is shifted to specific features.

- Lesioning (or inactivating) these regions impairs a subject's ability to attend to features.

lPFC   FEF   LIP

Fronto-parietal
network

Template ——— **?** ——→ Choice

?

Sensory input
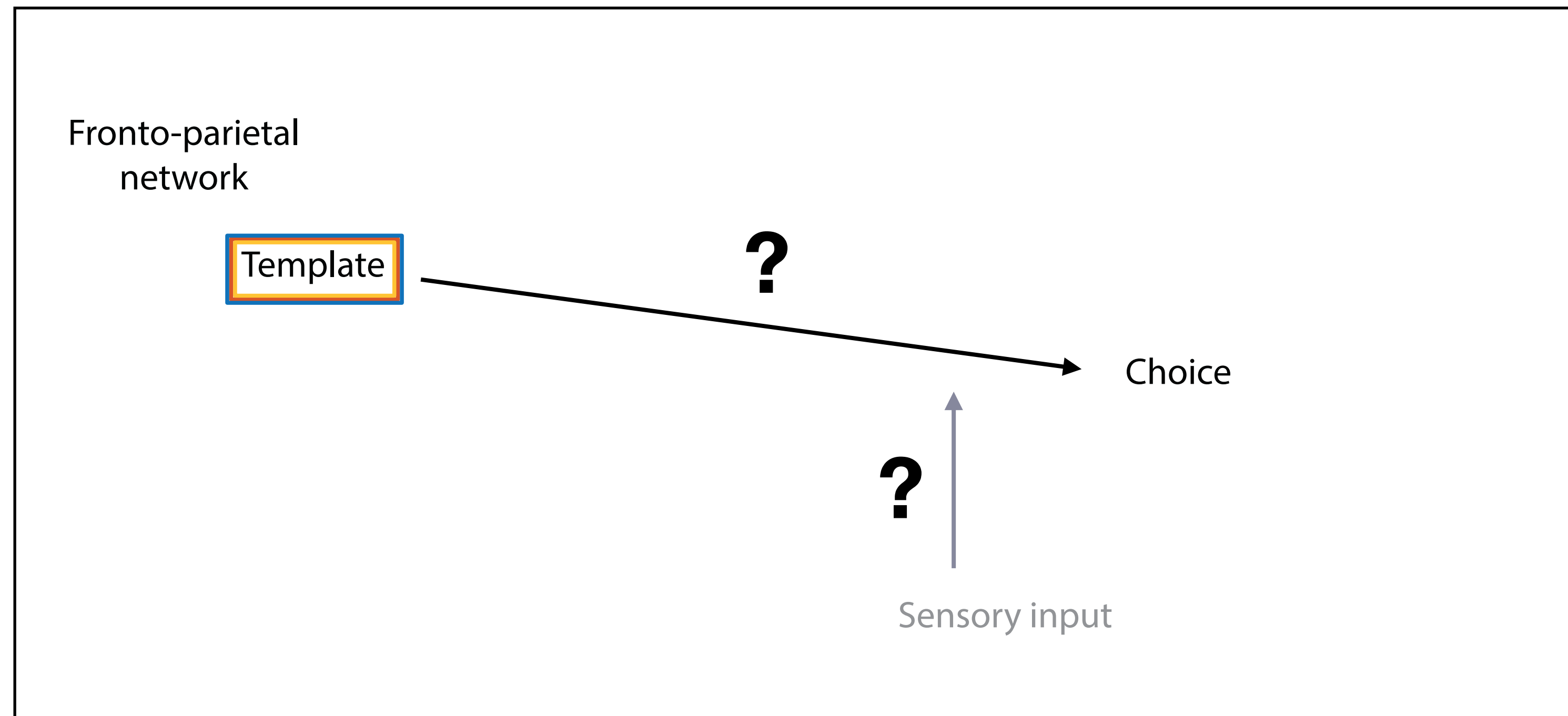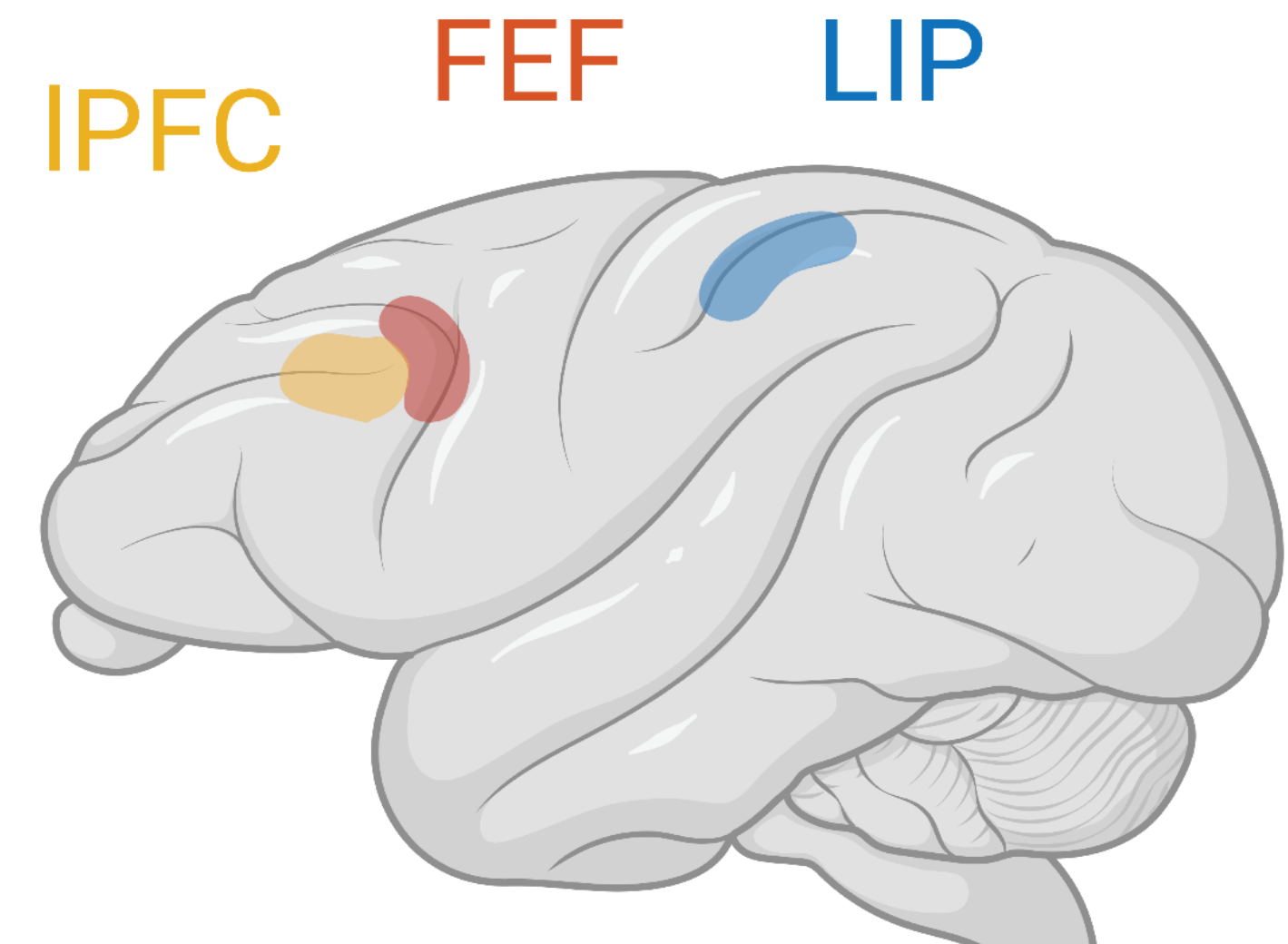
Attentional templates are flexible

New York City

Barcelona

London

Venice

Attentional templates are flexible

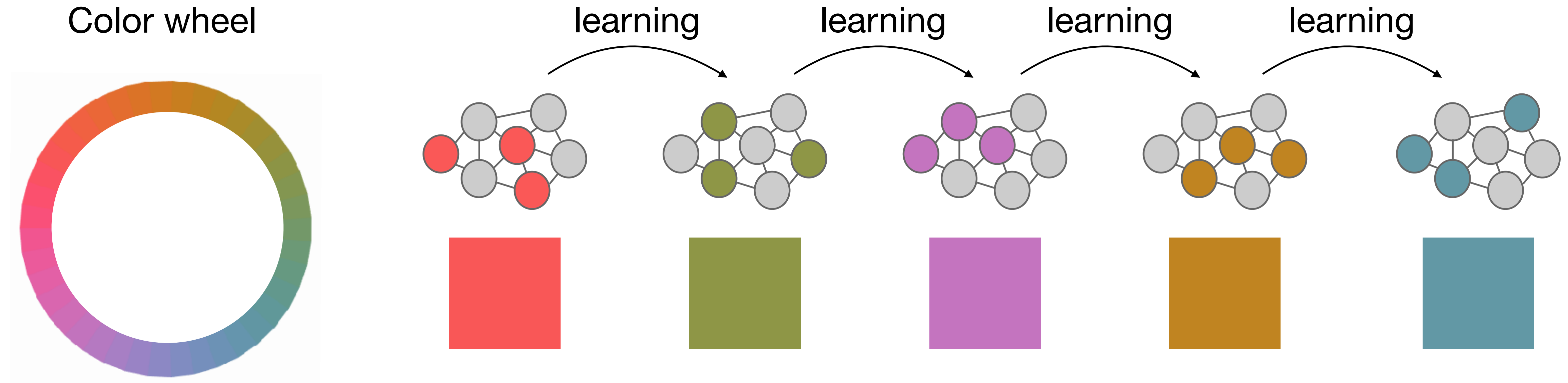learning · learning · learning
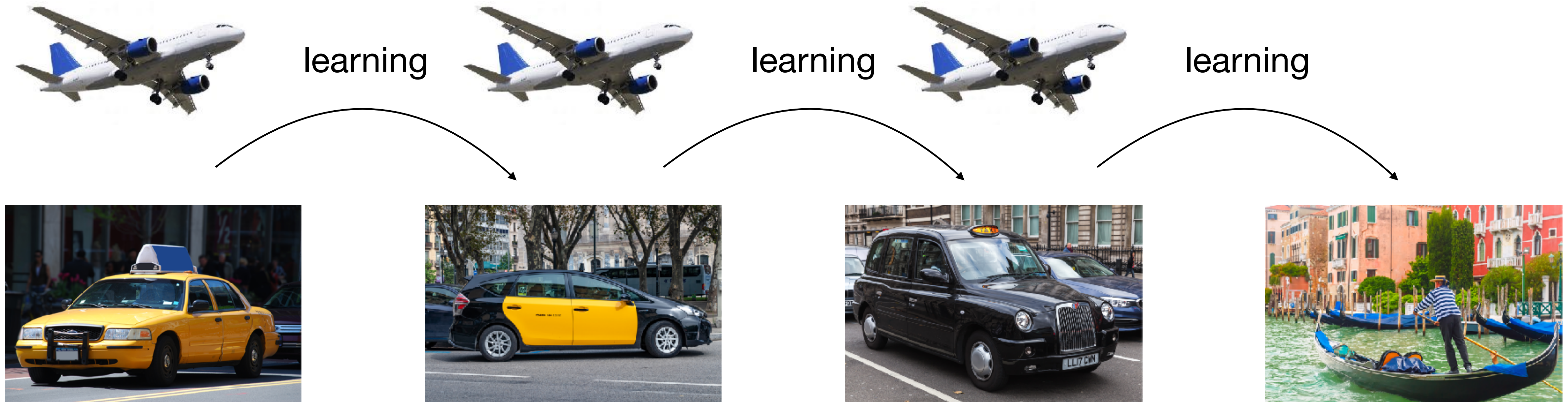
How do you learn a new attentional template?

How do you learn multiple attentional templates?

Learning to attend a color in a semantically structured space

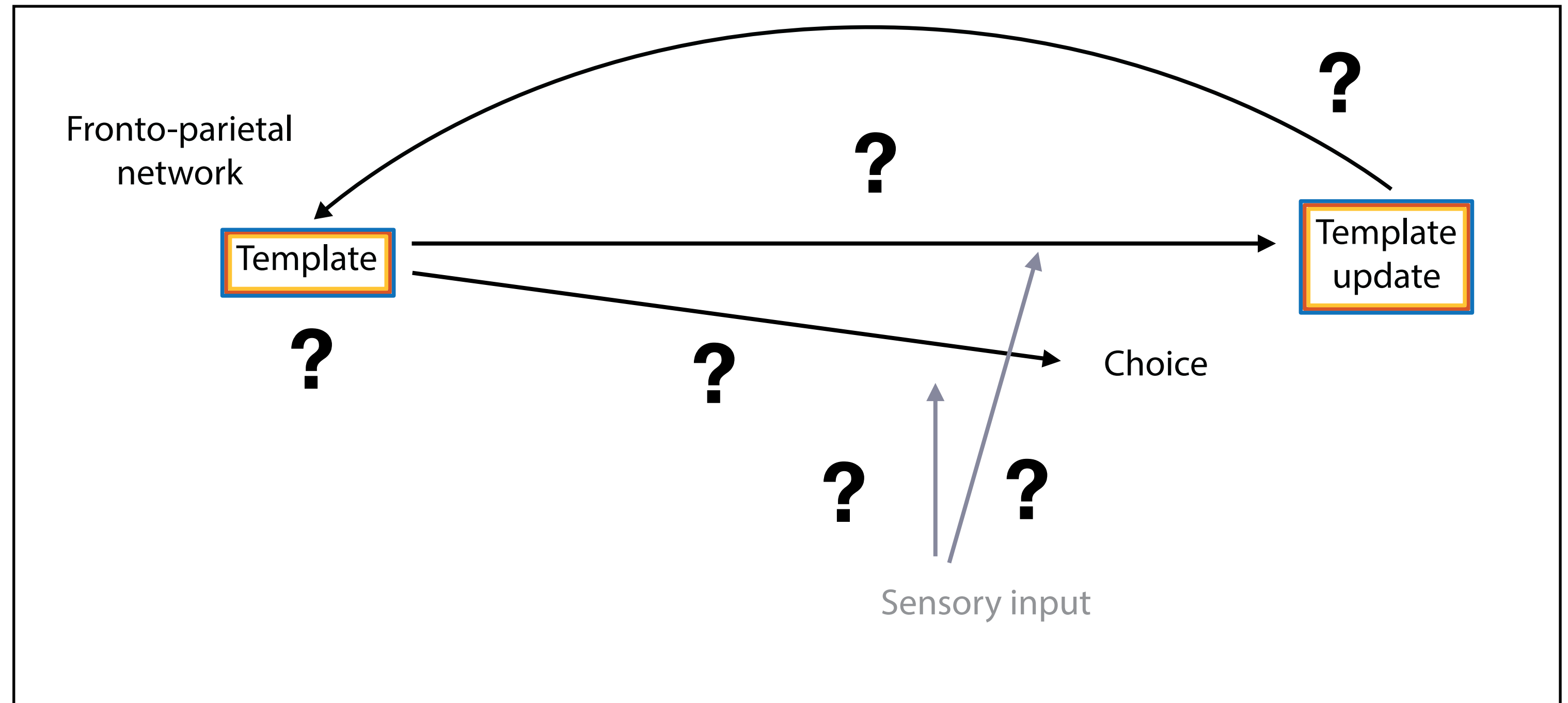How is the attentional template represented?

How do you learn a new attentional template?

How do attentional templates relate to one another?
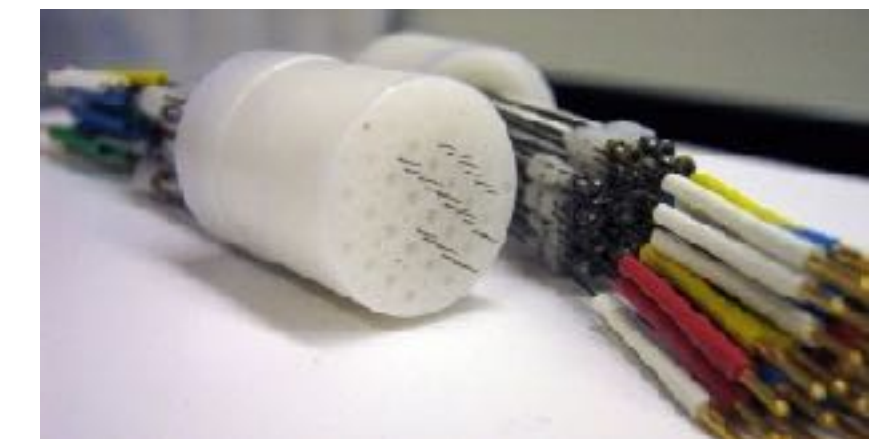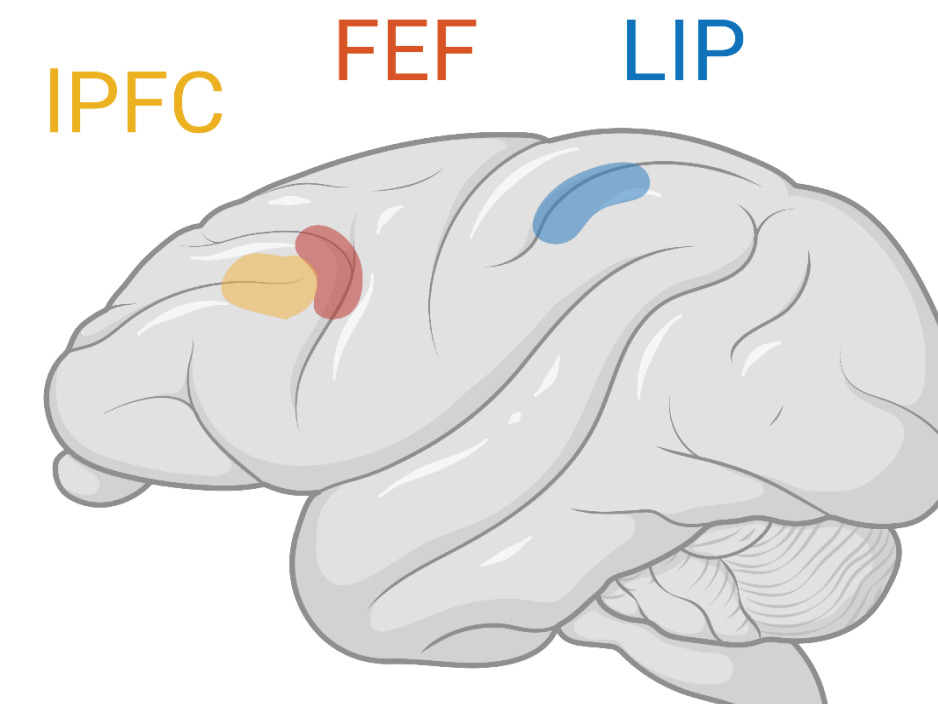
Questions

How are attentional templates:

- Represented

- Organized

- Learned
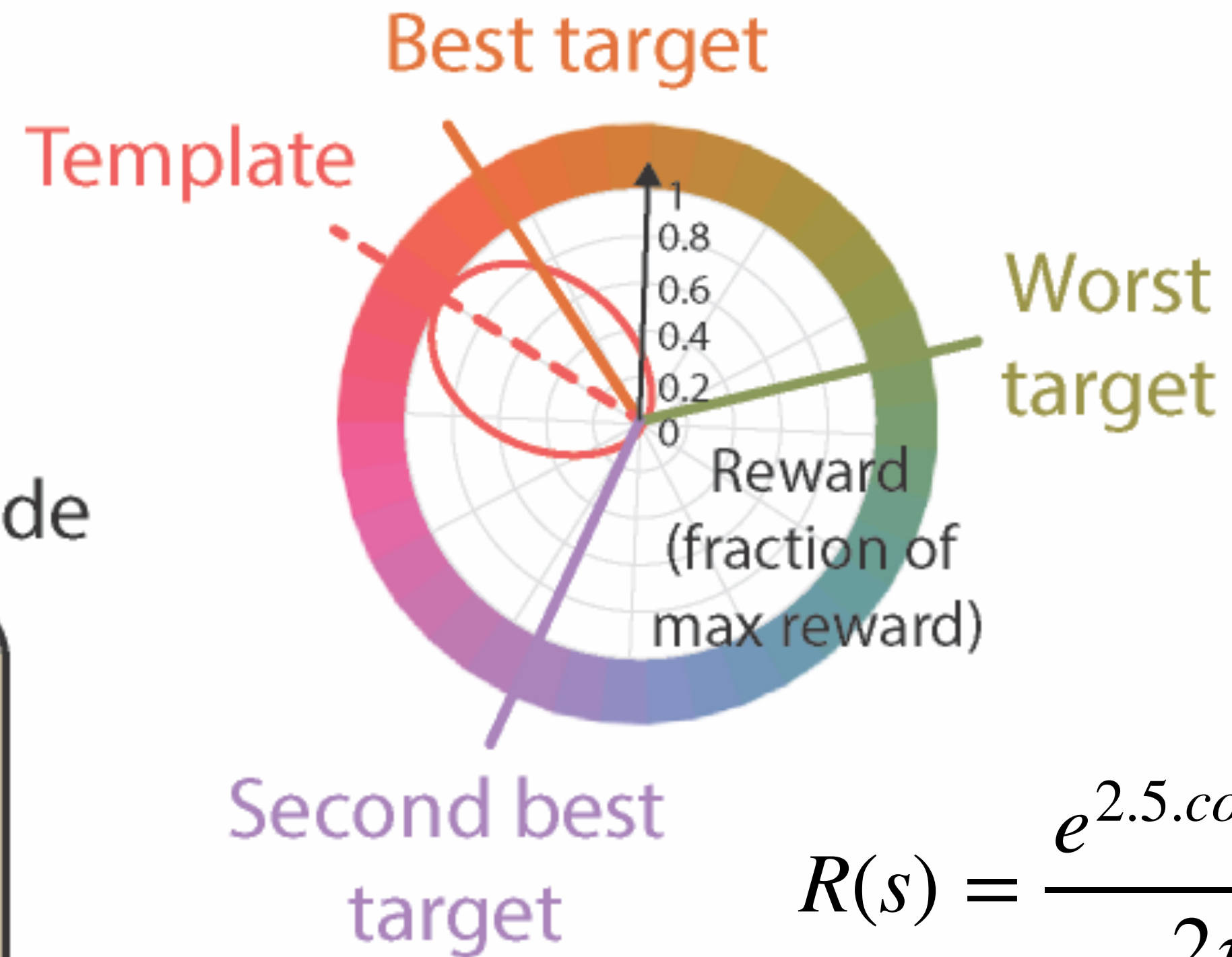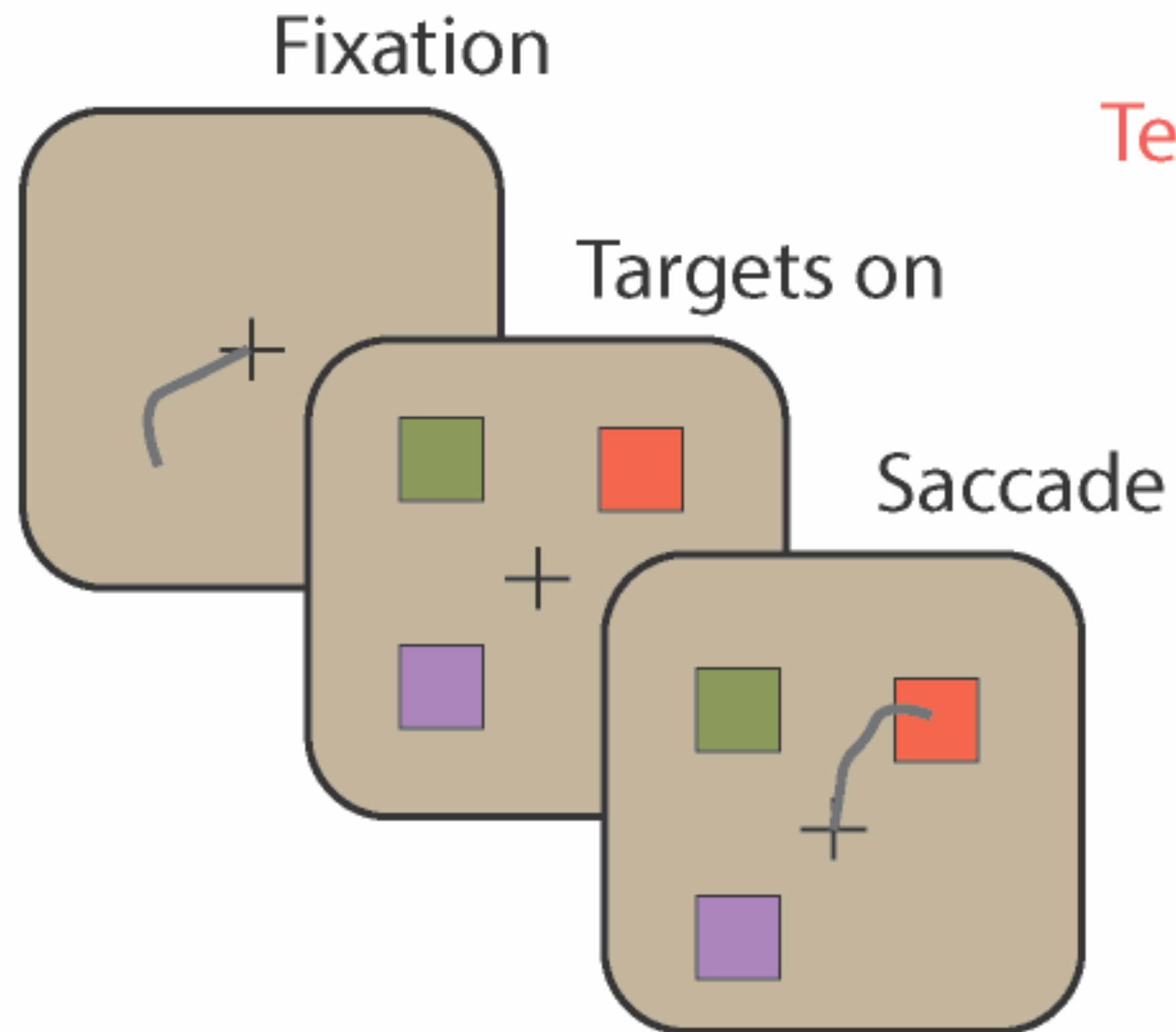
- Used to make a choice

Task requirements:

- Learning **multiple attentional templates**

- Template as a **cognitive state** dissociable from the *sensory perception* (chosen color) and the *motor execution* (location on screen)

Learning attentional templates in a semantically structured space
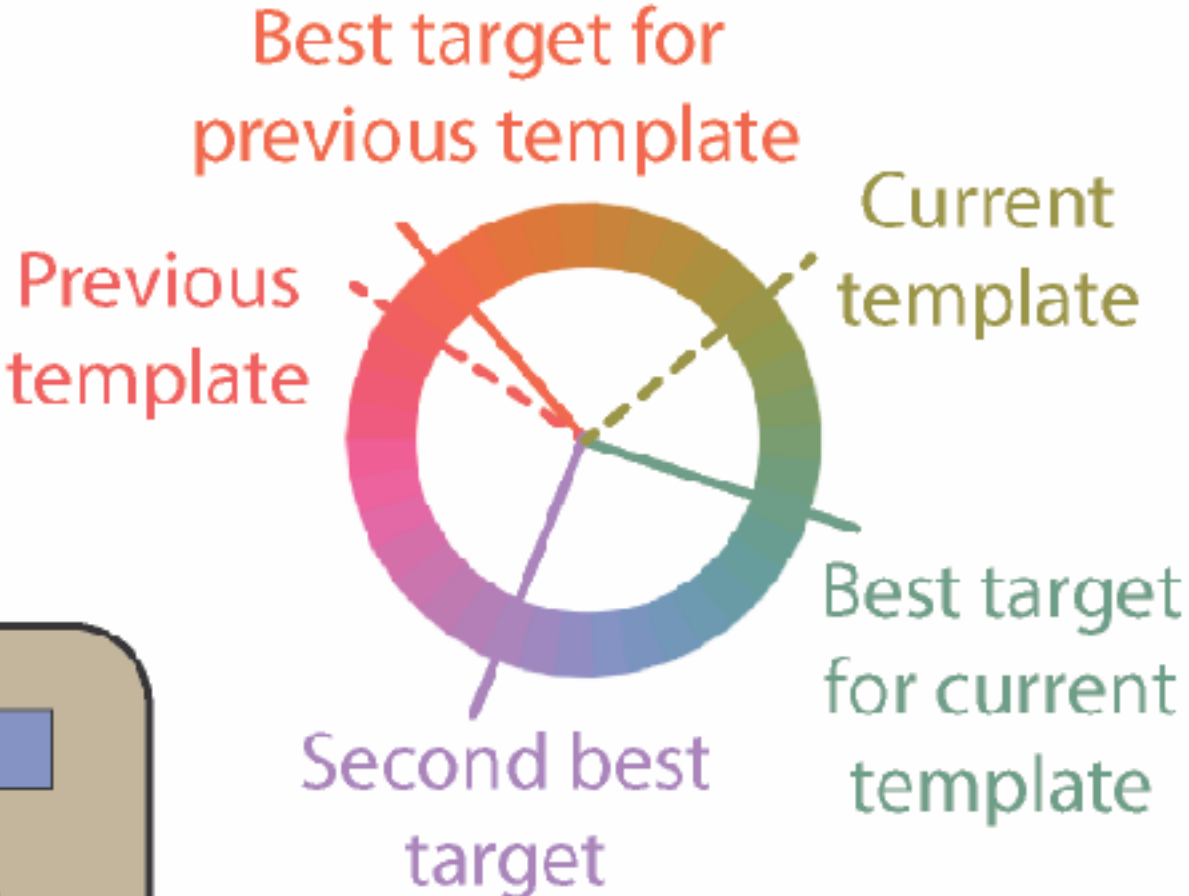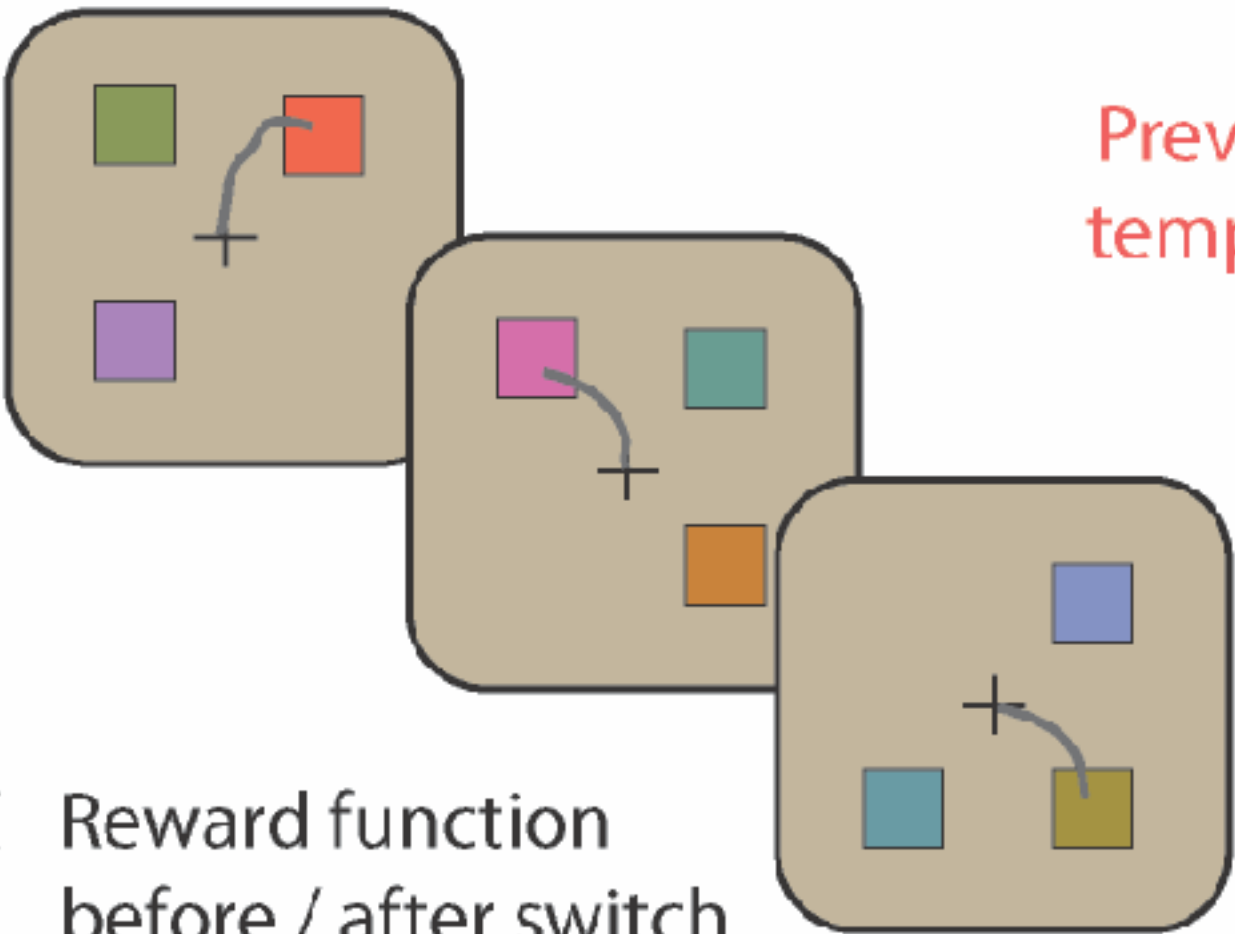
Attentional template learning task
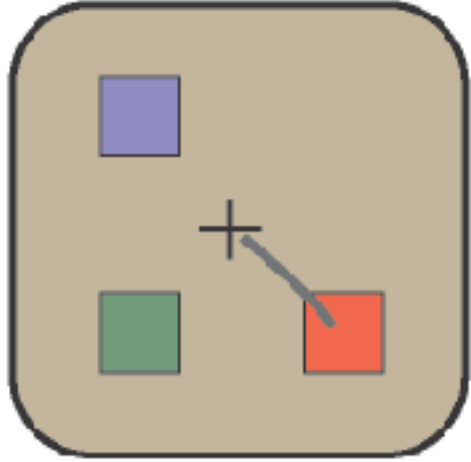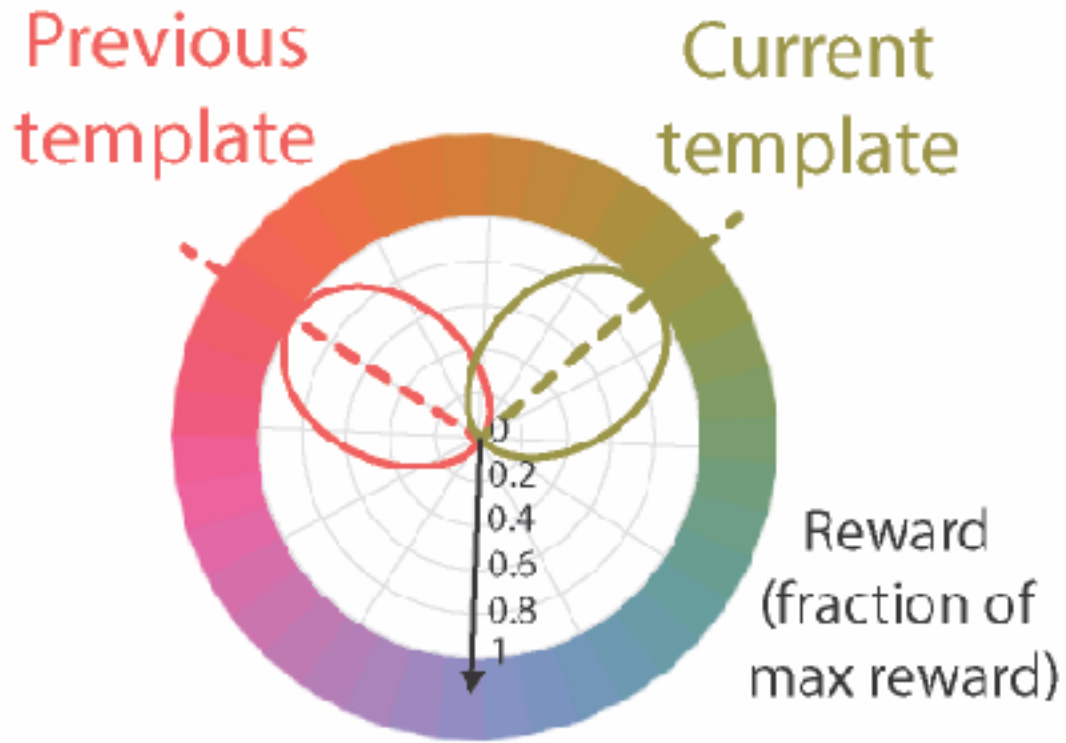

A Example trial

Fixation

Targets on

Saccade

Template

Best target

Worst target

Second best target

Reward (fraction of max reward)

$$R(s) = \frac{e^{2.5 \cdot cos(s - Template)}}{2\pi I_0(2.5)}$$

Attentional template learning task

Behavior & model

Learning curve

Current template
— Data
---- Model
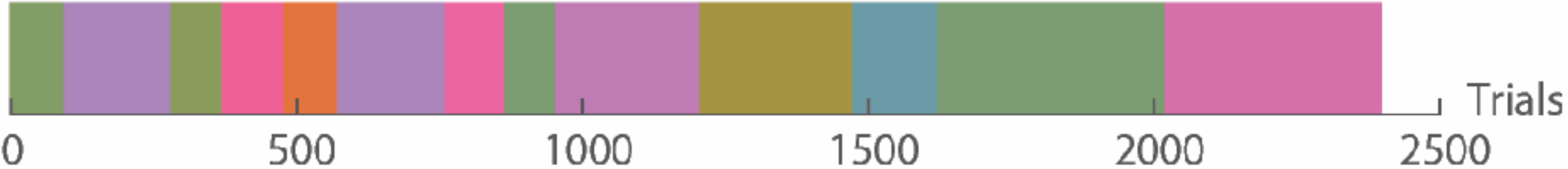
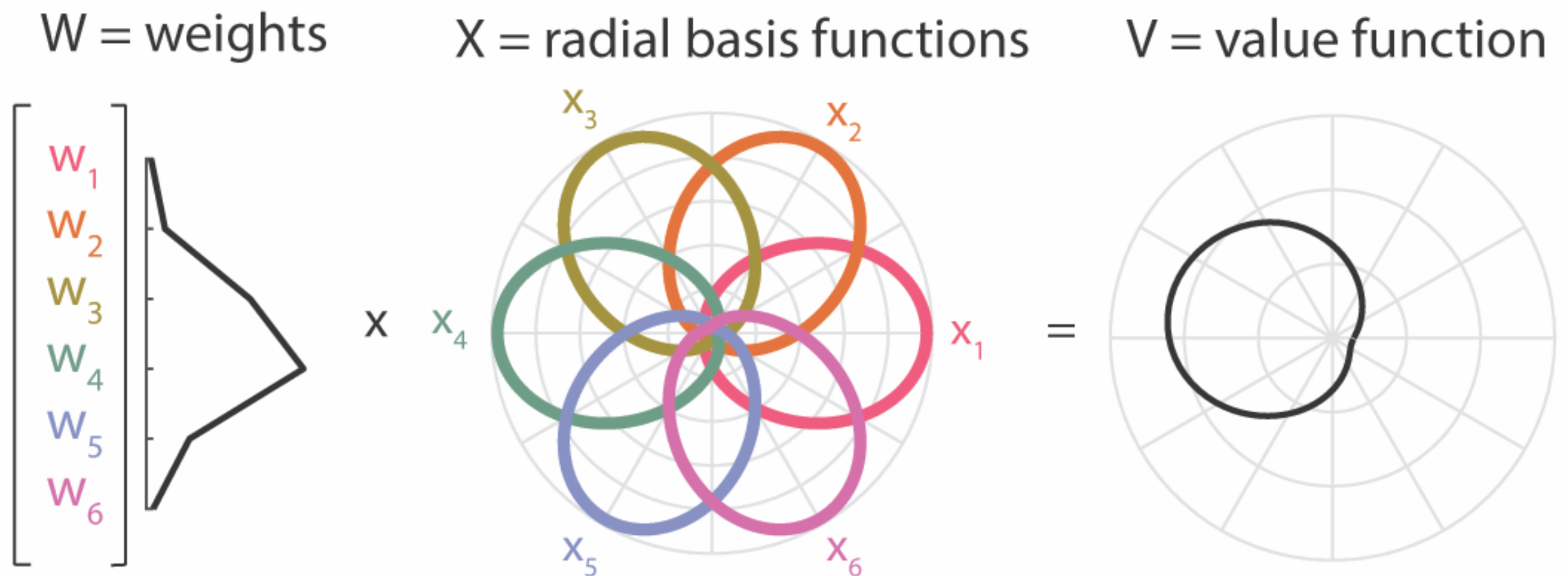Previous template
— Data
---- Model
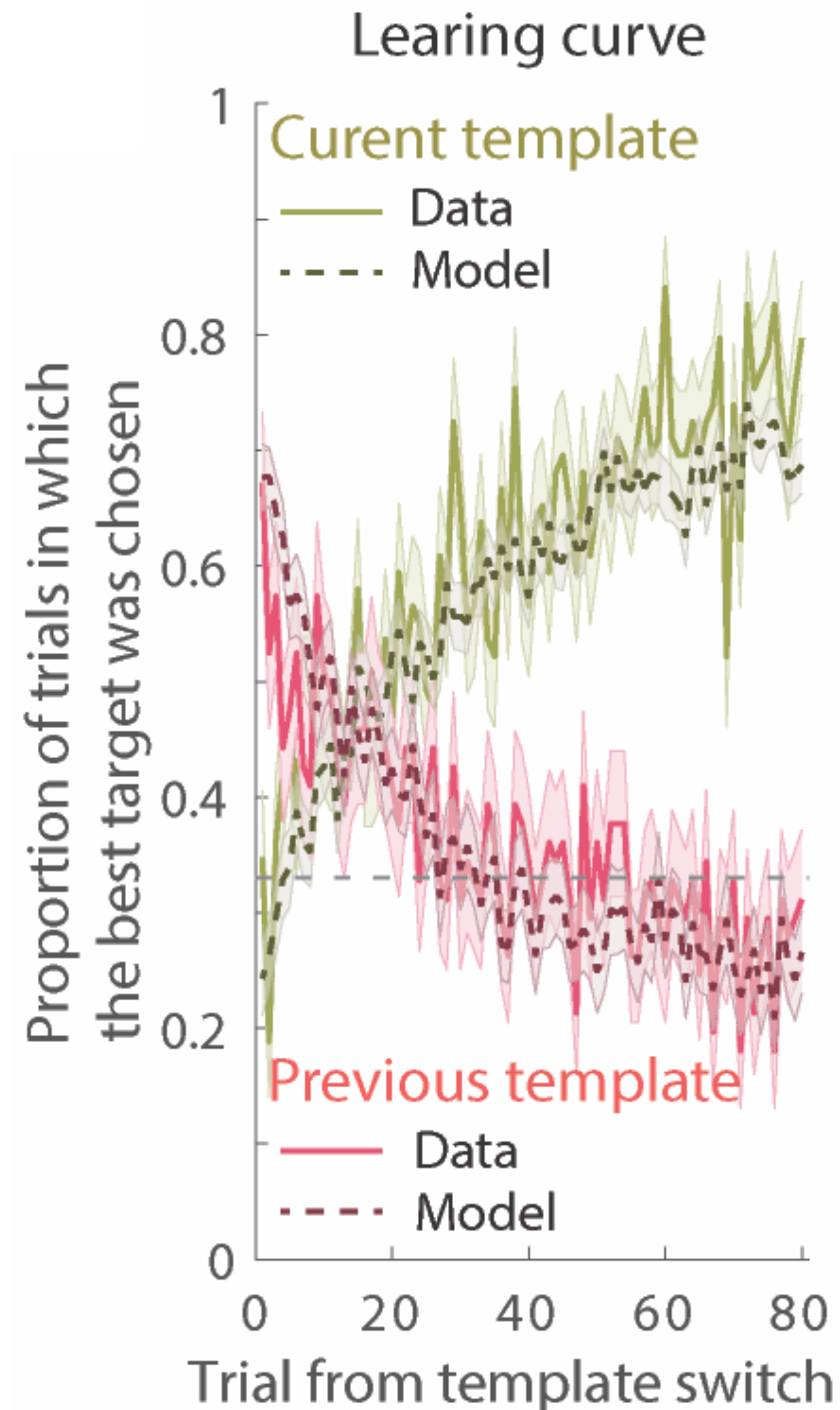
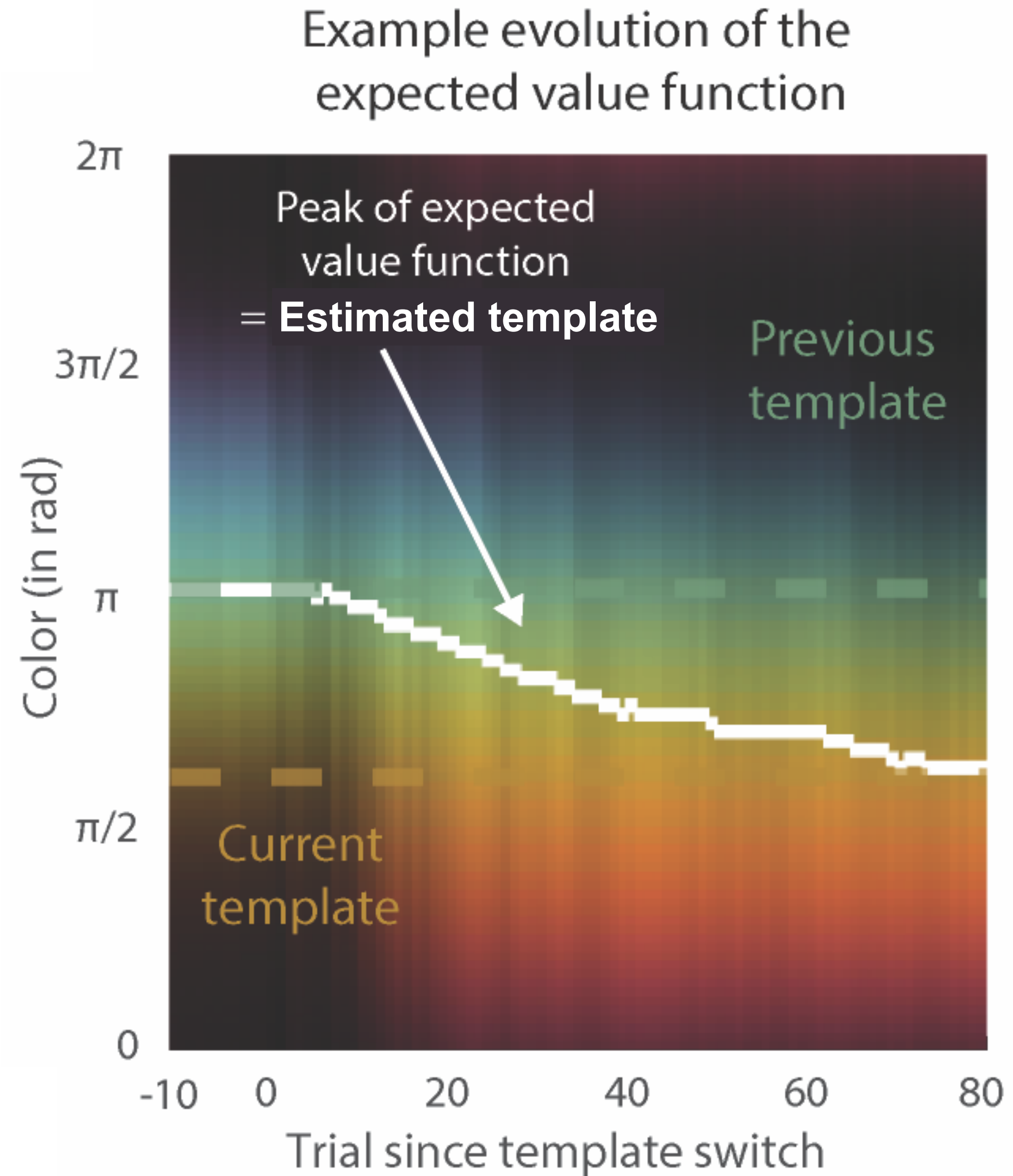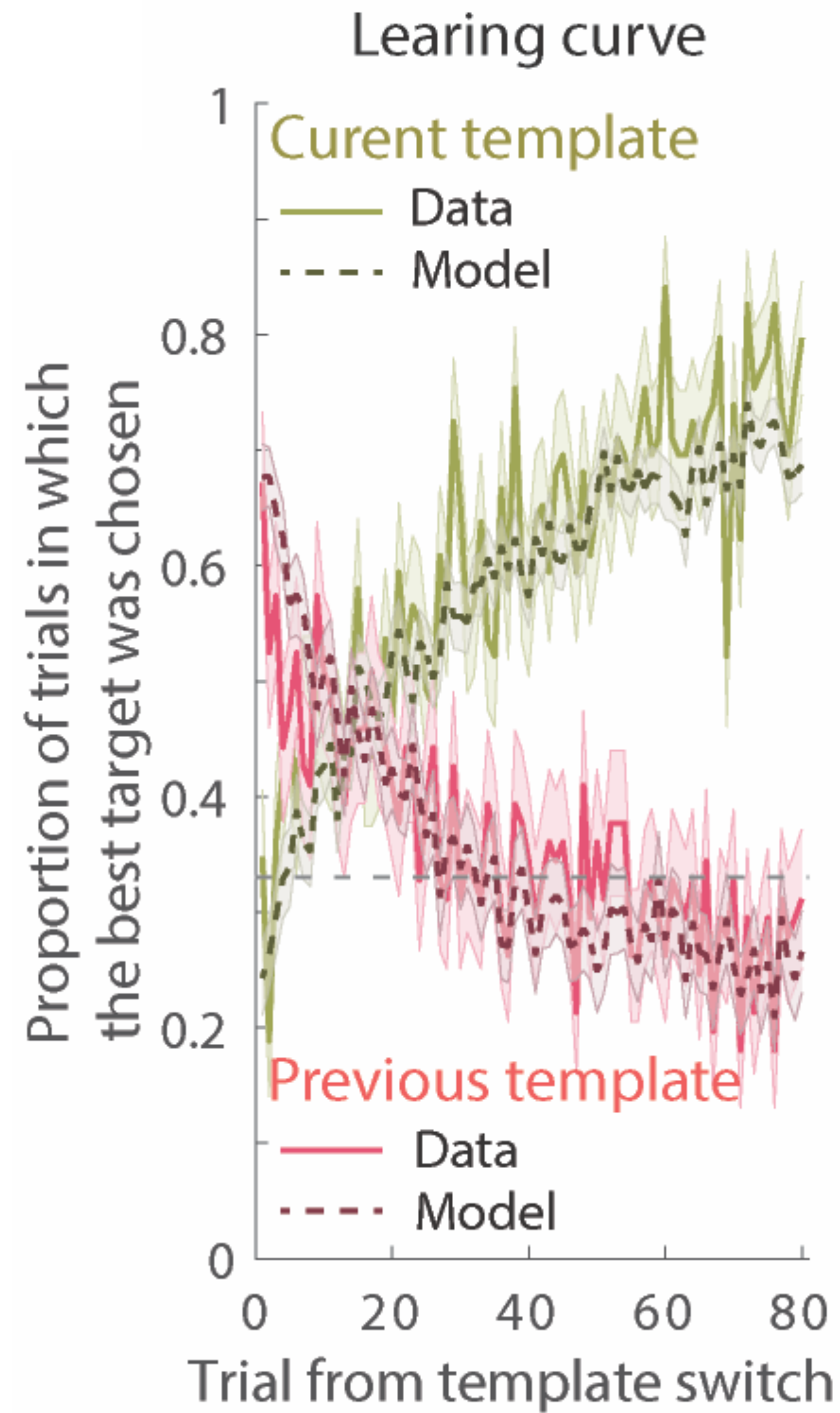Q-learning with function approximation

Compute the expected value of the colors in the color wheel

The space is represented by 6 radial basis functions (RBF)
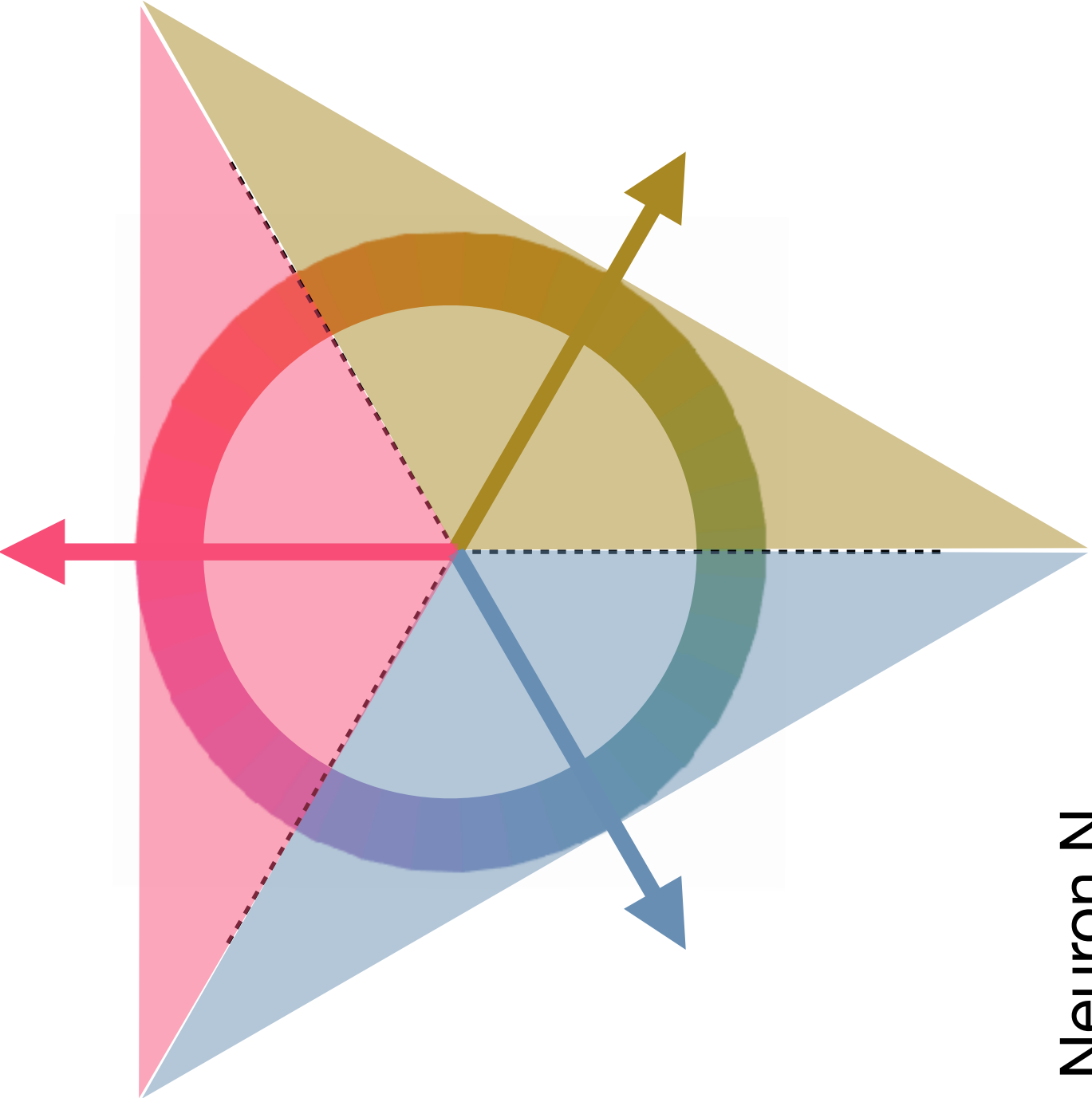
Learning = update of the weights of these RBF

W = weights   X = radial basis functions   V = value function

Behavior & model

Learing curve

Current template
— Data
--- Model

Previous template
— Data
--- Model

Proportion of trials in which the best target was chosen

Trial from template switch

Example evolution of the expected value function

Peak of expected value function = **Estimated template**

Previous template

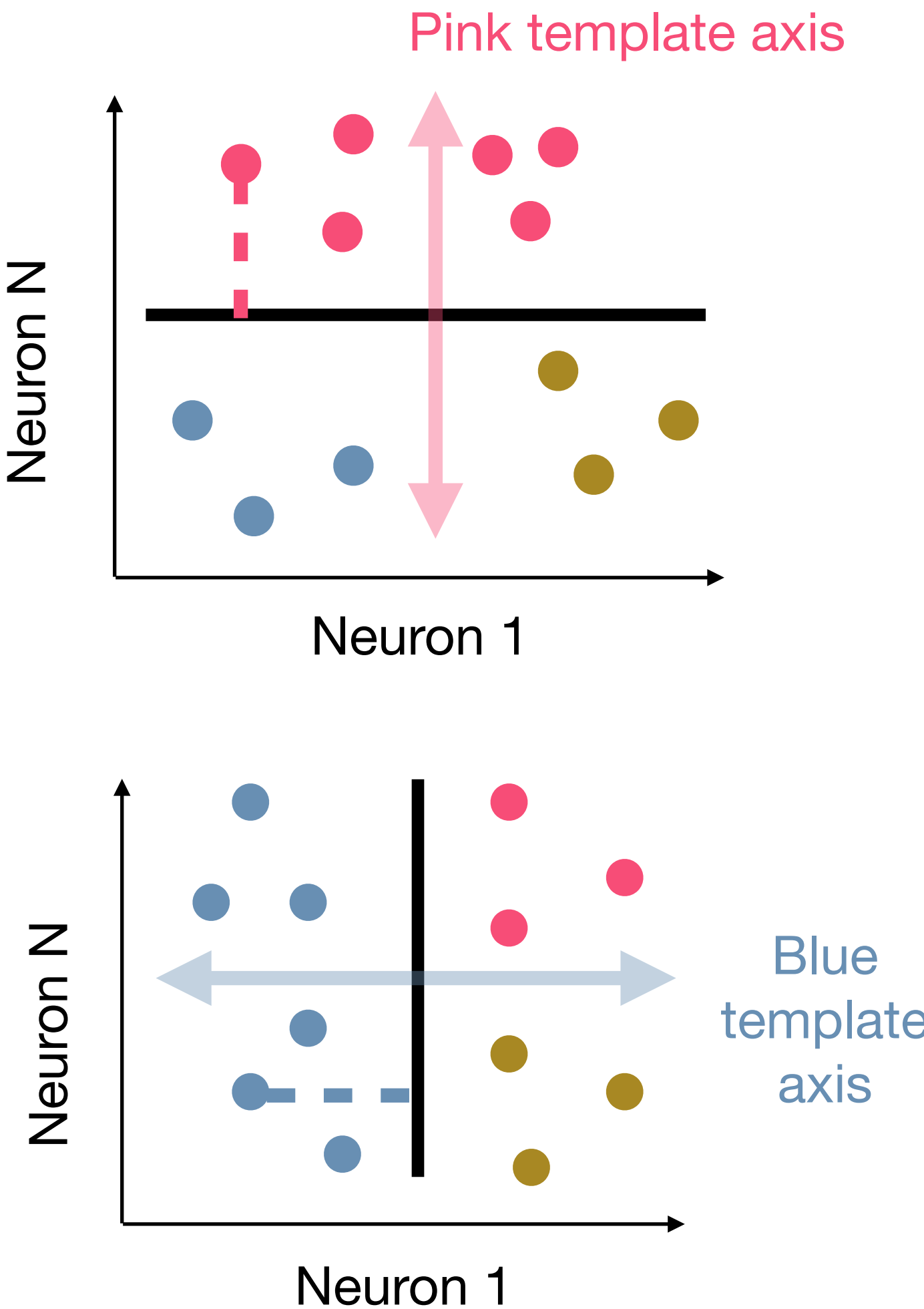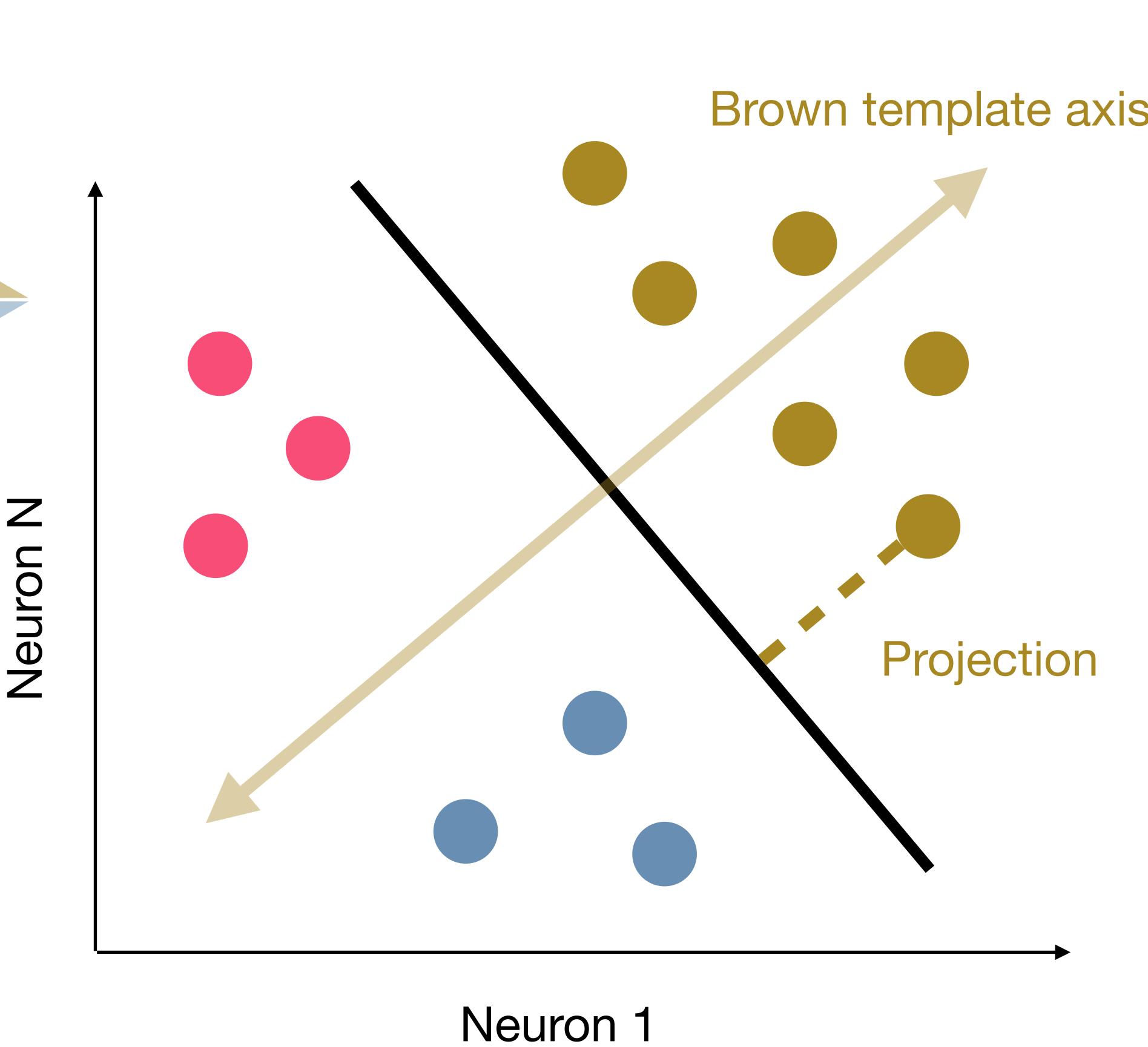Current template

Color (in rad)

Trial since template switch

Estimated template representation in the frontoparietal cortex

Estimated template representation at the population level

Pseudo-population
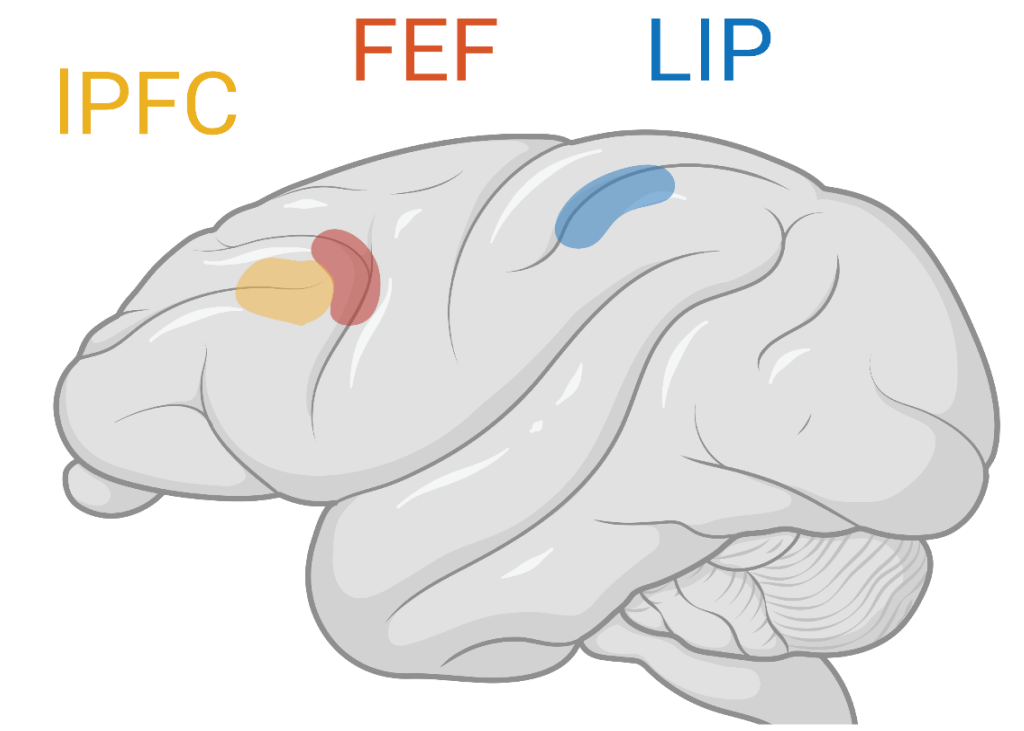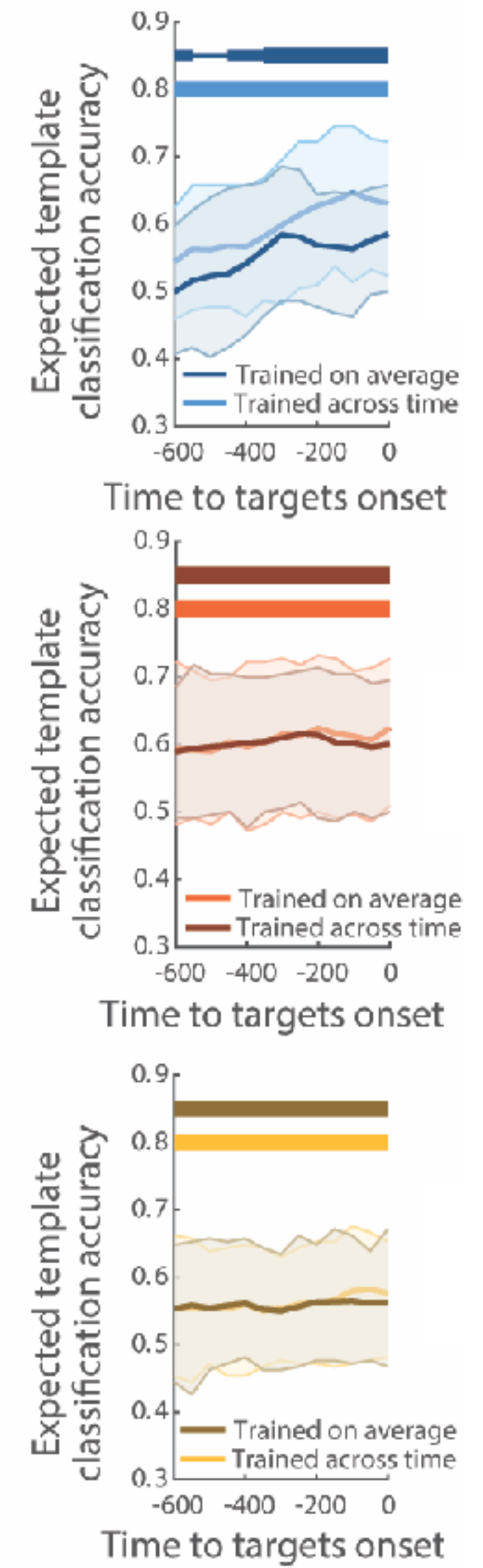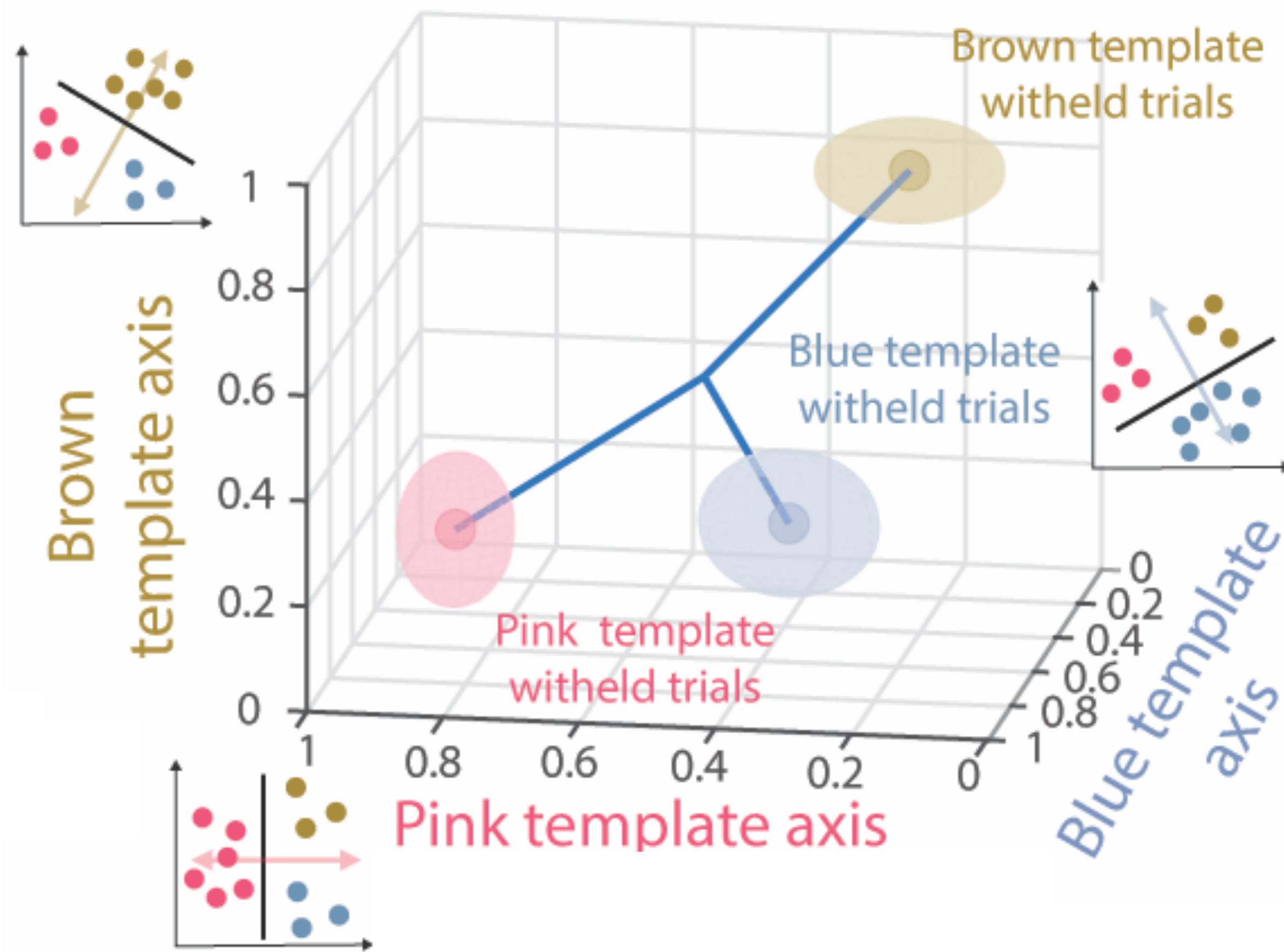100 bootstraps

Estimated template classifier

Brown template axis

Neuron N

Projection

Neuron 1

Pink template axis

Neuron N

Neuron 1

Neuron N

Blue template axis

Neuron 1

Estimated template representation at the population level
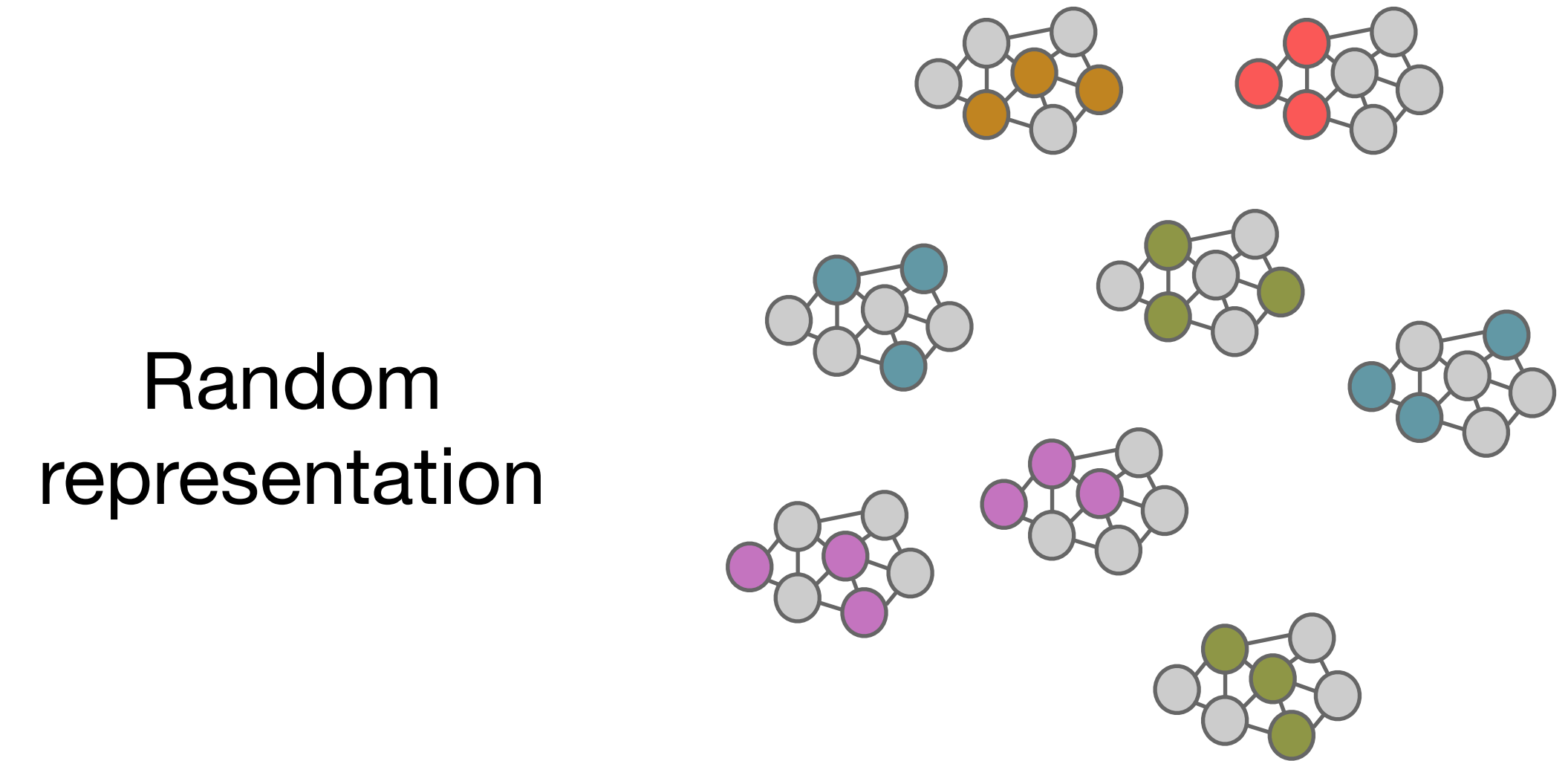

Estimated template subspace projection

The estimated template was represented in a **distributed** fashion across prefrontal and parietal cortex.

Estimated templates structural organization

Learning to attend a color in a semantically structured space
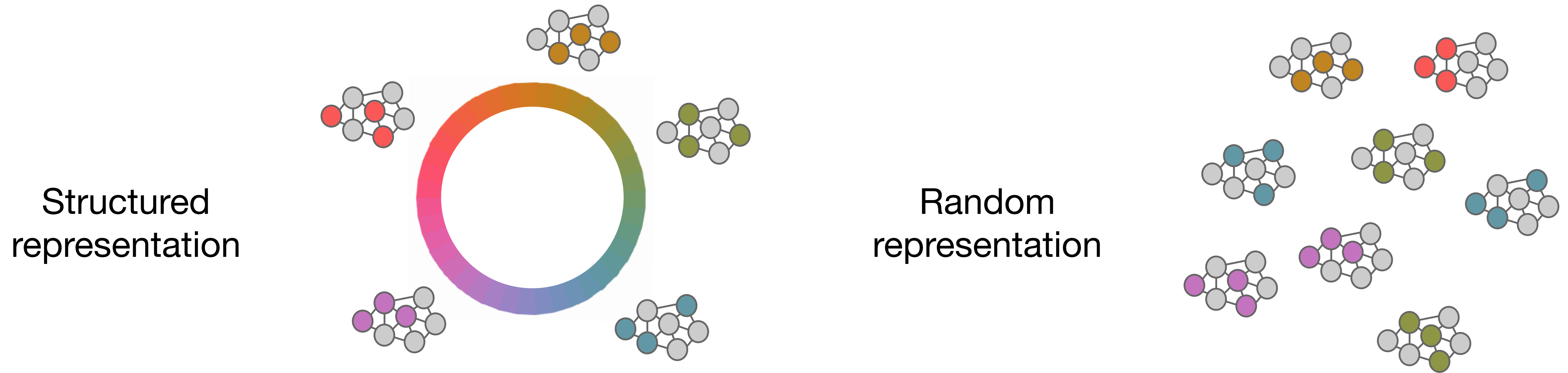

Structured representation

Random representation

Perception: colors have a semantic relationship
- Structured such that similar templates have similar neural representations
- Facilitate generalization (interpolation)

Mixed-slectivity: attentional template are unique for each context
- Multiple top-down representations converge to have the same impact on sensory processing
- Simpler to learn (no constraints)
- Avoid interference between contexts

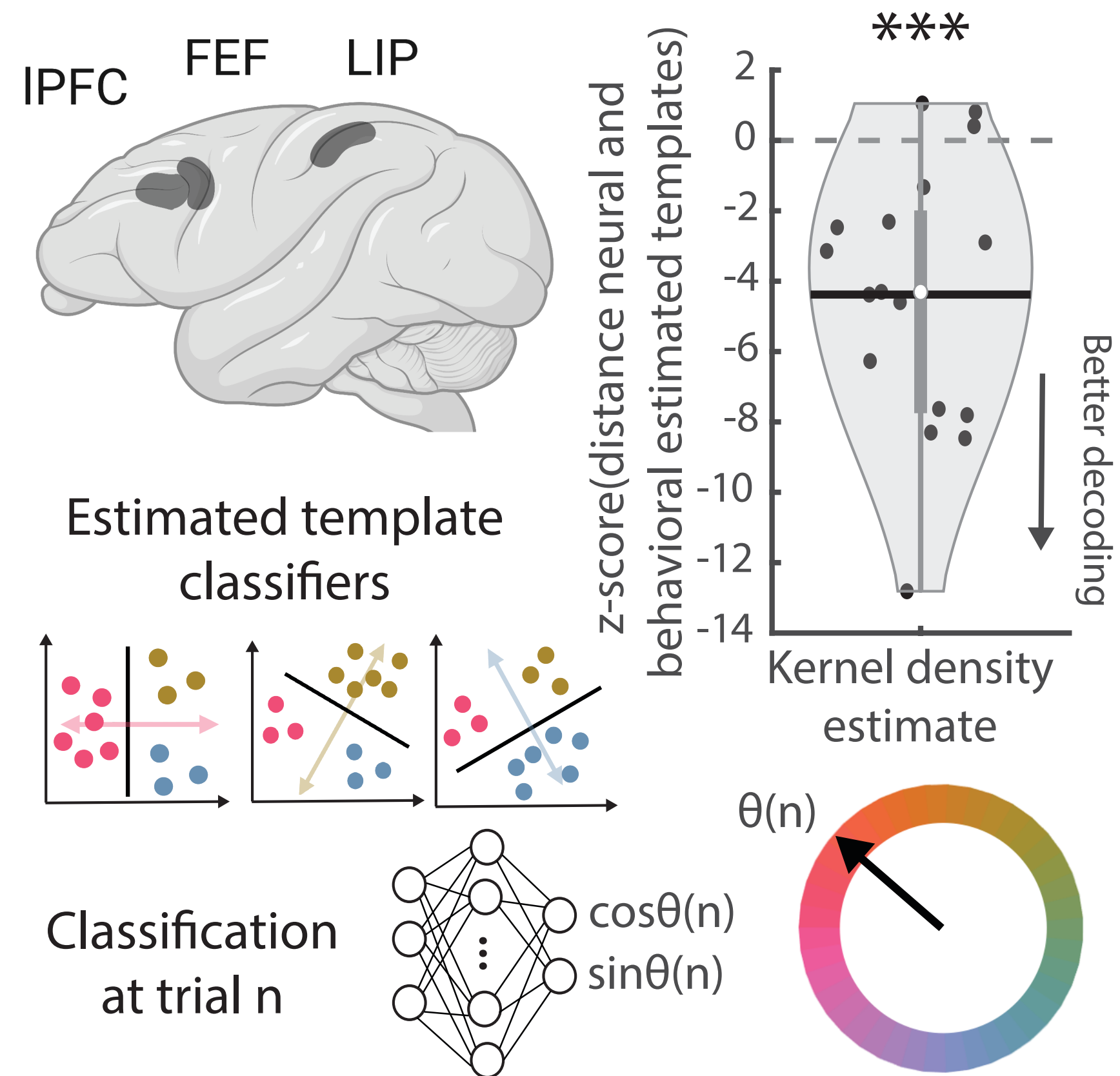# Learning to attend a color in a semantically structured space

Structured representation

Random representation

D Example session: templates

Trials

0   500   1000   1500   2000   2500
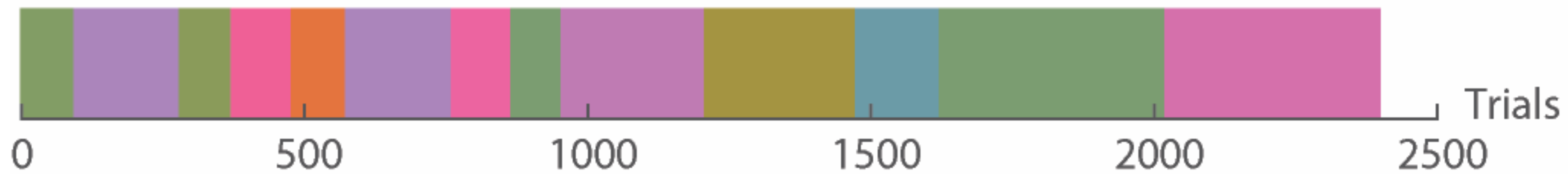
Trial-by-trial estimated template decoding

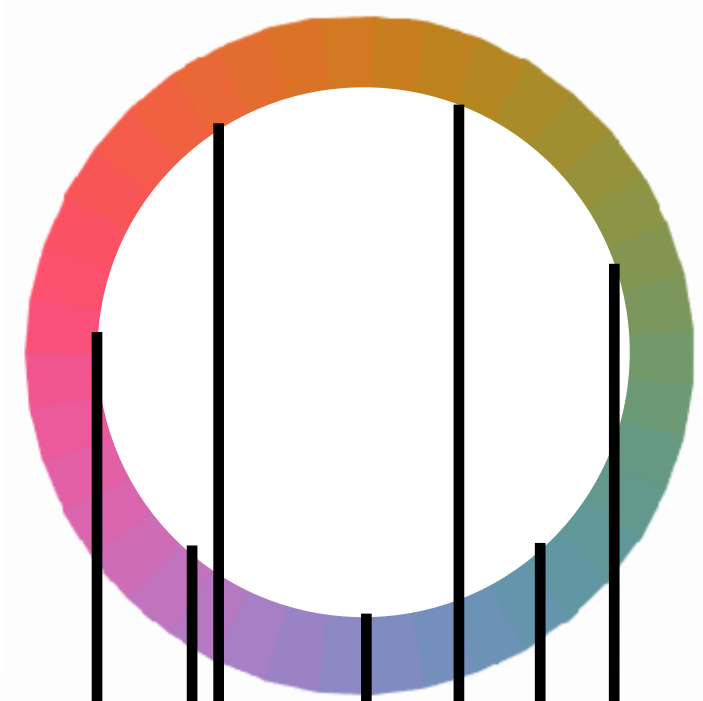A Trial-by-trial estimated template decoding on witheld trials
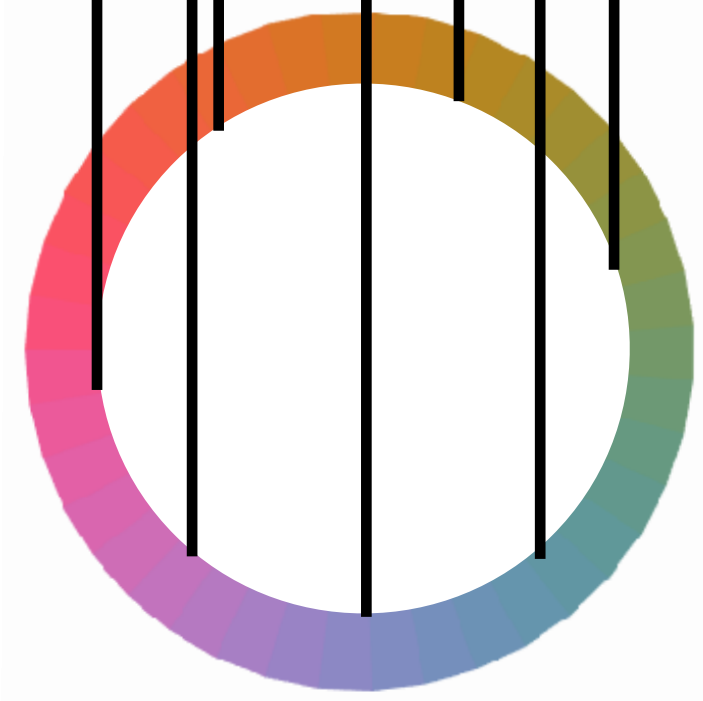
Estimated templates structural representation

Are attentional templates organized in a semantically structured space?
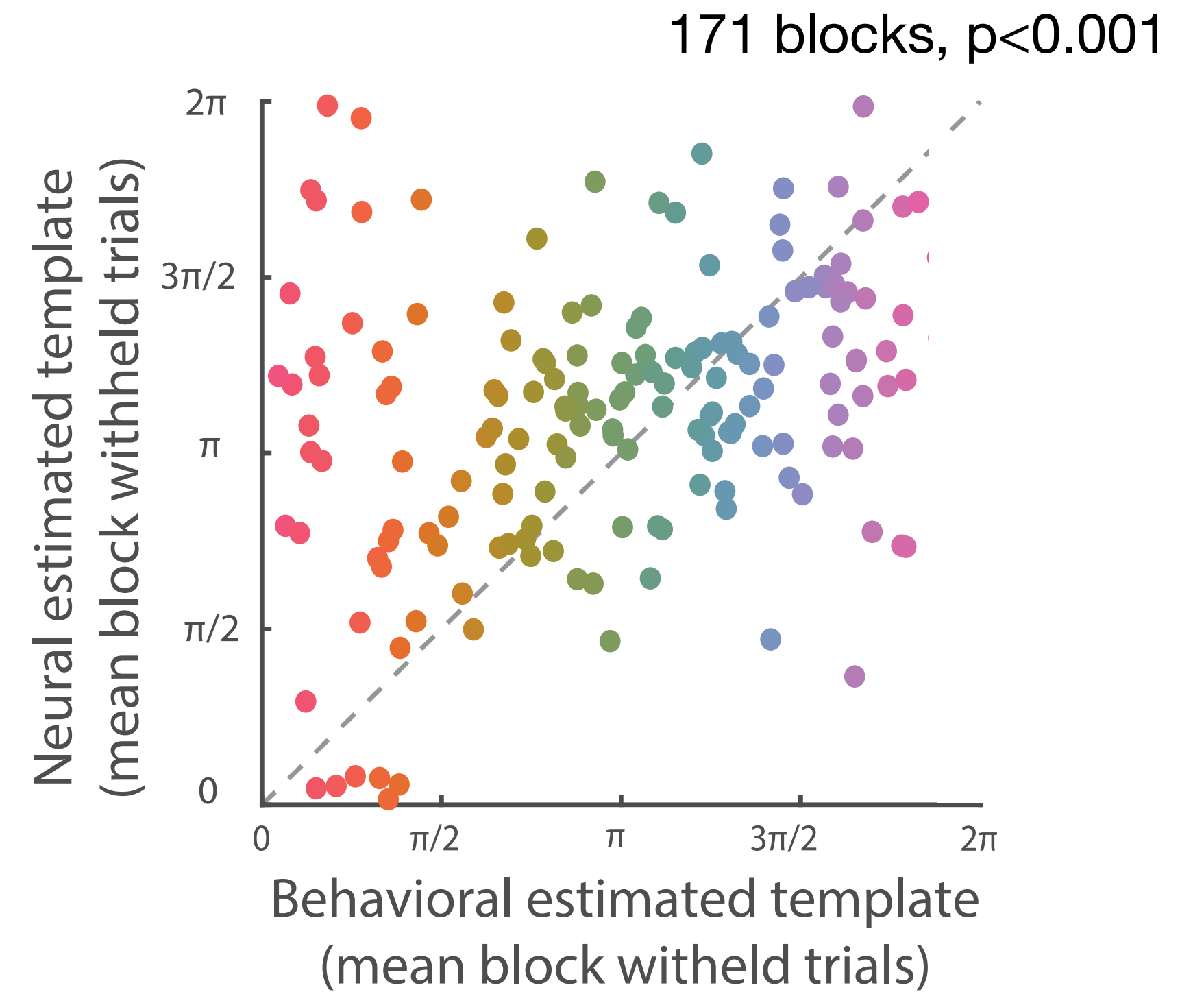
If structured:

Behavioral color wheel

Neural estimated template representation

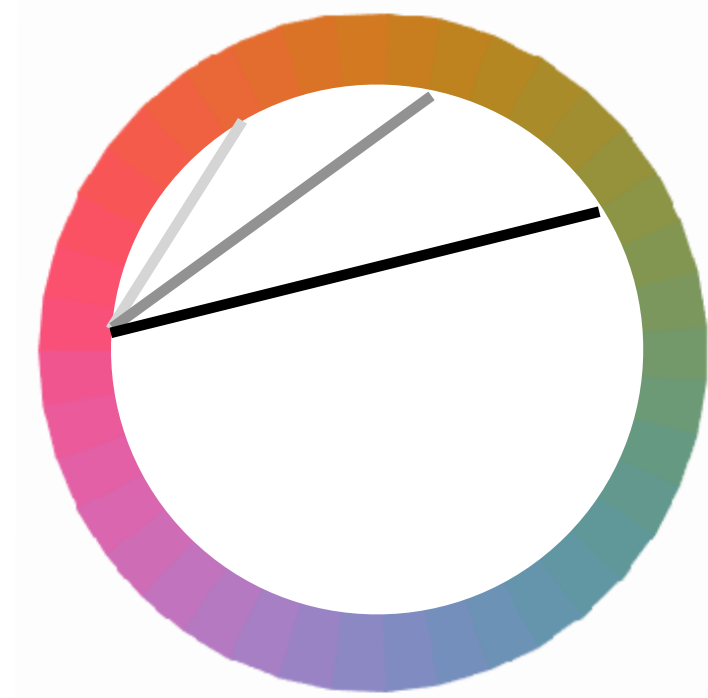Neural estimated template representation
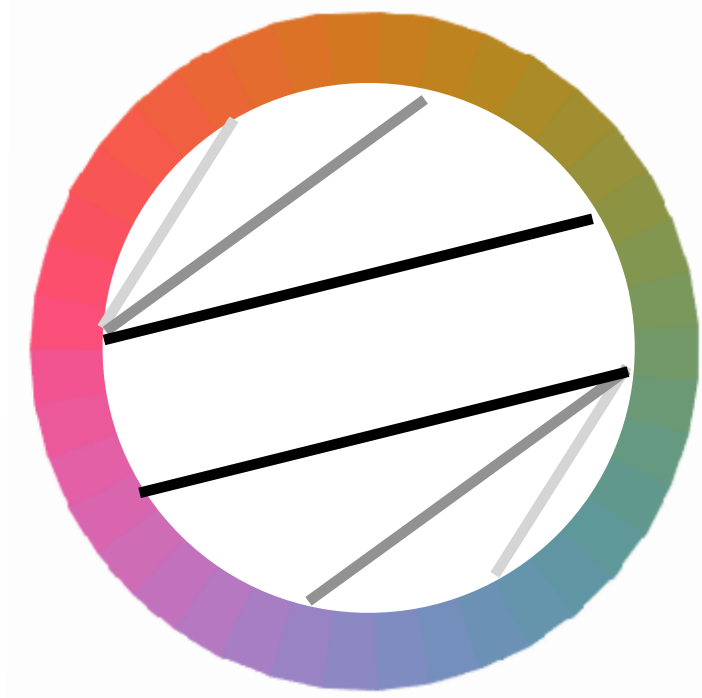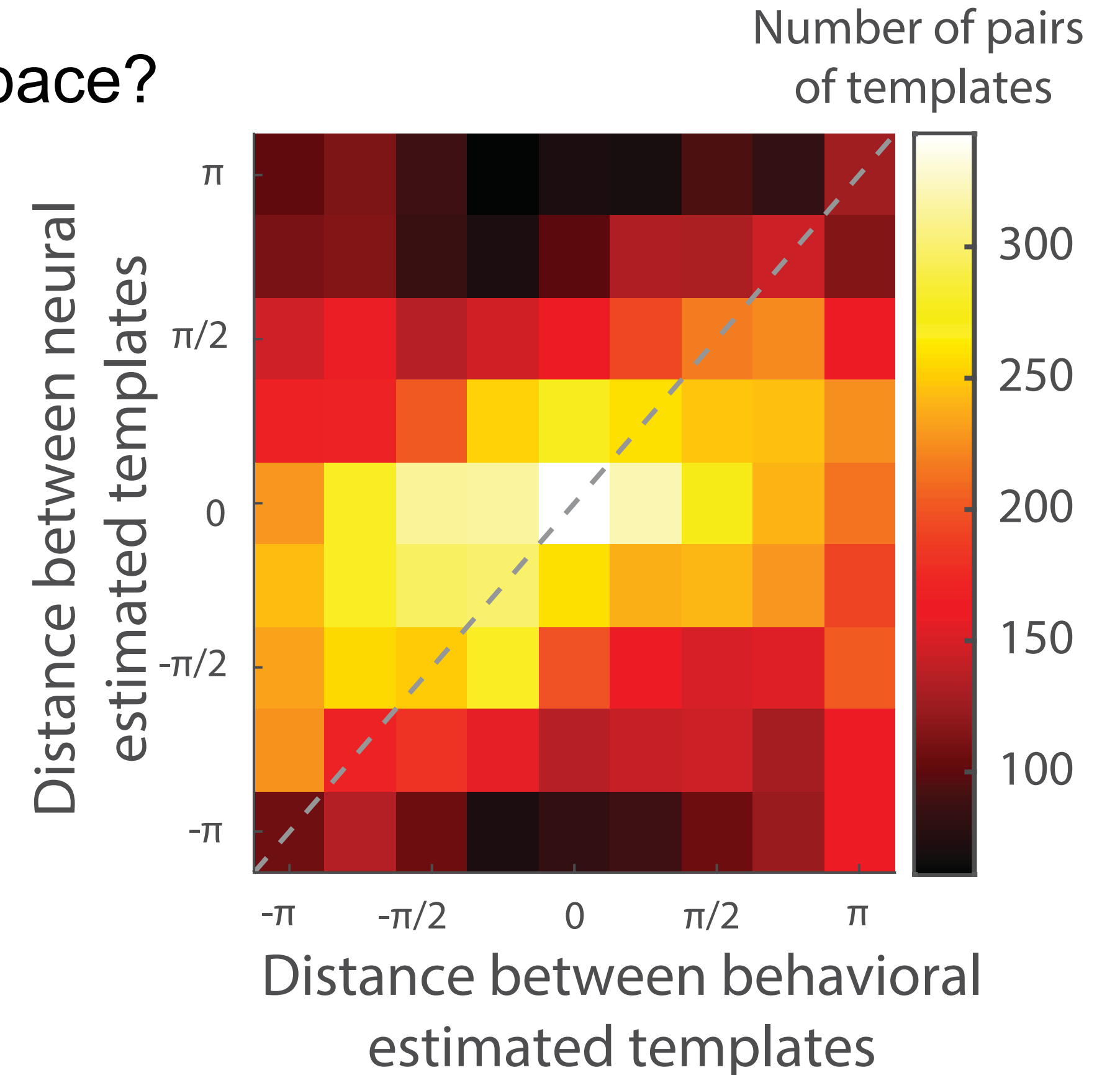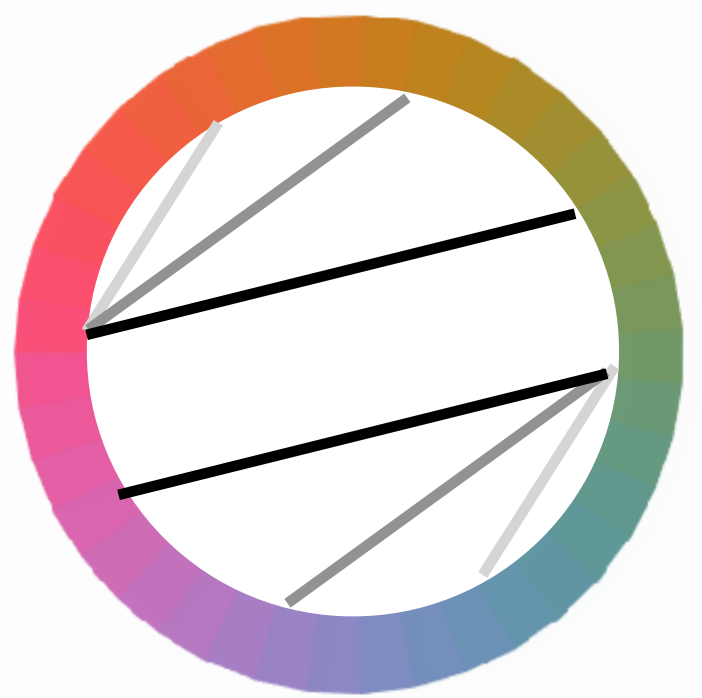

Behavioral color wheel

Estimated templates structural representation

Are attentional templates organized in a semantically structured space?
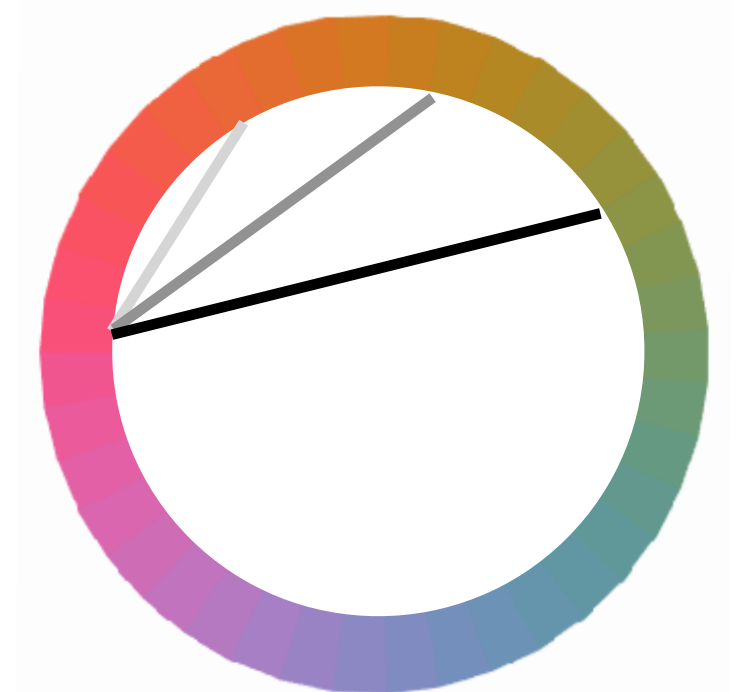

If structured:

Behavioral color wheel

Neural estimated template representation
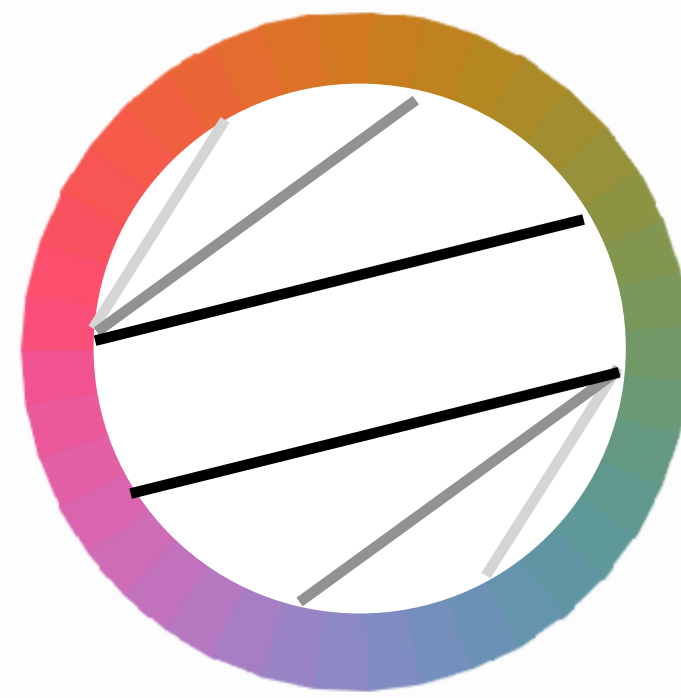
Neural estimated template representation
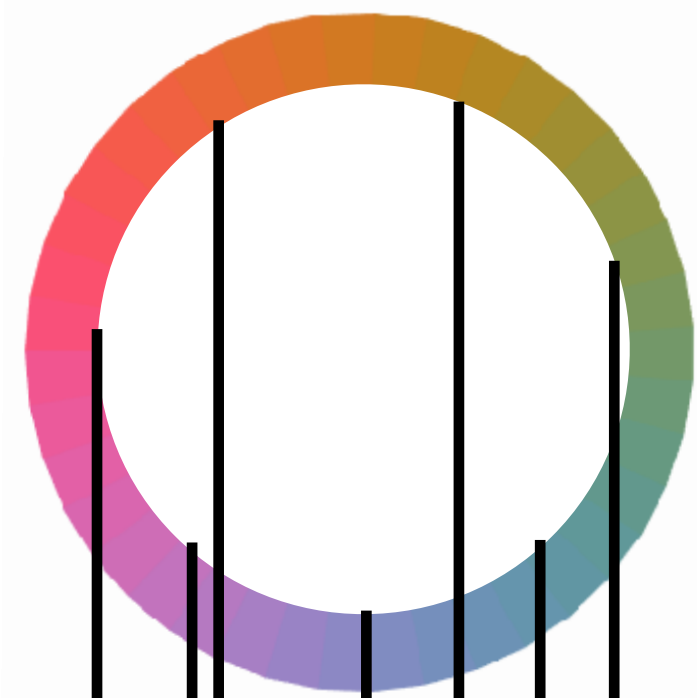
Behavioral color wheel

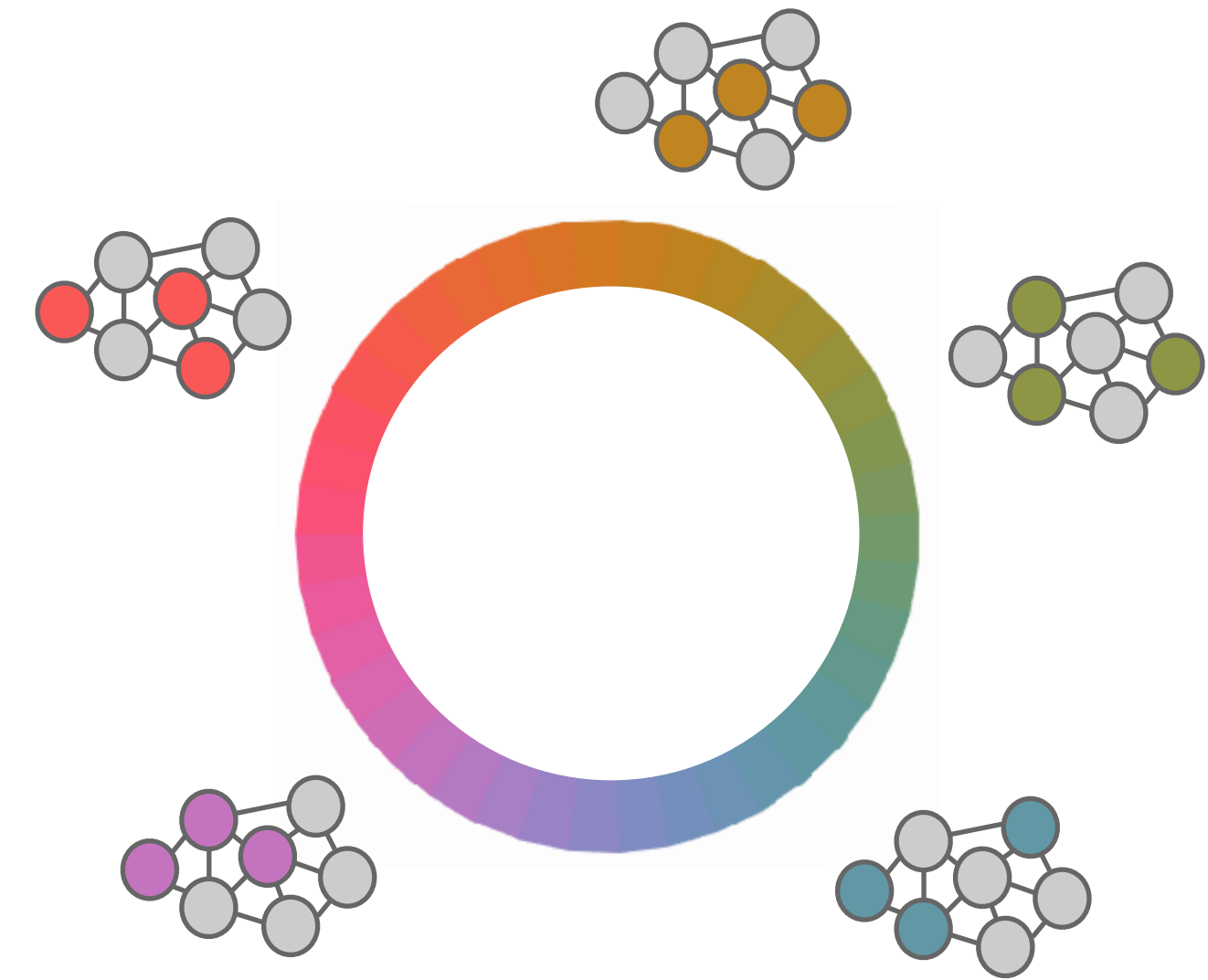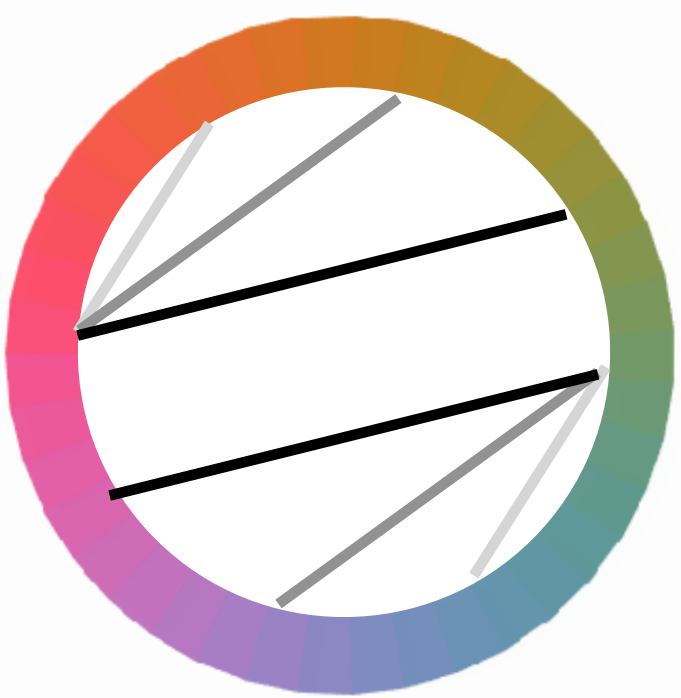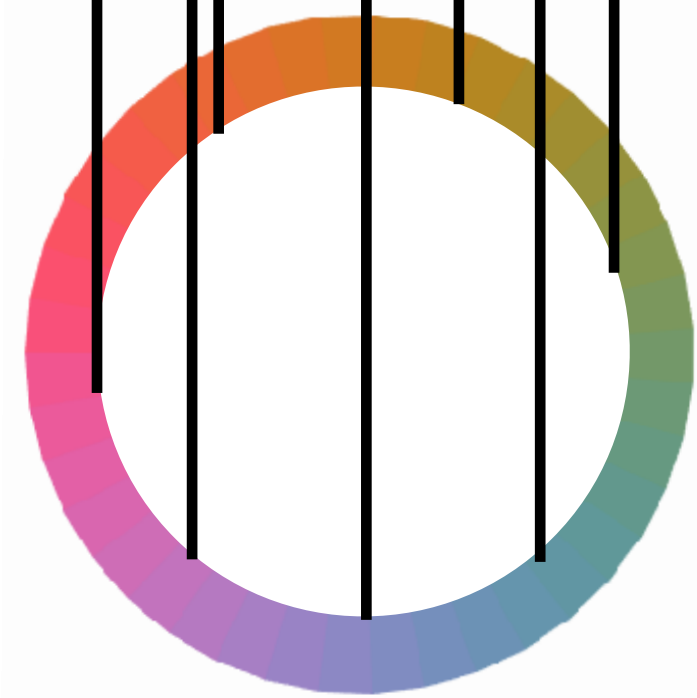# Attentional templates structural representation

Are attentional templates organized in a semantically structured space?

If structured:

Behavioral color wheel

Neural estimated template representation

LIP, FEF and IPFC represent the monkeys' internal model of the estimated attentional template in a **structured** fashion.

Updating the expected template

How does the network learn which template is relevant?

The neural template is updated **toward the chosen color after a positive RPE**.

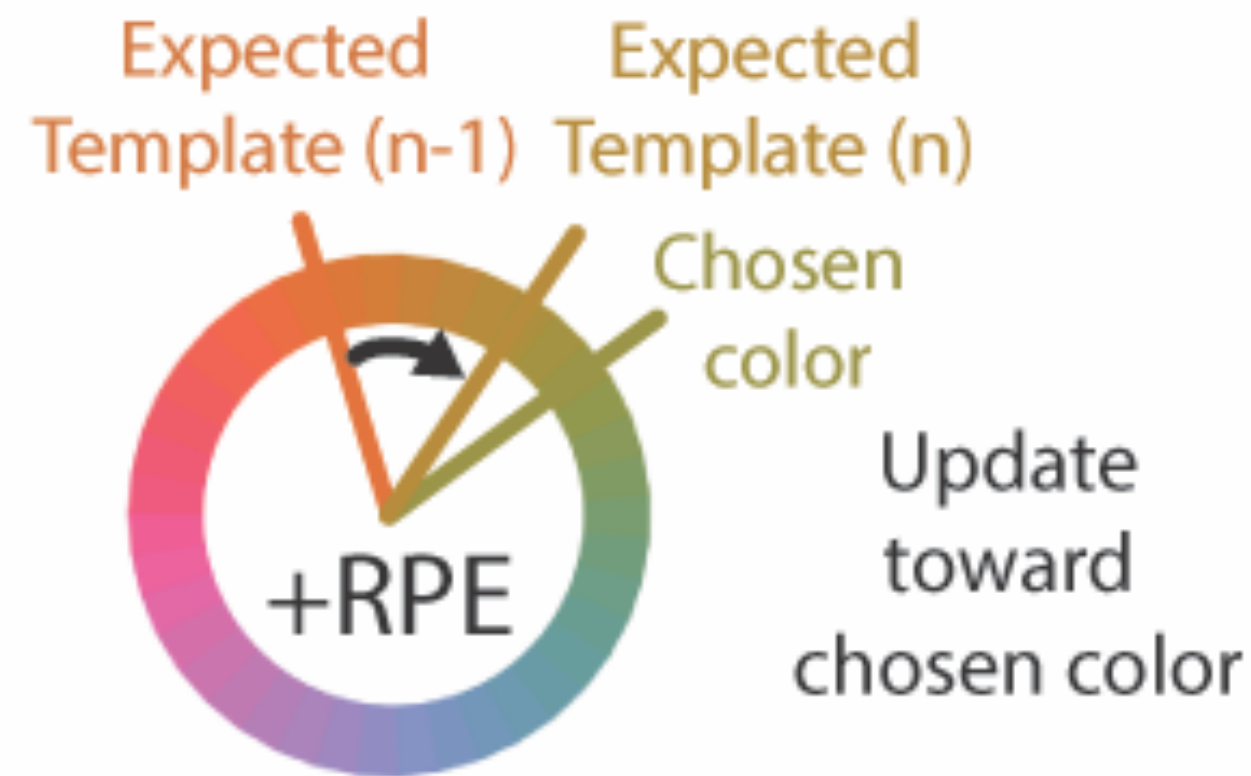The magnitude of the update is predicted by the model.
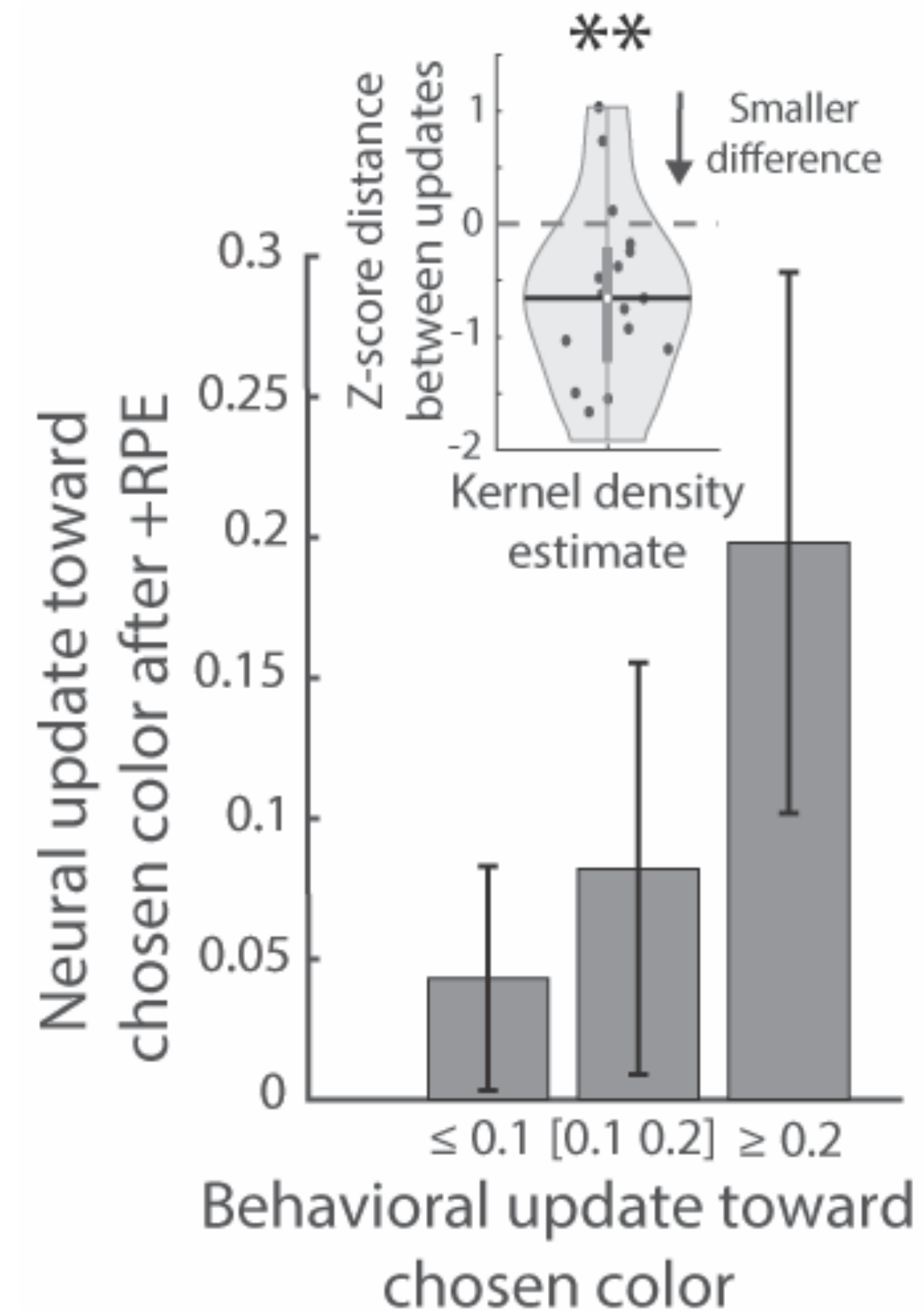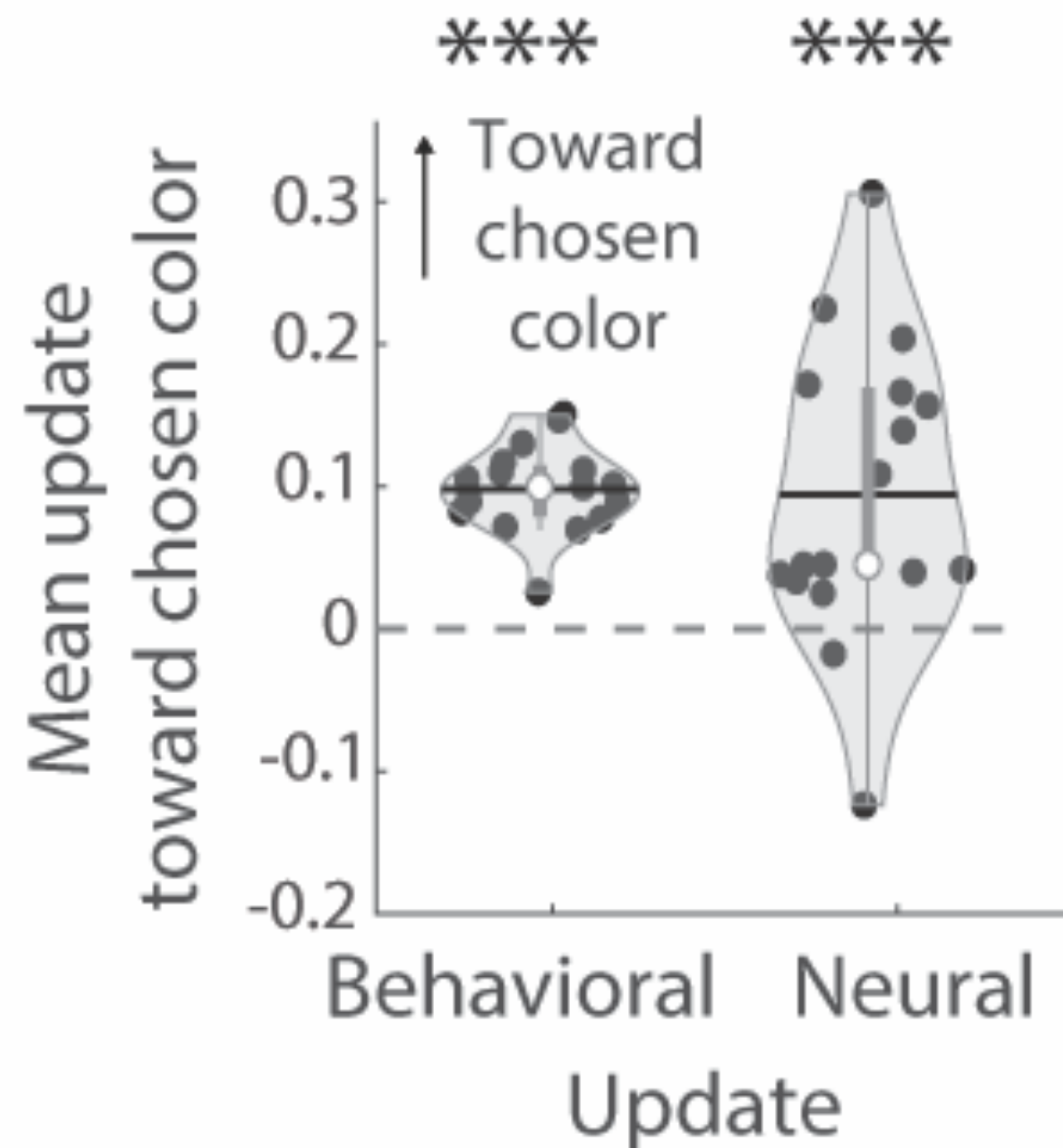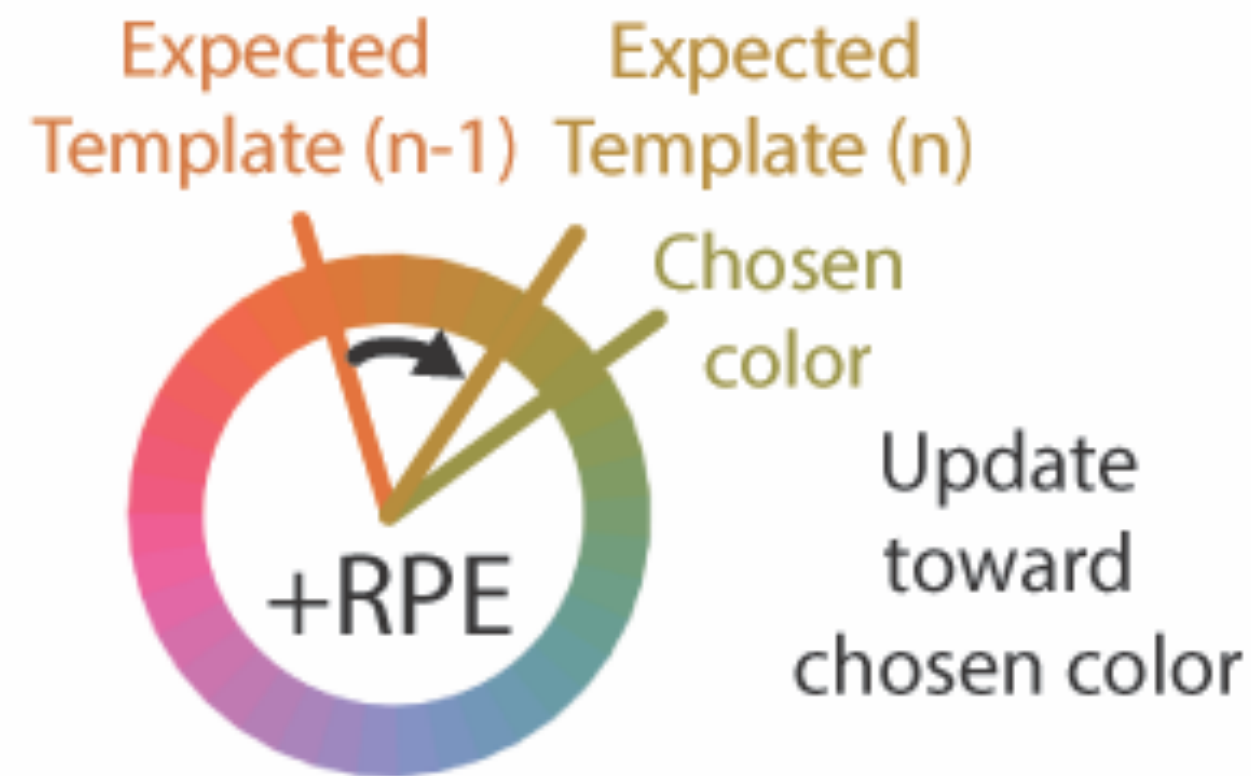
How does the network learn which template is relevant?

The neural template is updated **toward the chosen color after a positive RPE**.

The magnitude of the update is predicted by the model.
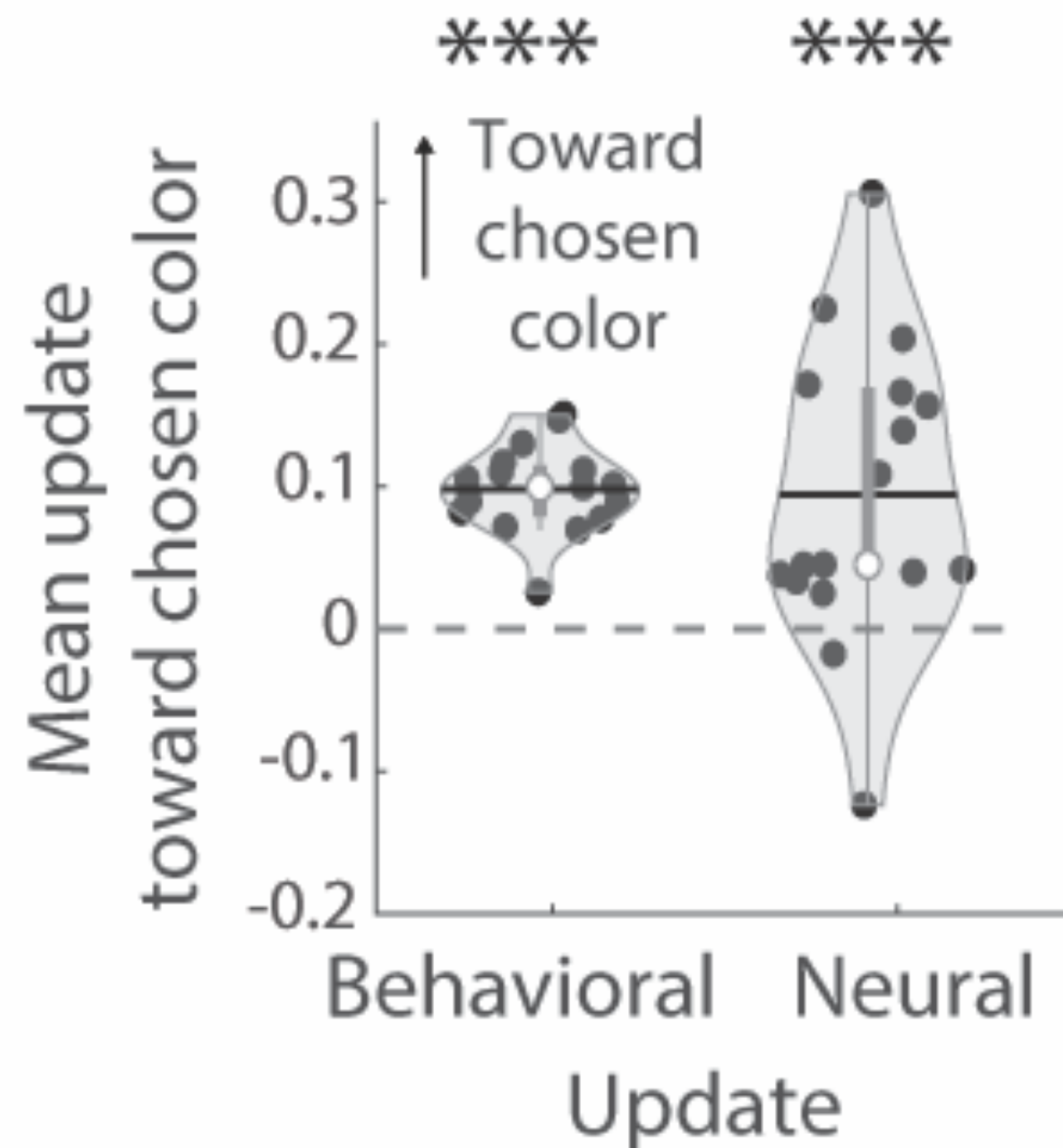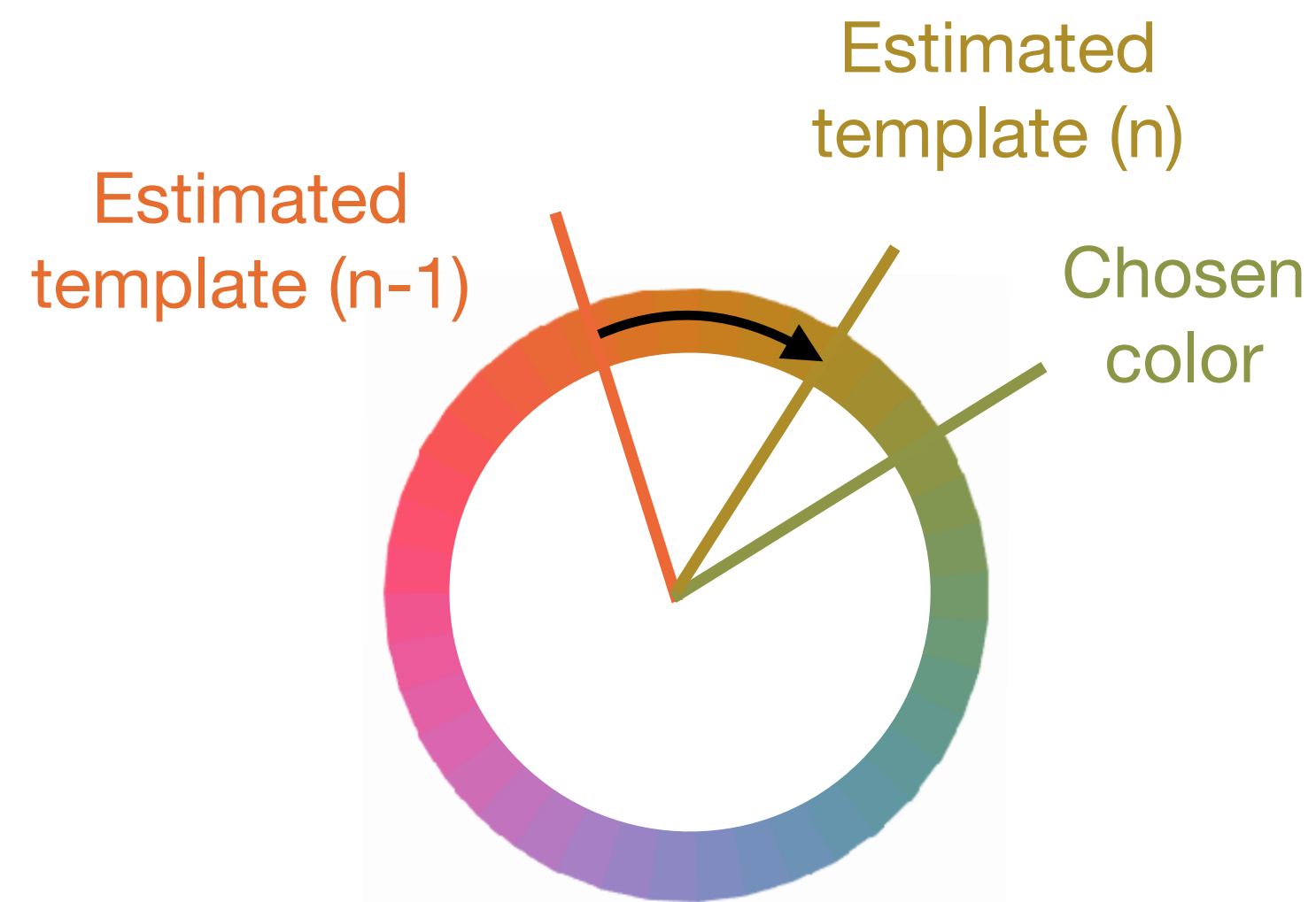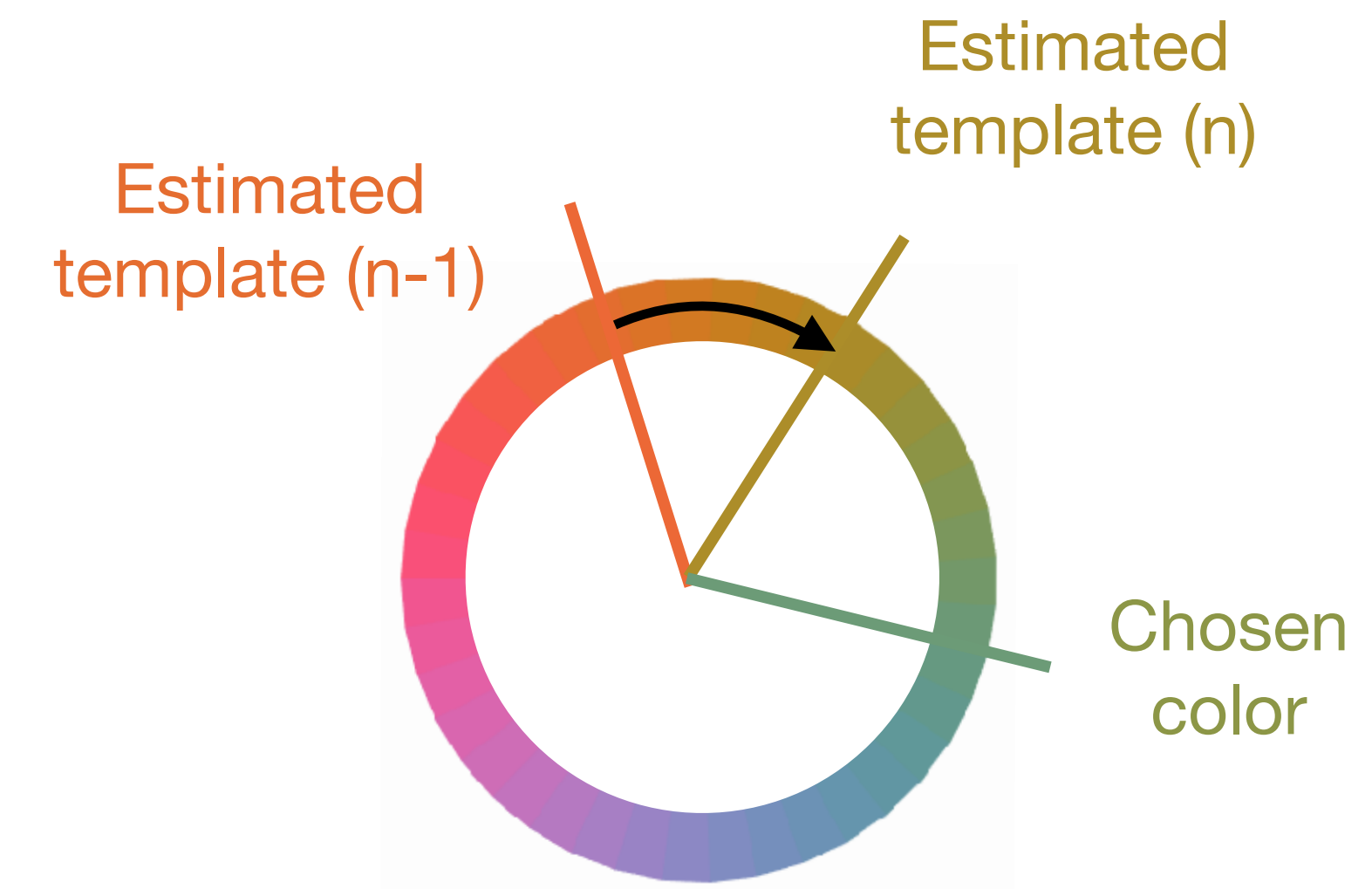
Updates after a negative RPE were not predicted by the model (exploration?)
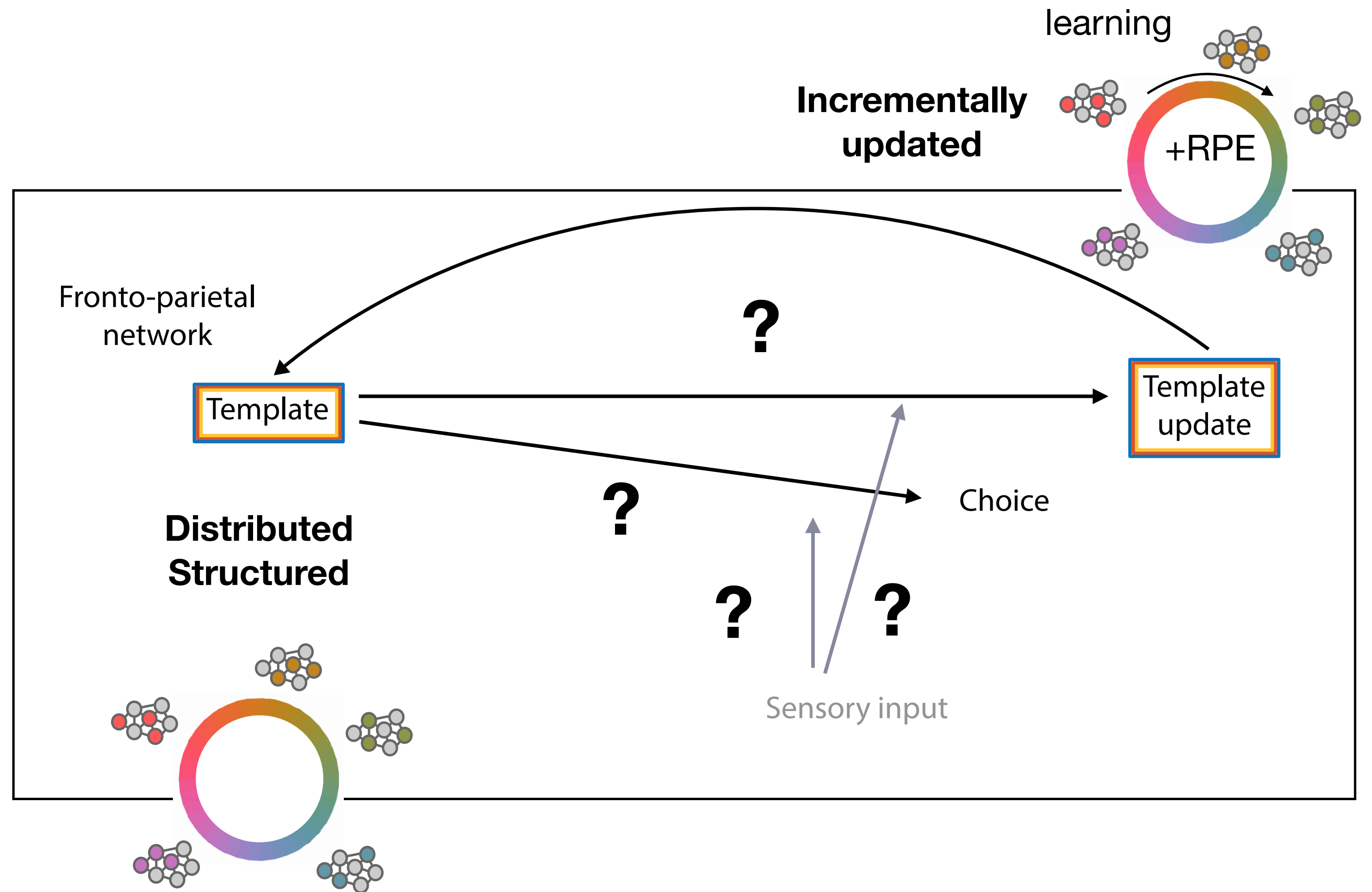
Increase +RPE

Increase distance to chosen color

Interim summary: learning an attentional template in a structured space
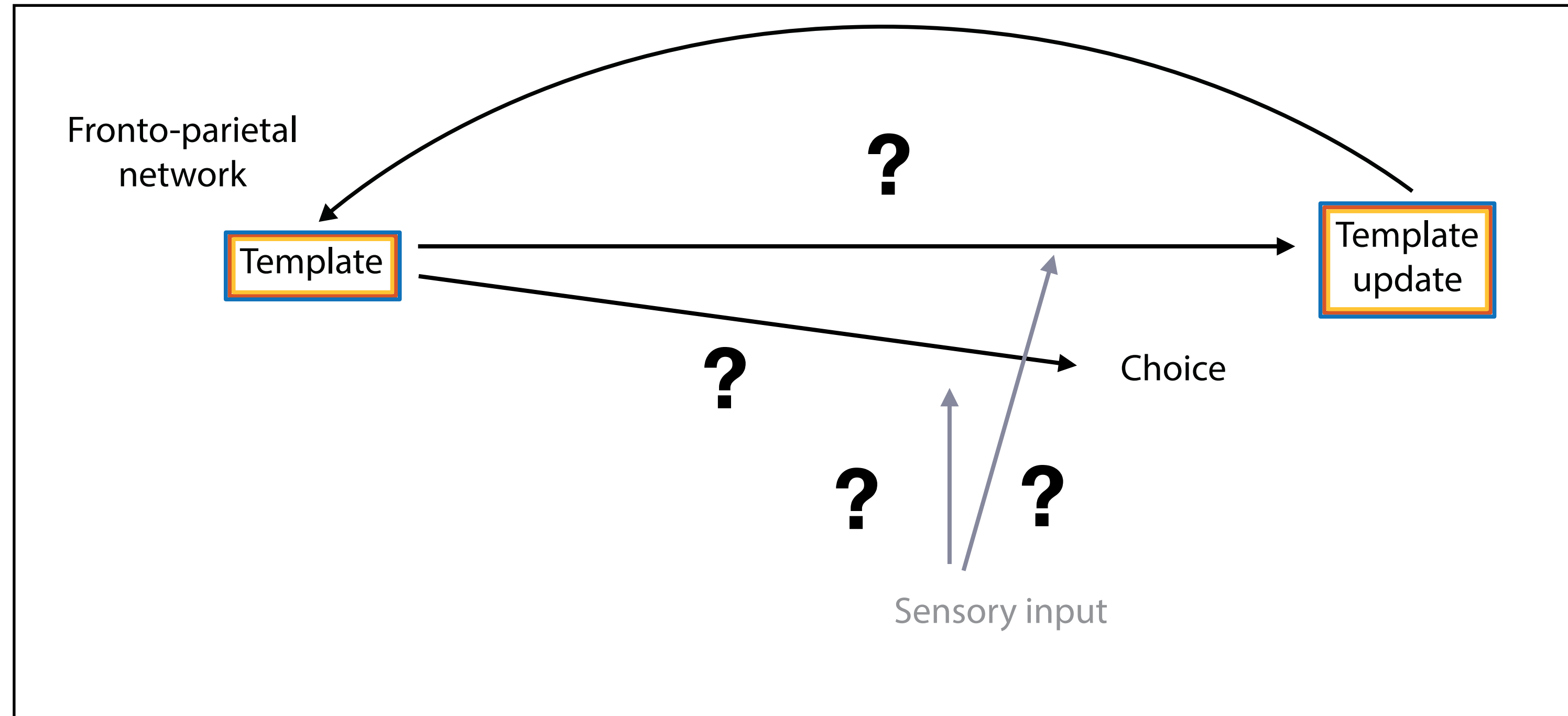
The attentional template representation is:

- **distributed** across LIP, FEF and lPFC

- **structured,** such that the same representations are revisited

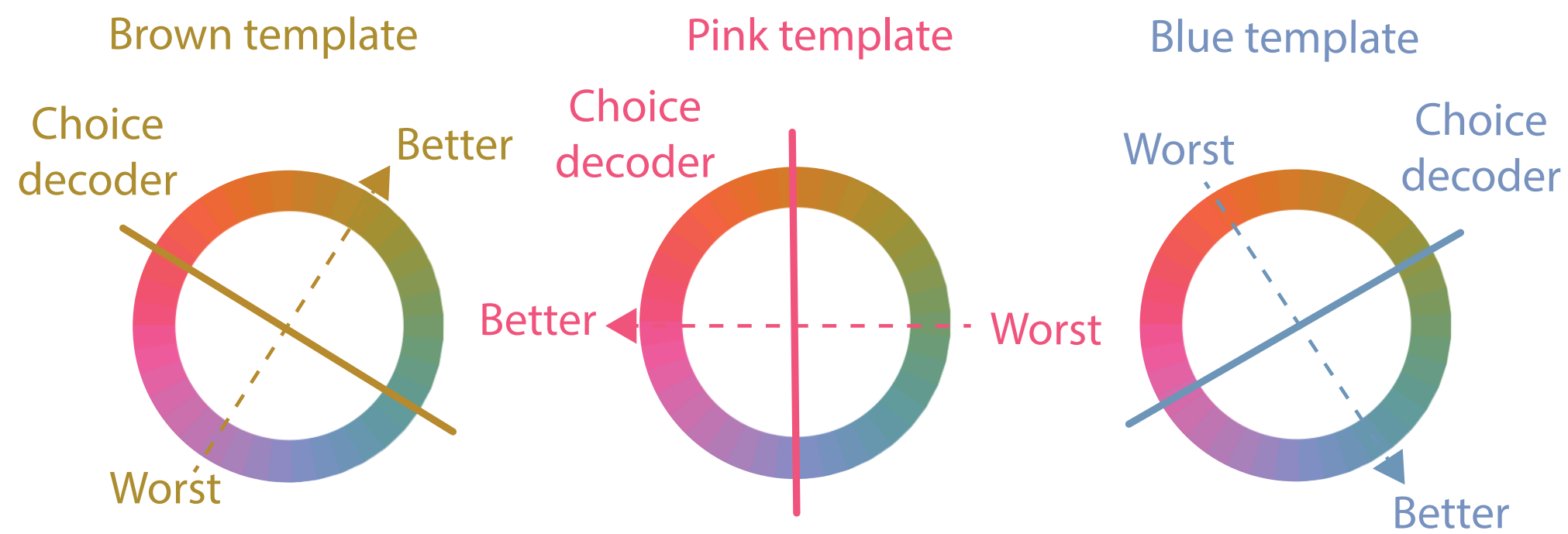- i**ncrementally updated** toward rewarded (positive RPE) colors

Using of the attentional template to guide choices

Using the attentional template

Attentional modulation model

Brown template
Choice decoder
Better
Worst

Pink template
Choice decoder
Better
Worst

Blue template
Worst
Choice decoder
Better

Generalized expected value model

Brown template
Better
Worst

Pink template
Better
Worst

Blue template
Better
Worst

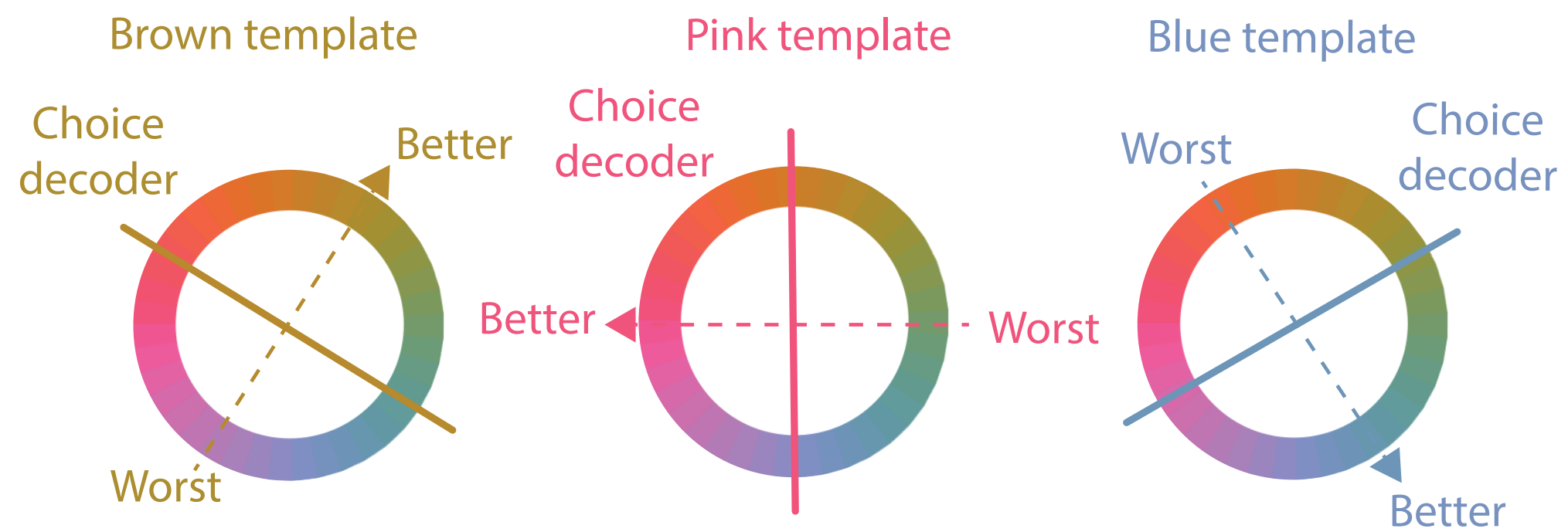Choice decoder all templates
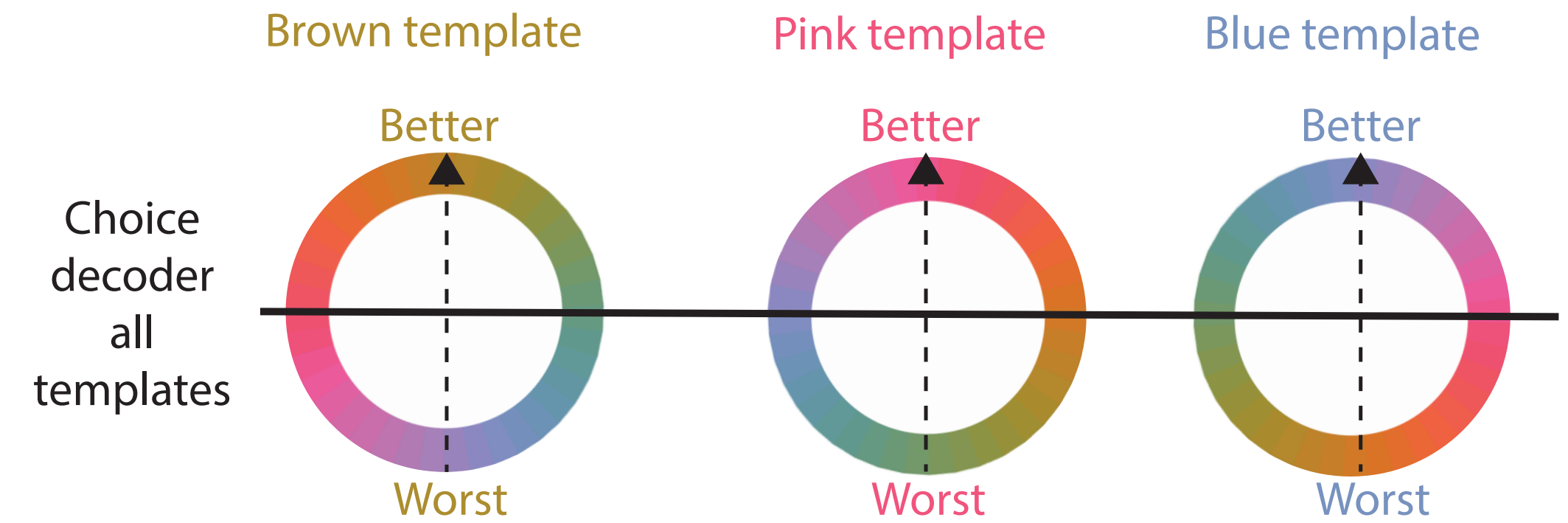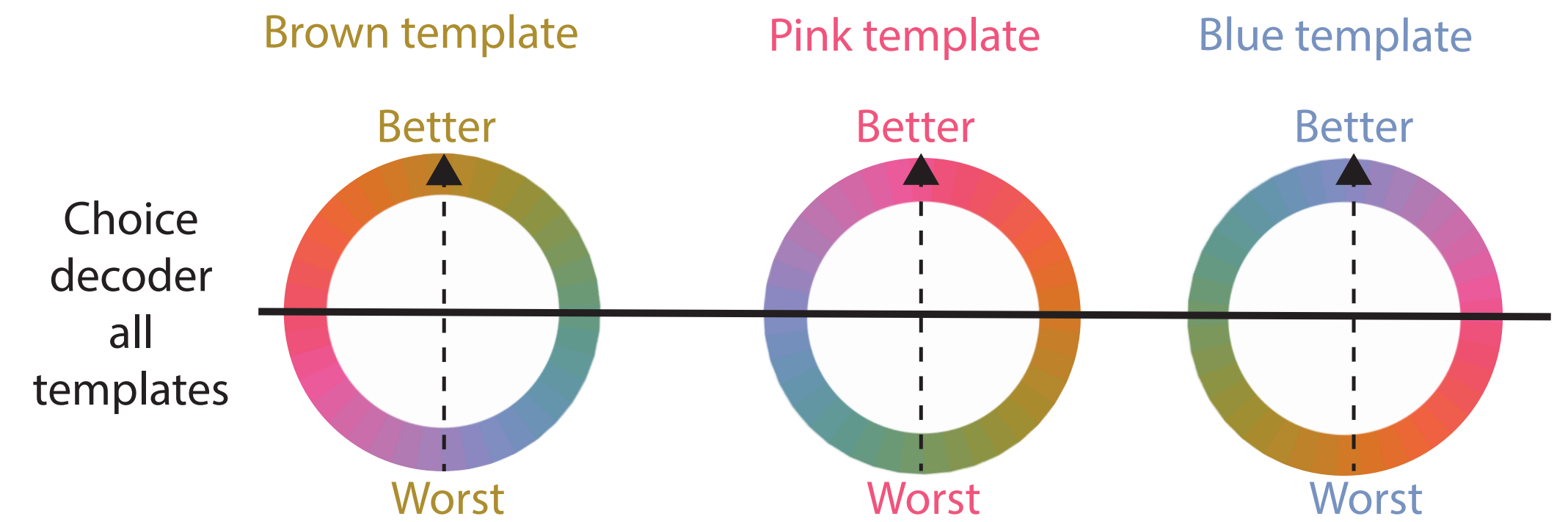
Using the attentional template

Attentional modulation model

Cross-template decoding of **color**.
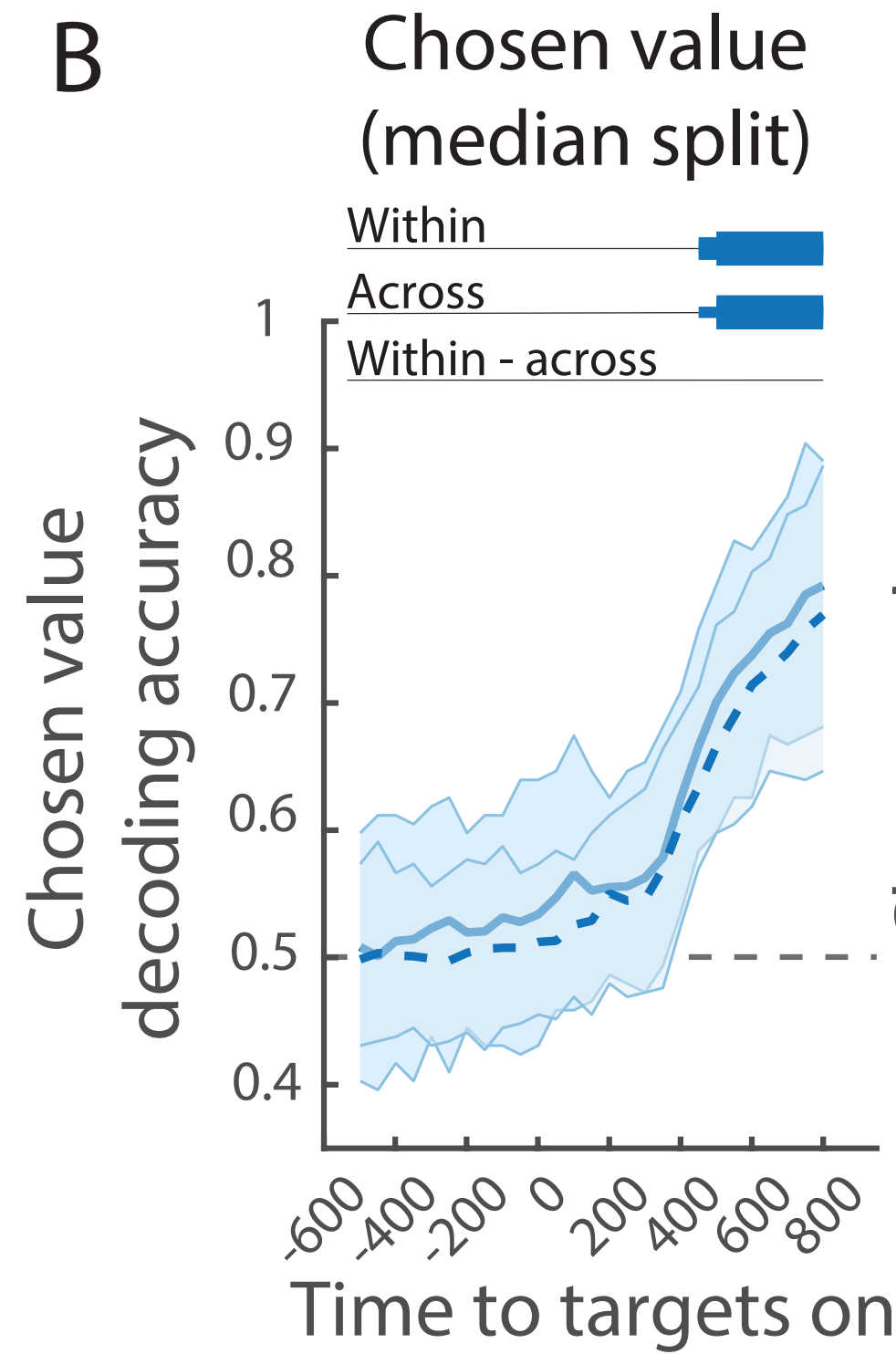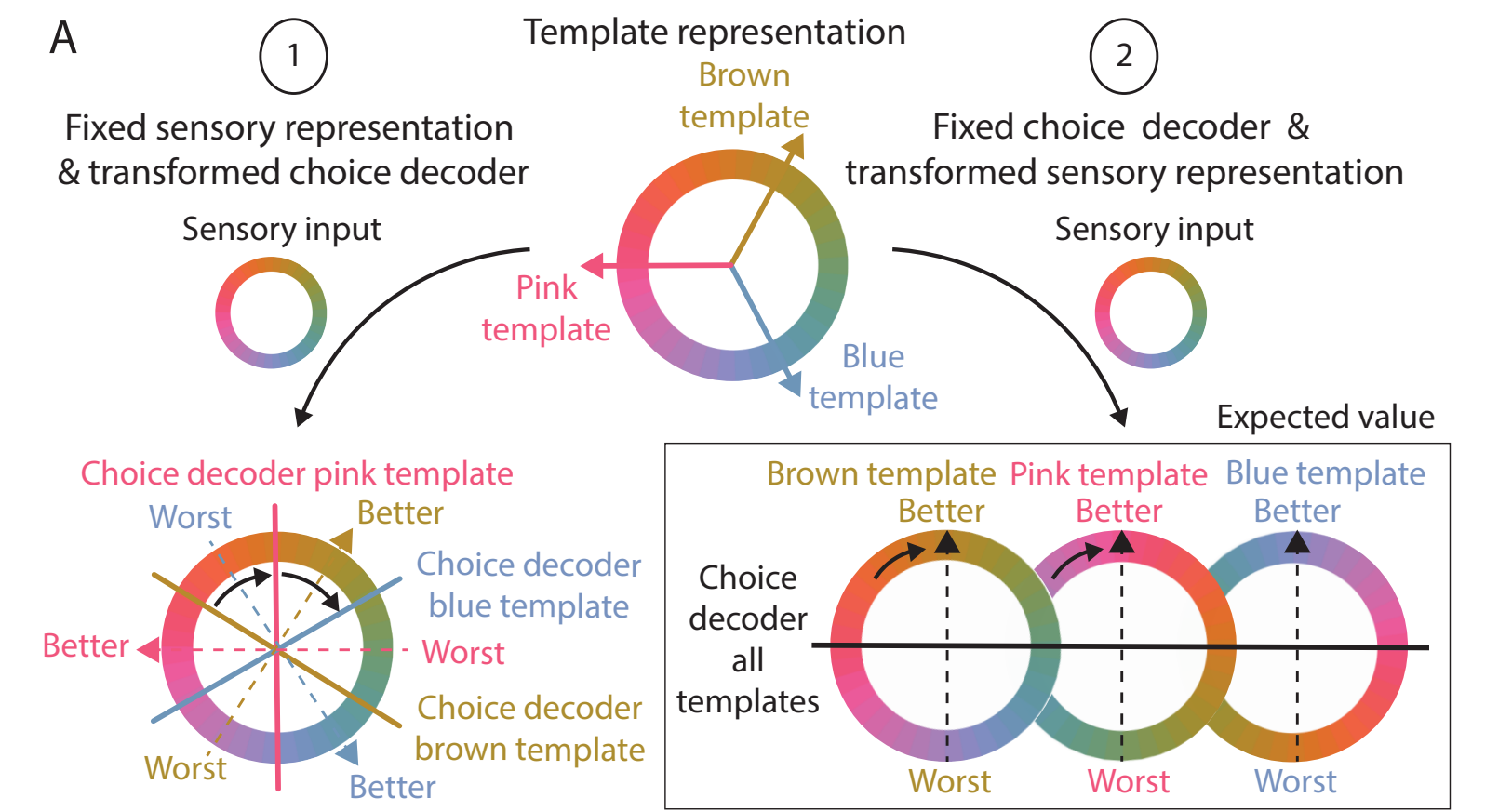Decrease in / no cross-template decoding of **choice and value**.
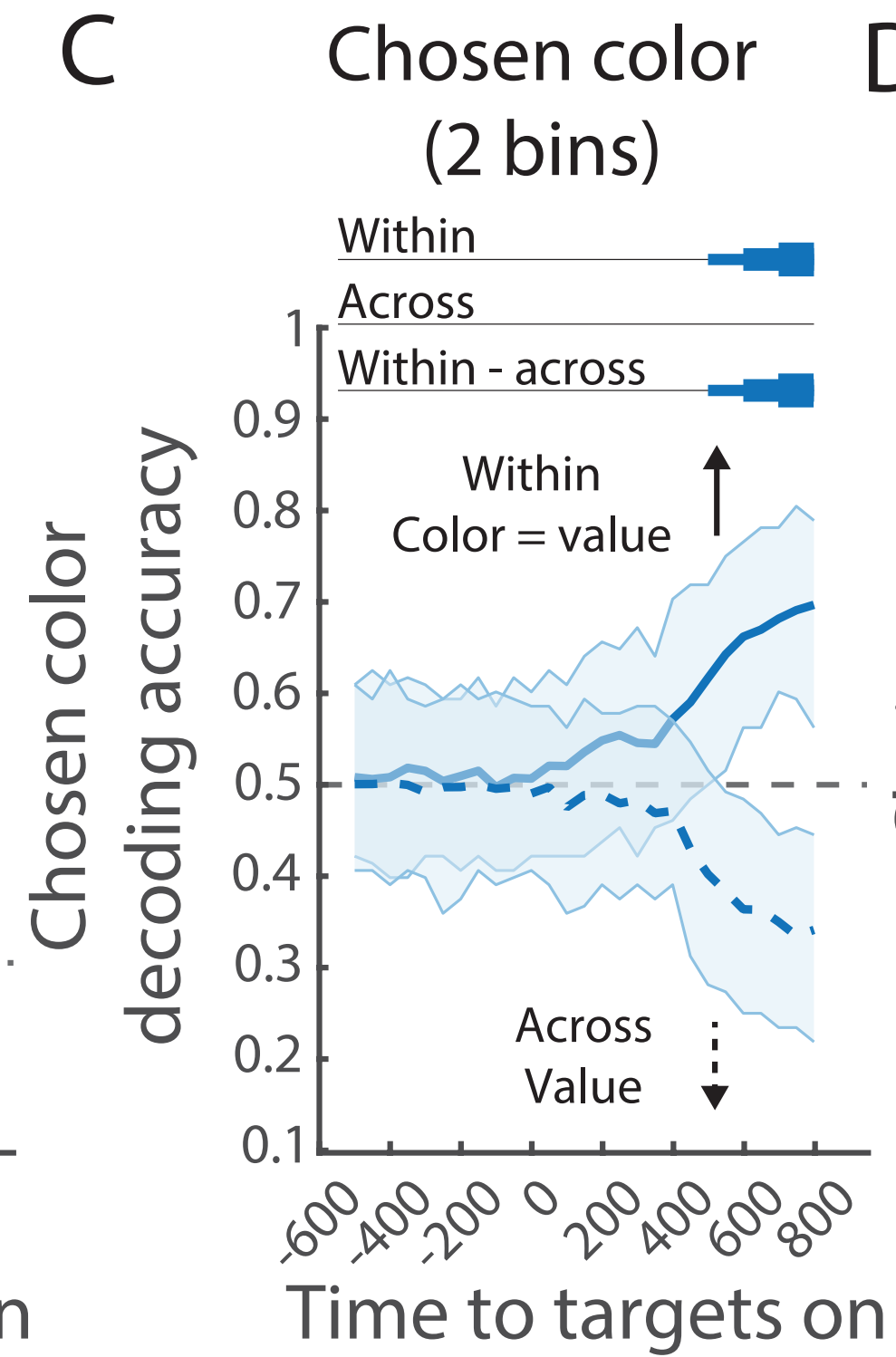
Generalized expected value model

Cross-template decoding of **choice and value**.
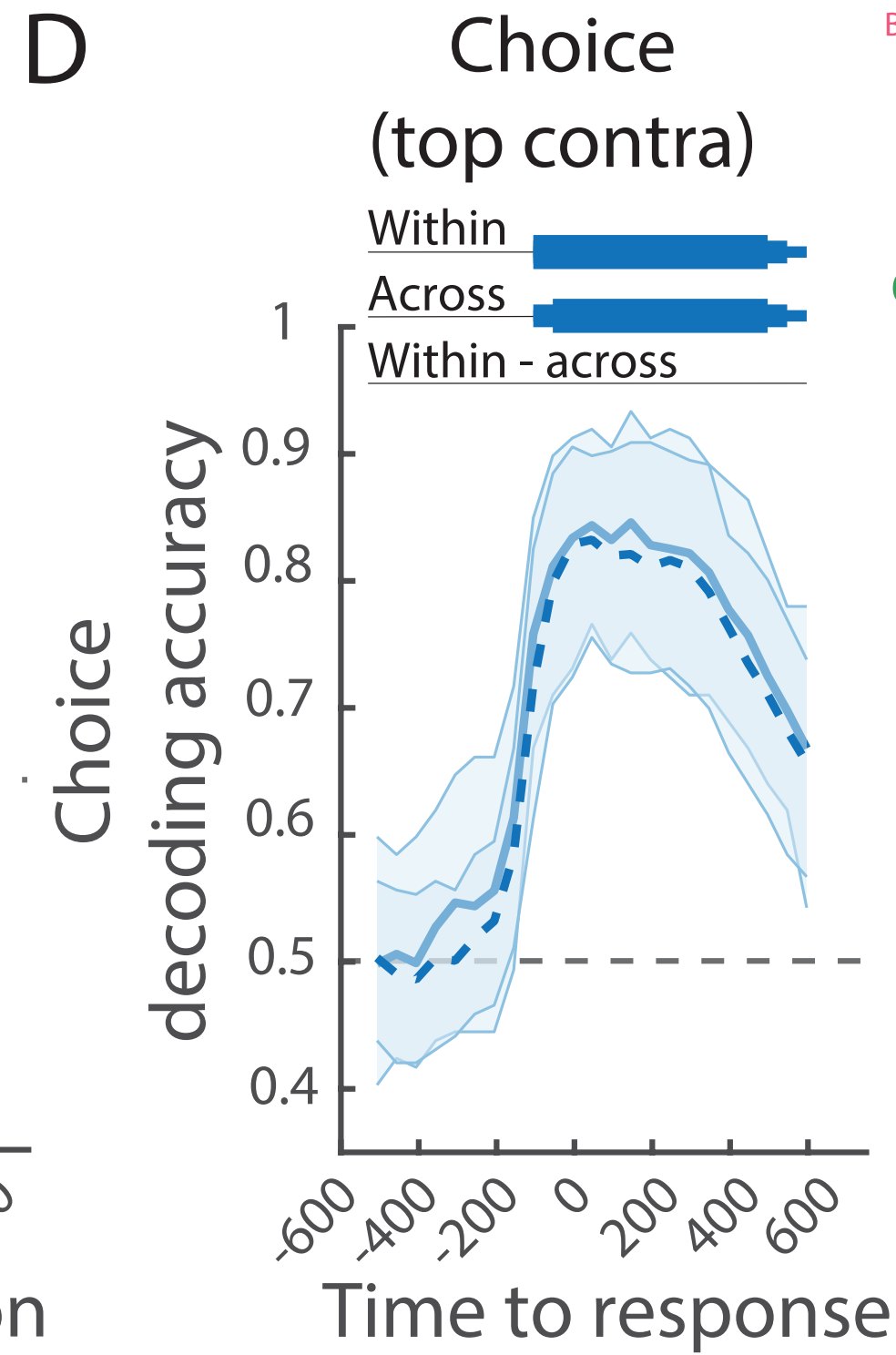Decrease in / no cross-template decoding of **color**.

Using the attentional template

B Chosen value (median split)

C Chosen color (2 bins)

D Choice (top contra)

LIP

Train/test
— within template
- - - across templates

A Template representation
Fixed sensory representation & transformed choice decoder ①
Fixed choice decoder & transformed sensory representation ②

Color / Choice and value   Choice and value / Color

Cross-template decoding of **value**

No cross-template decoding of **color**

Cross-template decoding of **choice**

Using the attentional template
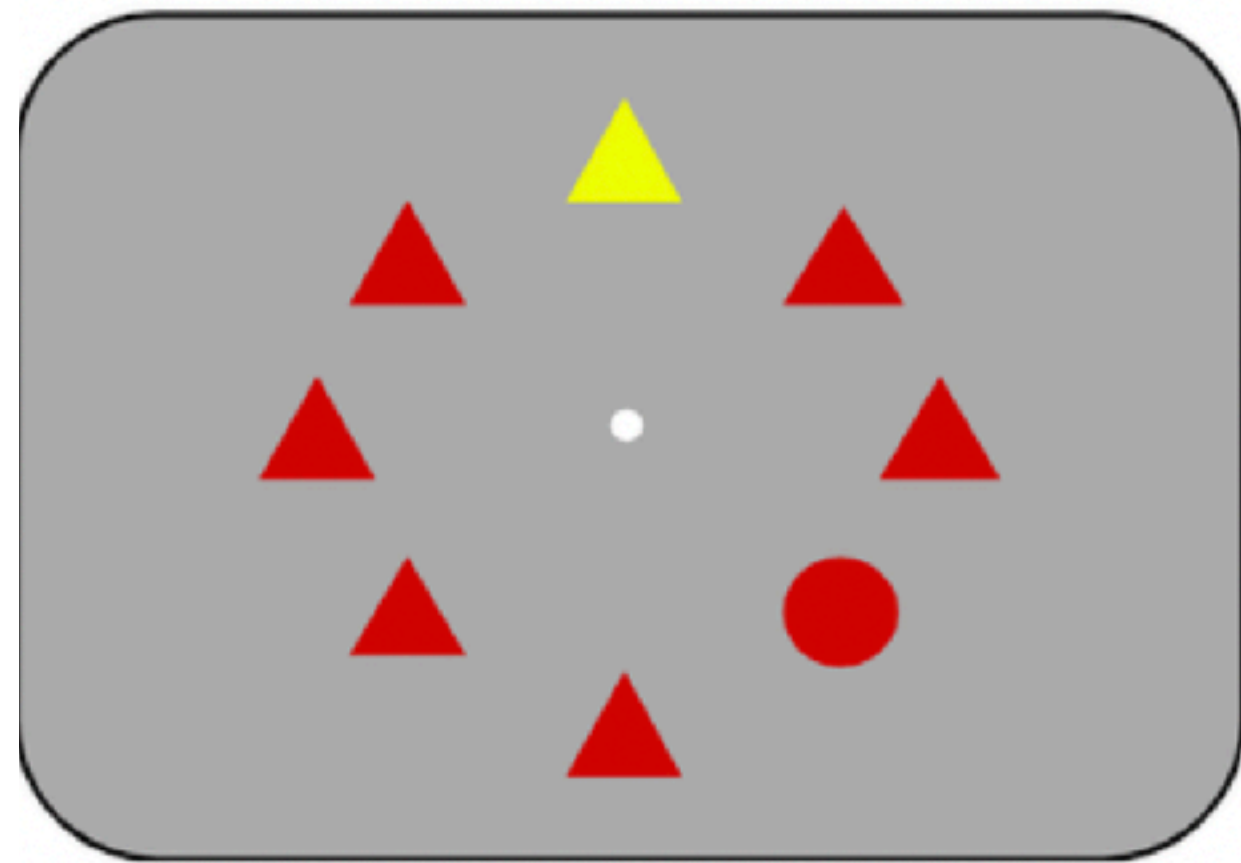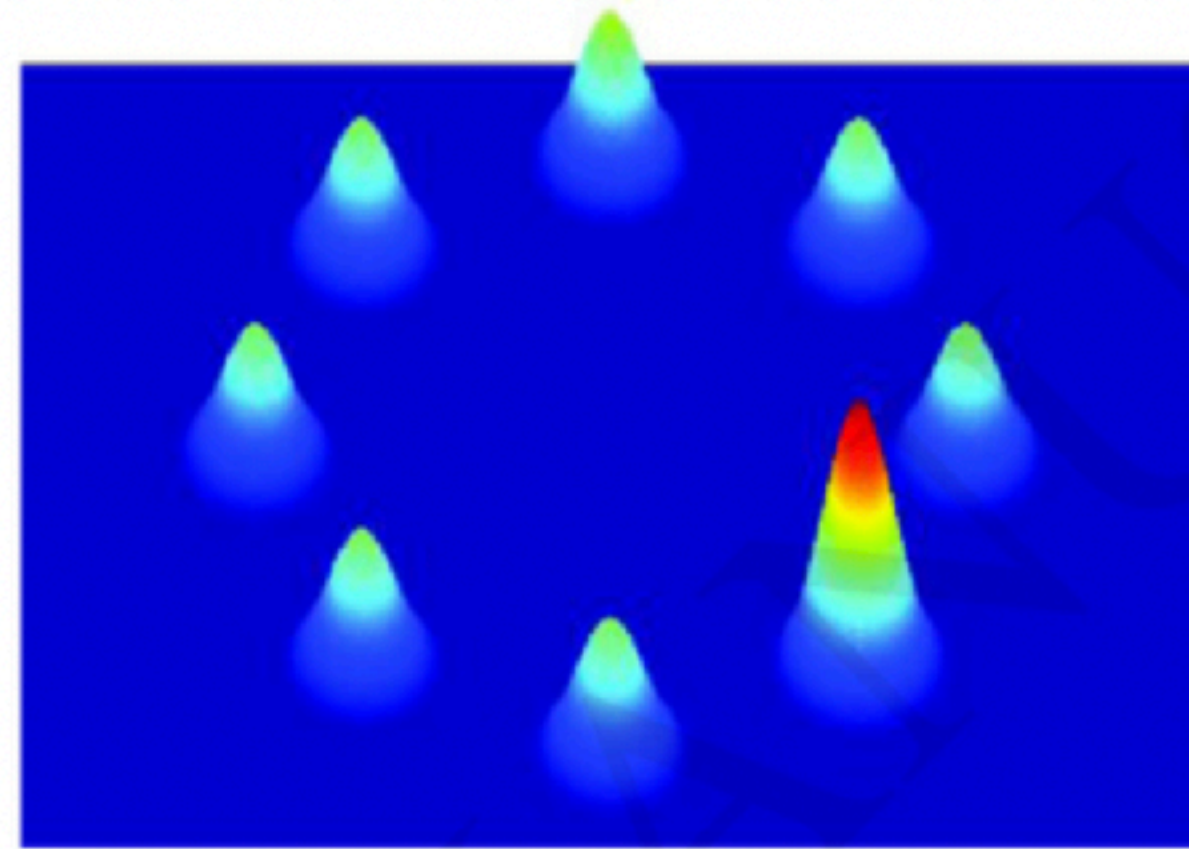
The attentional template transforms sensory inputs into a **sensory-agnostic generalized value** representation.

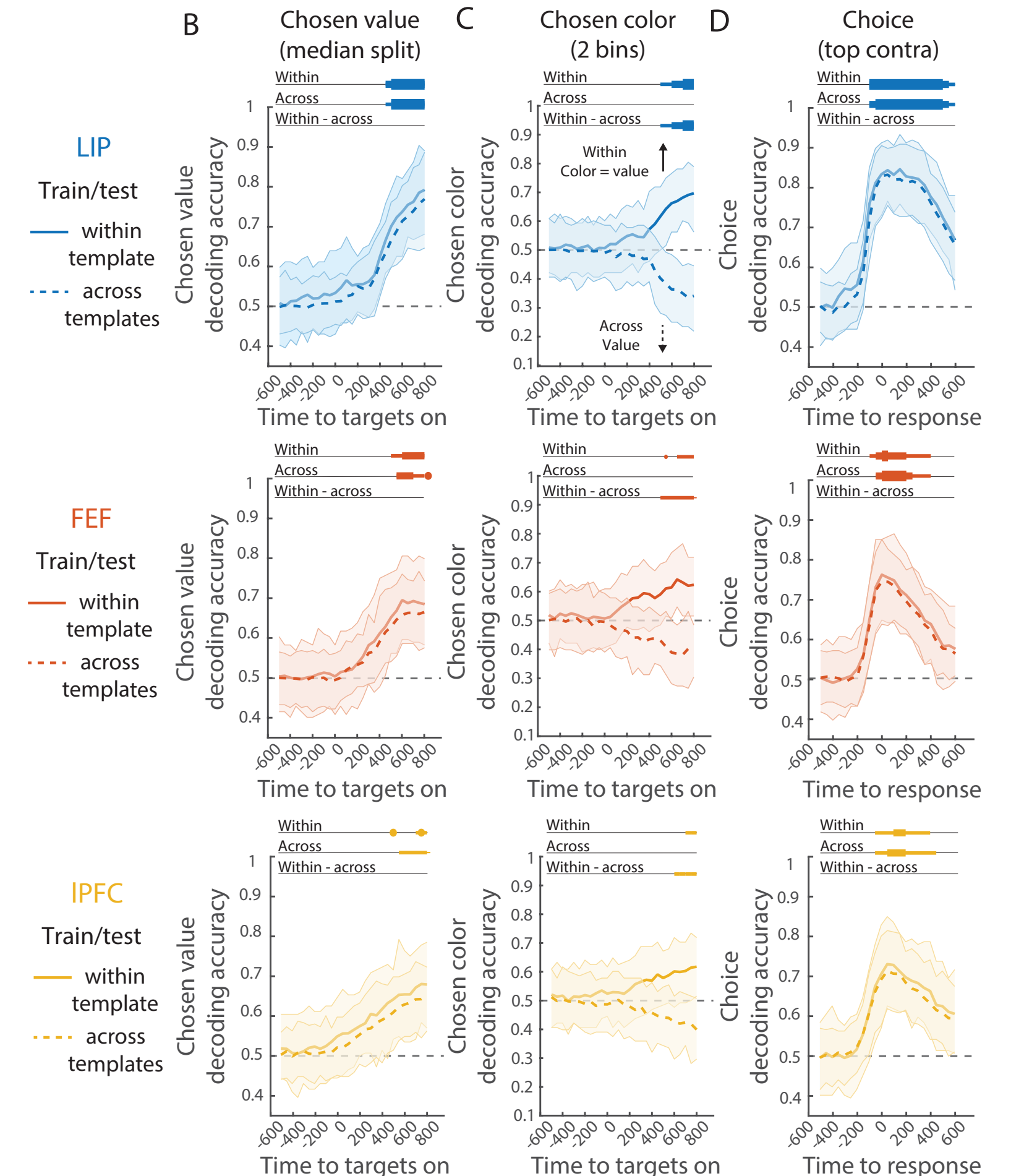This avoids the need to build a new circuitry for each decision and to decide whether to update the template.
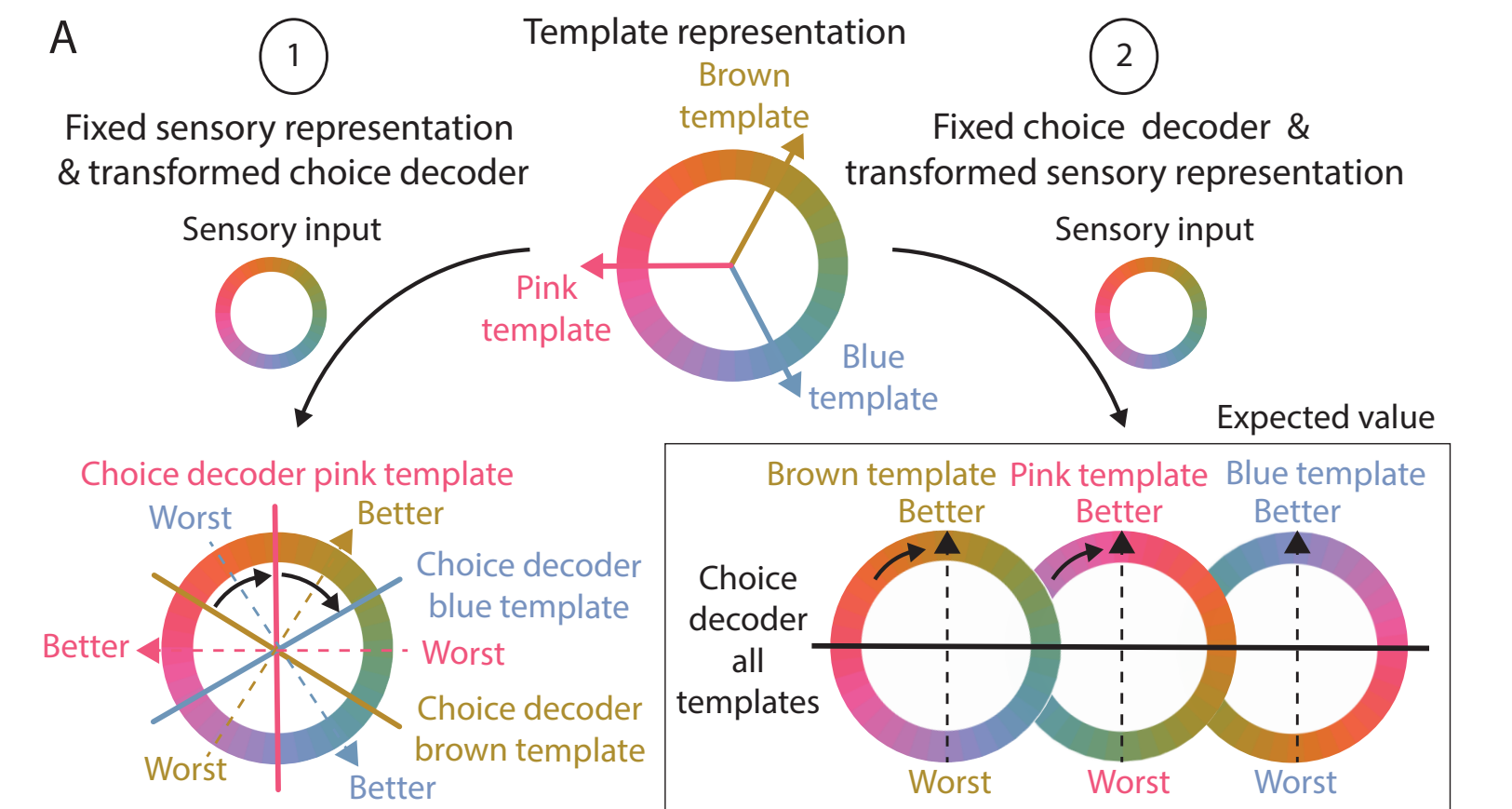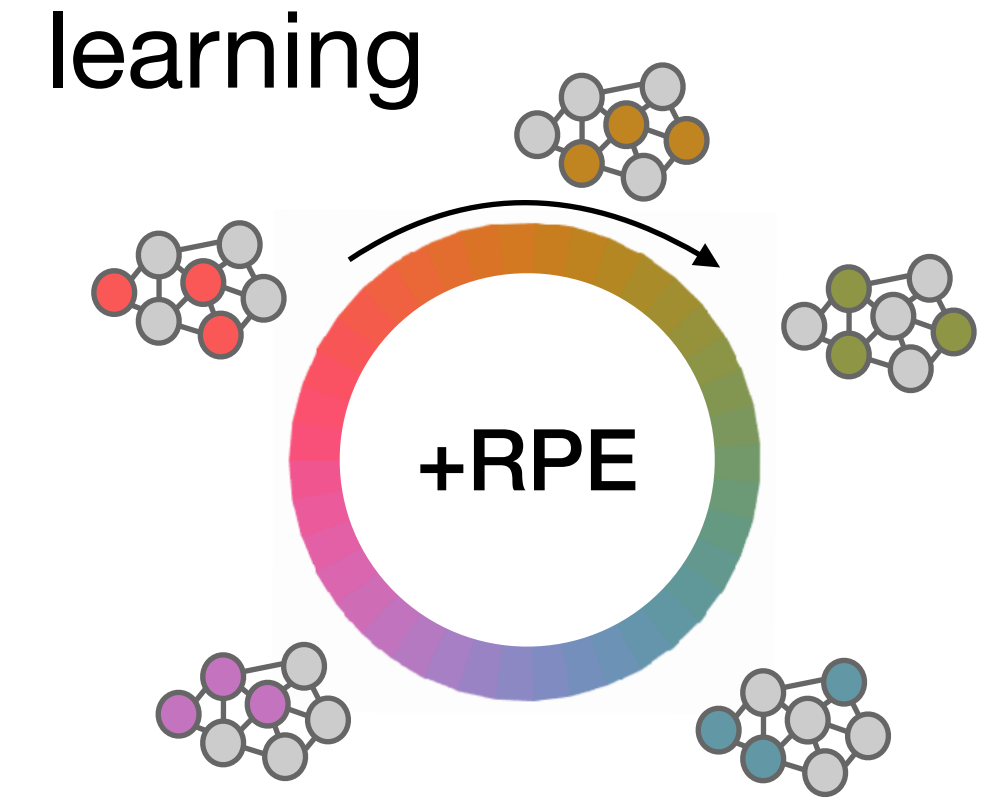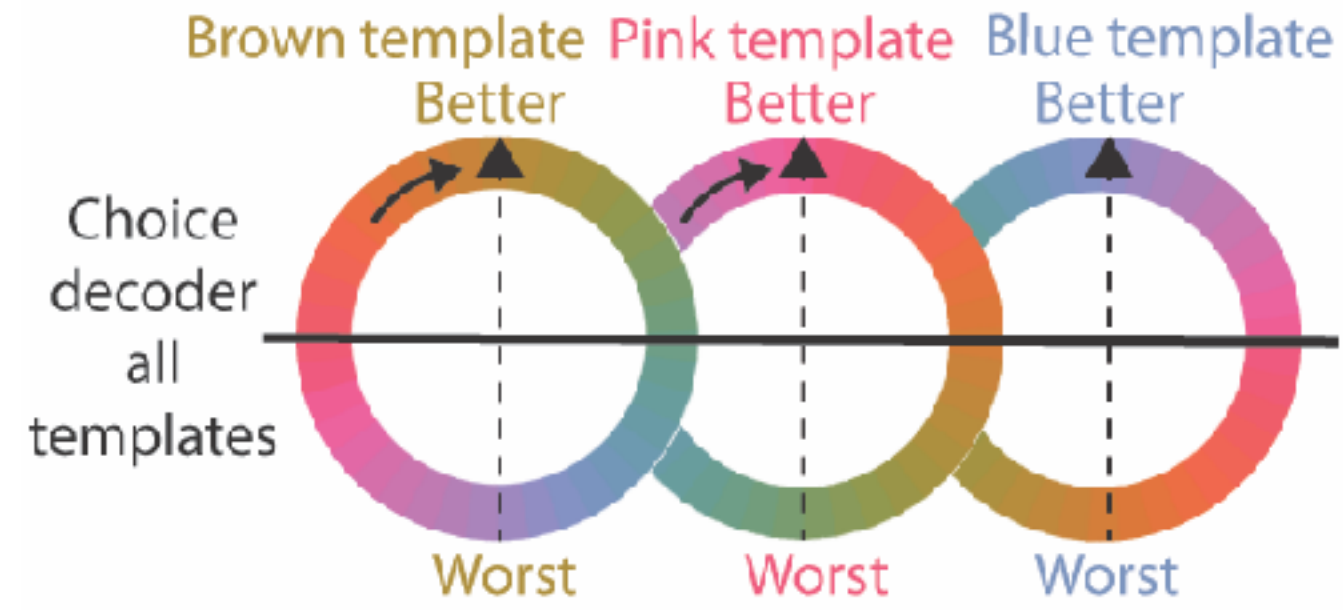
Screen

Priority map

Bisley & Mirpour, 2019

Summary

Brown template Better — Pink template Better — Blue template Better

Choice decoder all templates

Worst — Worst — Worst

learning

+RPE

IPFC   FEF   LIP

Fronto-parietal network

Global chosen value — Reward

Fig 4&5

Template

Fig 2

Local value (contralateral) ---▶ Choice

Fig 5

Template update

Fig 3
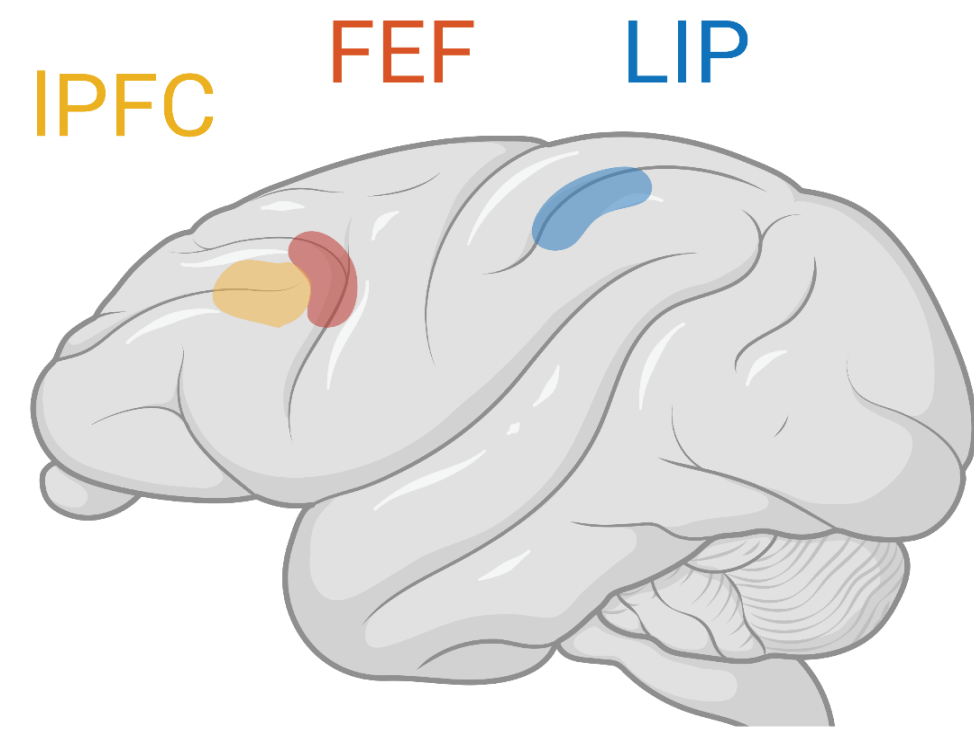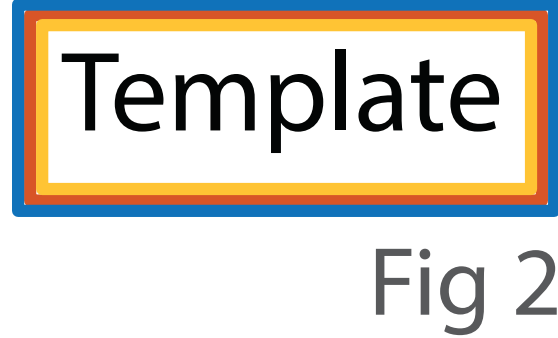
Not in the fronto-parietal network

Color at each location

Sensory input

Chosen color

Thank you!

Tim Buschman

Beck Ebitz*
Nikola Markov*
Britney Morea
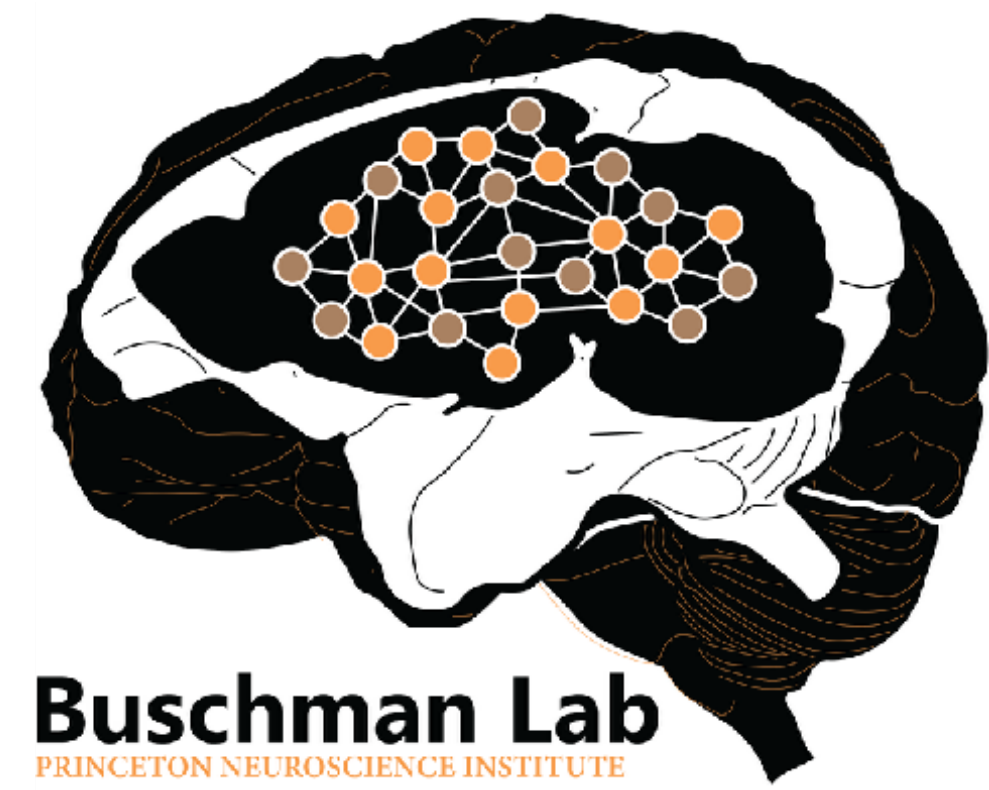
Seth Akers-Campbell
Adel Ardalan
Qinpu He
Polina Iamshchinina
Alex Libby
Junchol Park
Sina Tafazoli
Motoaki Uchimura
Jessica Ye

Flora Bouchacourt*
Camden McDowell*
Pavlos Kollias*
Matt Panichello*
Eleni Papadoyannis*
Neeraja Rajagopalan*

alumni*

Buschman Lab
PRINCETON NEUROSCIENCE INSTITUTE