The frontoparietal sensorimotor loop for reaching -- Encoding of rule-based motor goals

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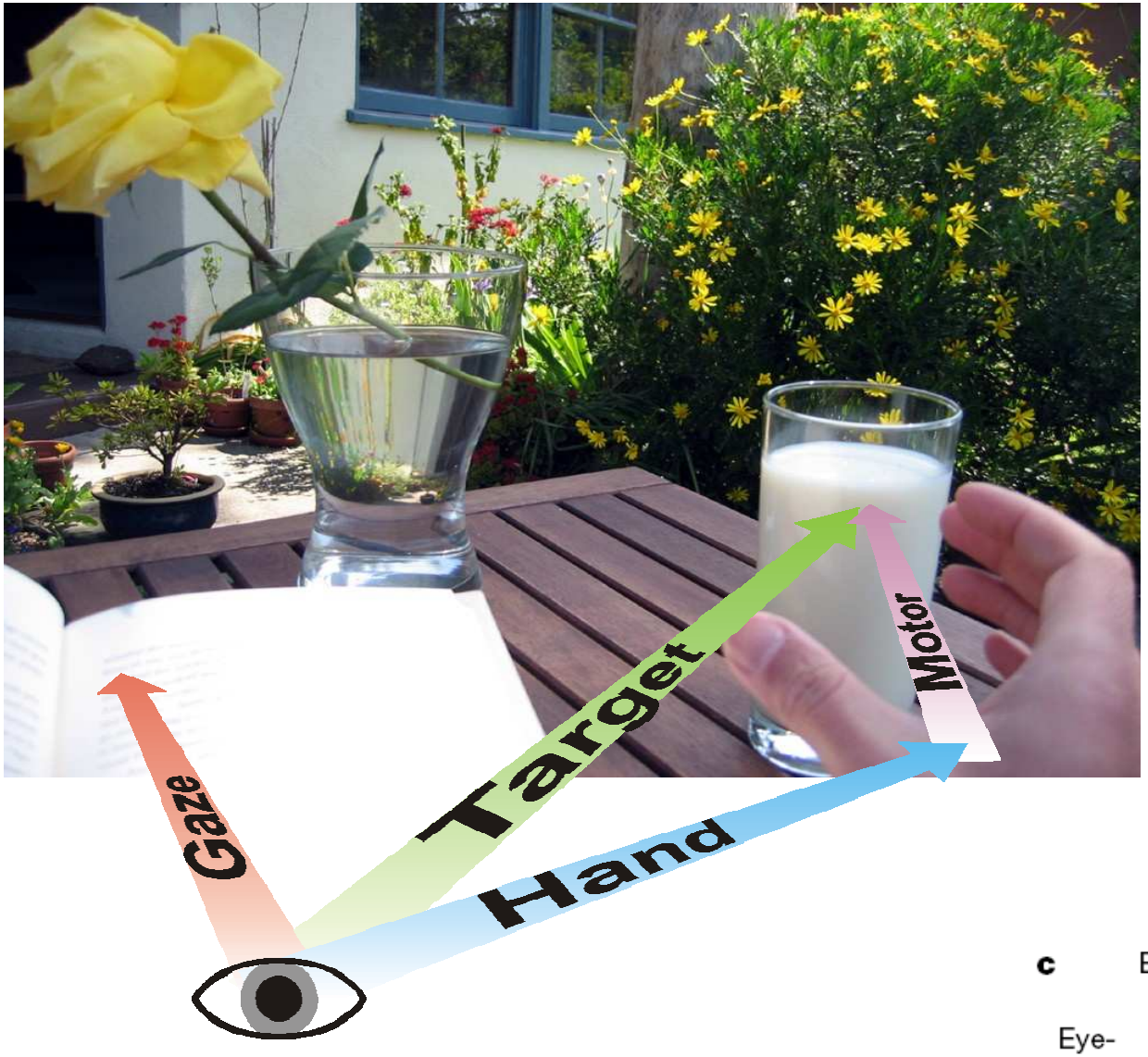
Integrating sensory cues for movement planning



(Buneo et al. 2002)

spatial constraints

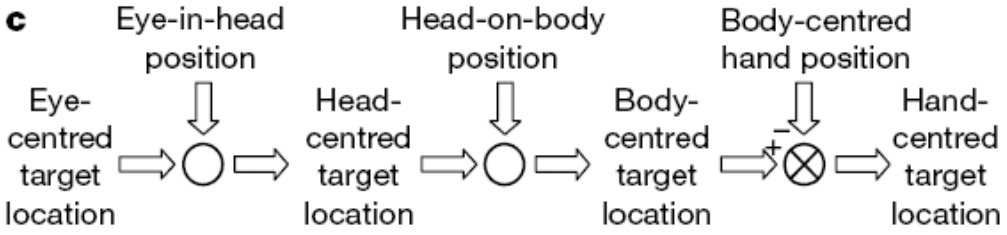
localize potential target objects, conduct sensorimotor transformations

‘eye-centered’ reference frame

Target position relative to direction of gaze. Visual coordinates

‘hand-centered’ reference frame

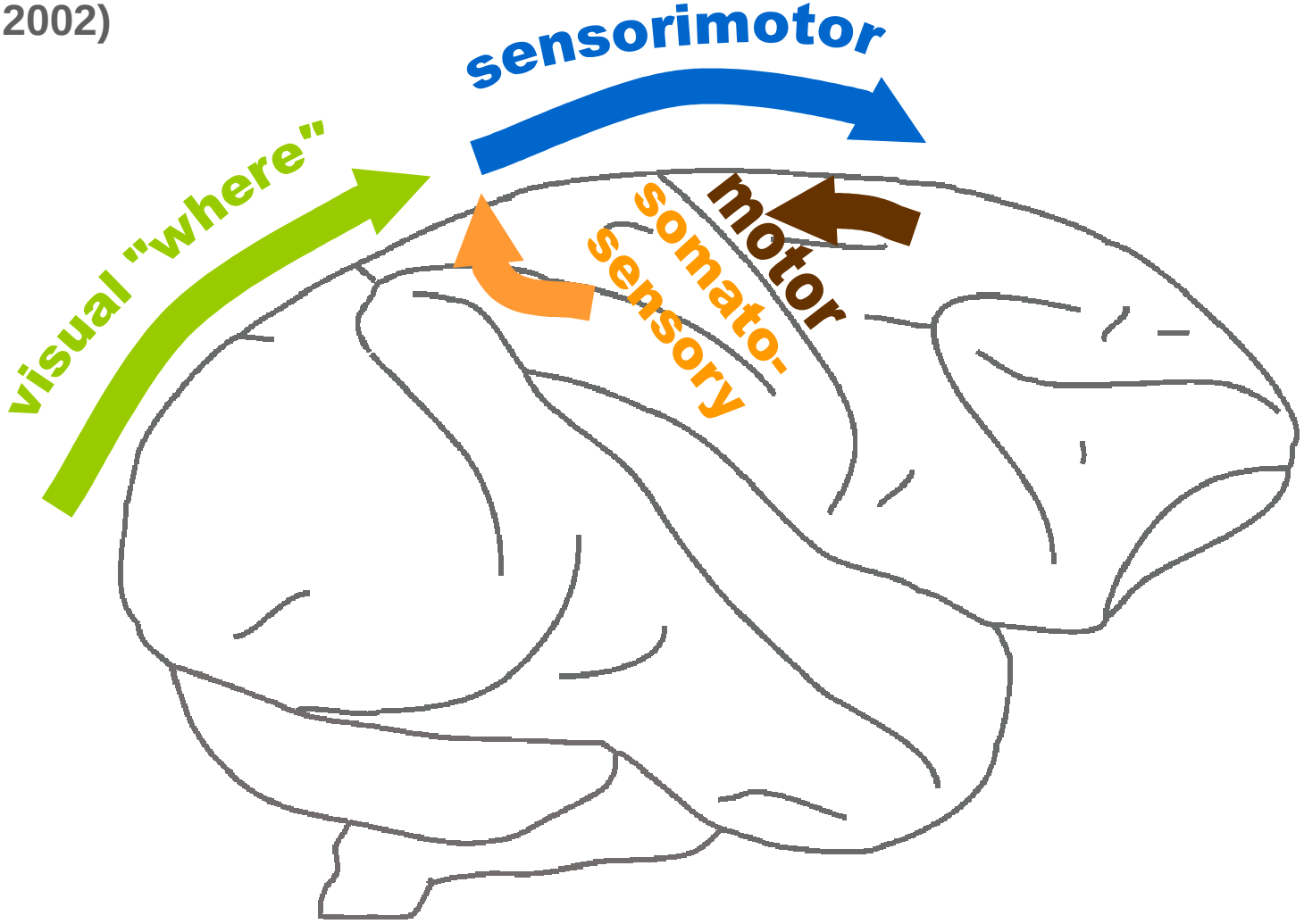
Target position relative to hand (motor error). Visual or joint-angle space.



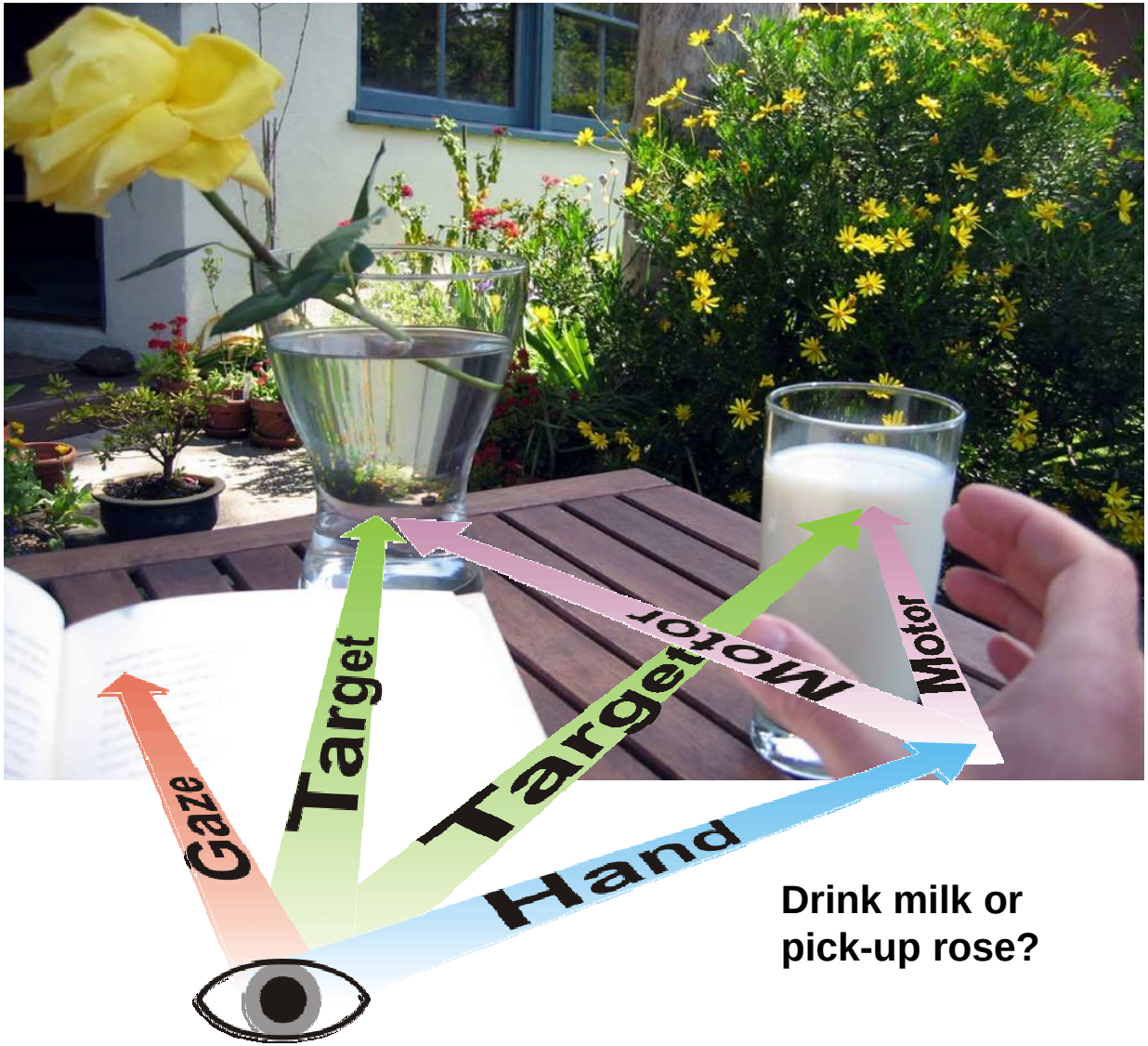
Feed-forward pathway for sensory cue integration

eye-centered reference frame
in parietal reach region PRR
(Buneo et al. 2002)

eye-hand-target reference frame
in dorsal premotor cortex PMd
(Pesaran et al. 2006, Batista et al. 2007)



Goal-directed movement planning – Integrating non-sensory cues



Drink milk or pick-up rose?

spatial constraints
localize potential target objects, identify motor-goal options

+

behavioral context
decide which action to perform based on goal-selection criteria

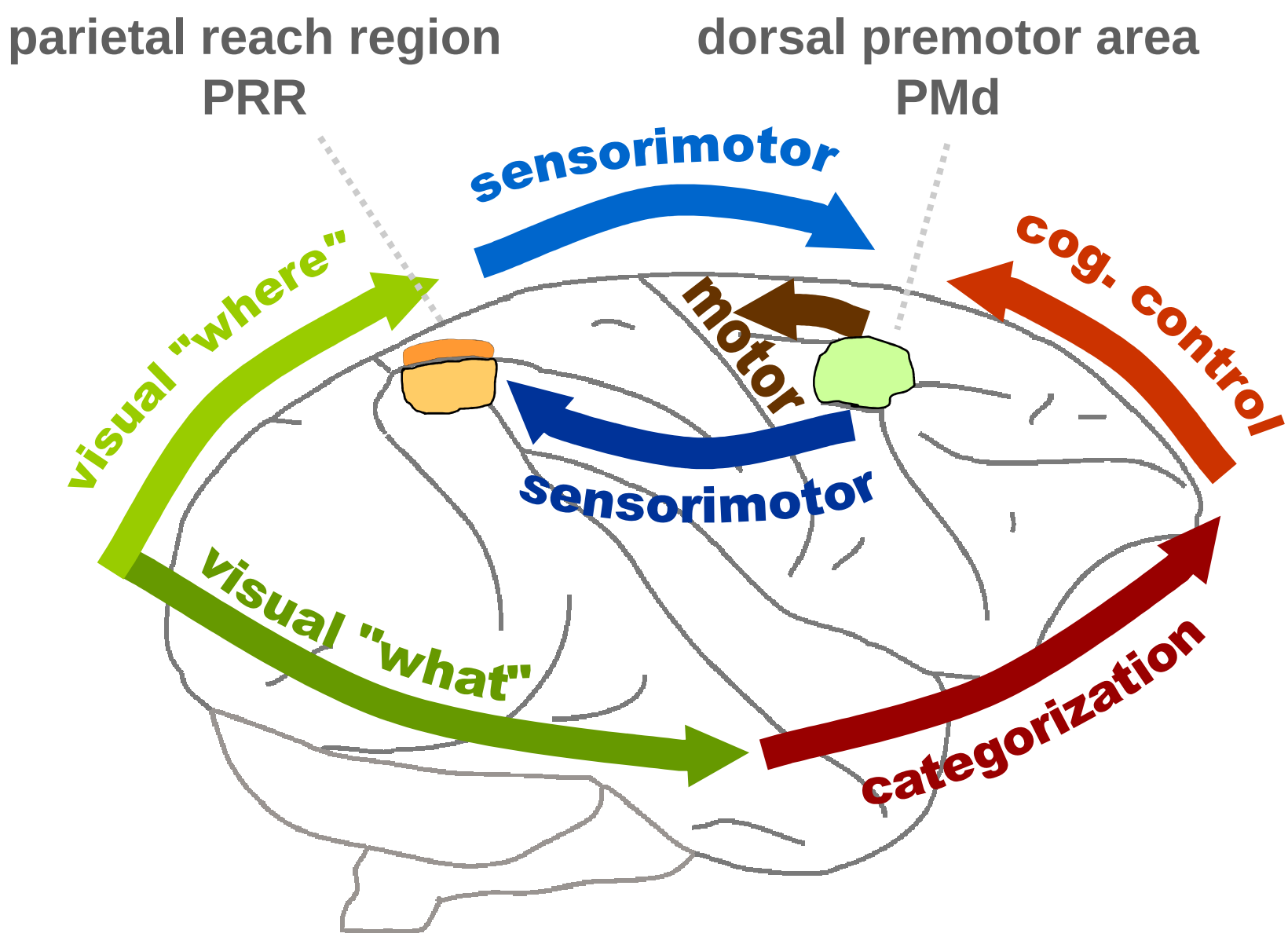
=

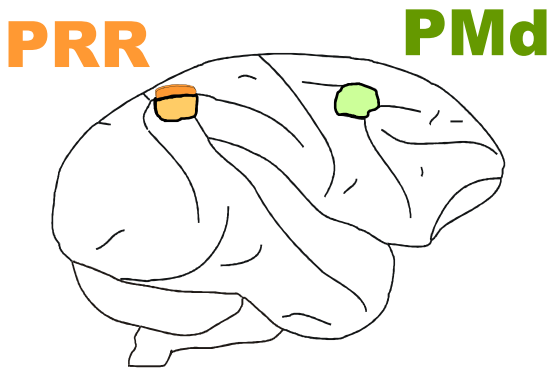
goal-directed movement plan
define motor-goal and specify movement kinematics

→ **movement:**
not (only) spatial working memory or attention

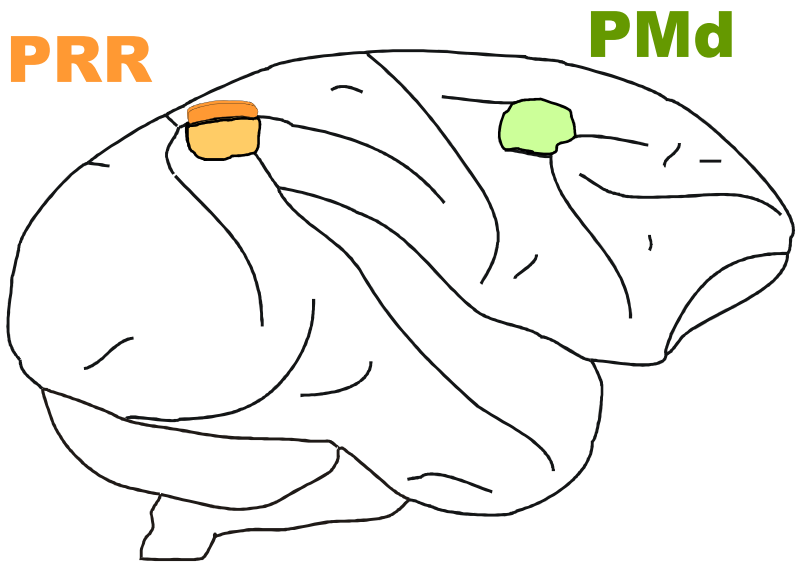
→ **planning:**
not motor-control

Feedback pathways for goal-directed reaching



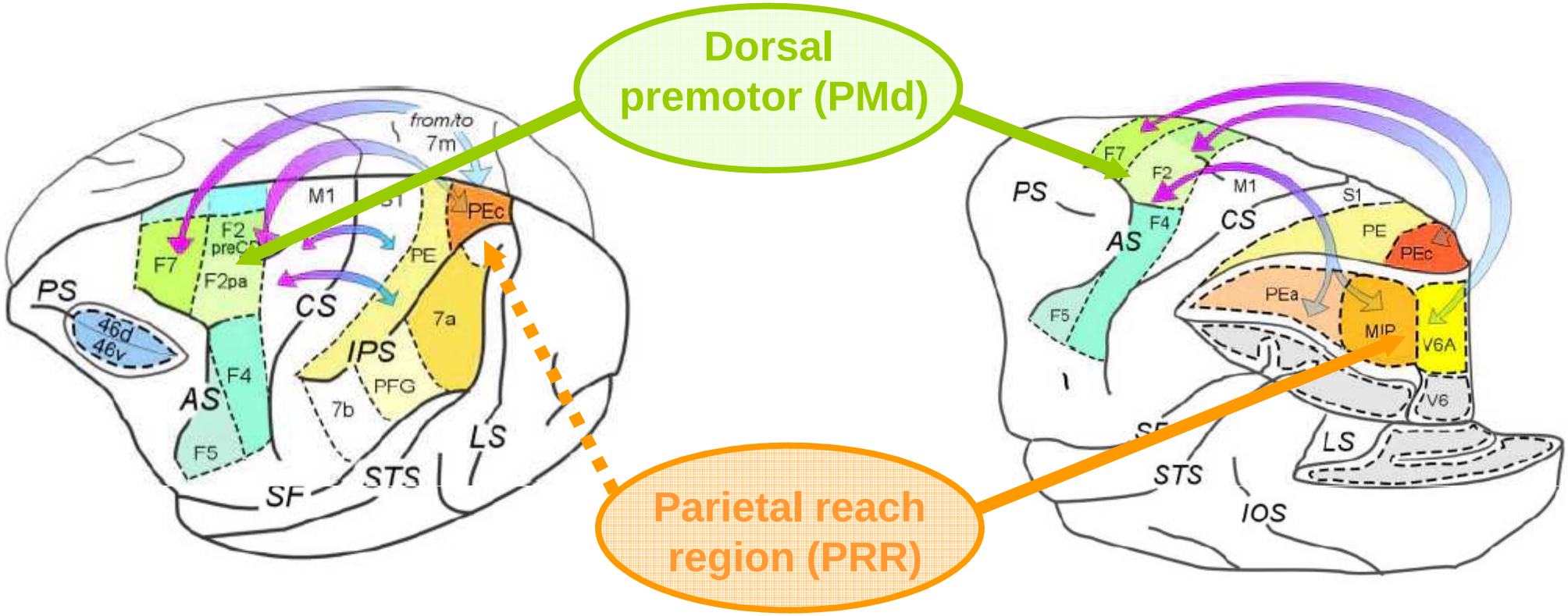


- Are rule-based reach goals represented in parietal cortex?
- Can rule-based reach goal representations be explained by feedback from motor-like structures (computationally)?
- Is there empirical evidence for fronto-parietal projections?
  - based on motor-goal latency?
  - based on effective functional connectivity?
- Are optional reach goals represented in parietal cortex?



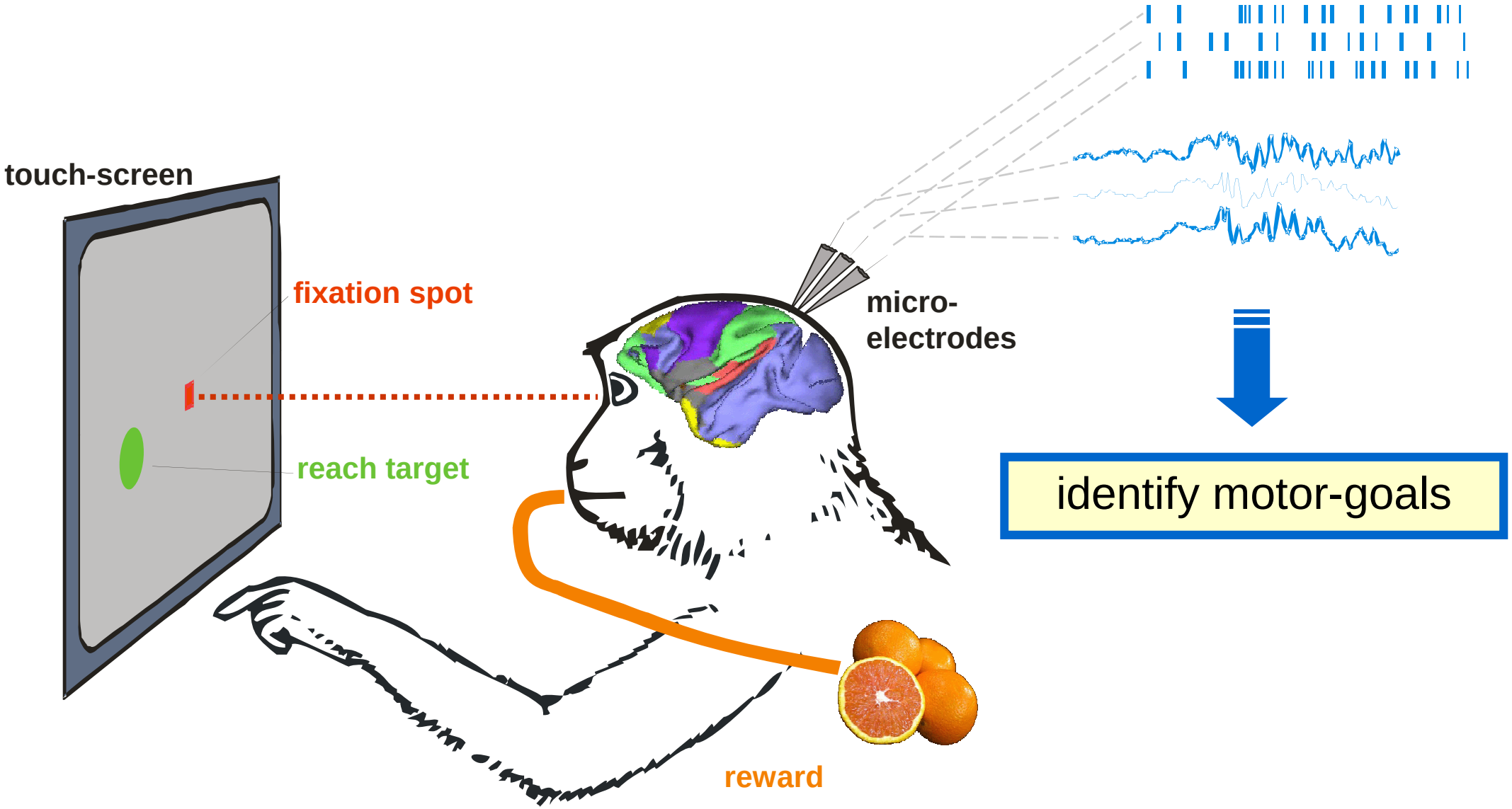
Are rule-based reach goals represented in parietal cortex?

Cortical sensorimotor network for reaching

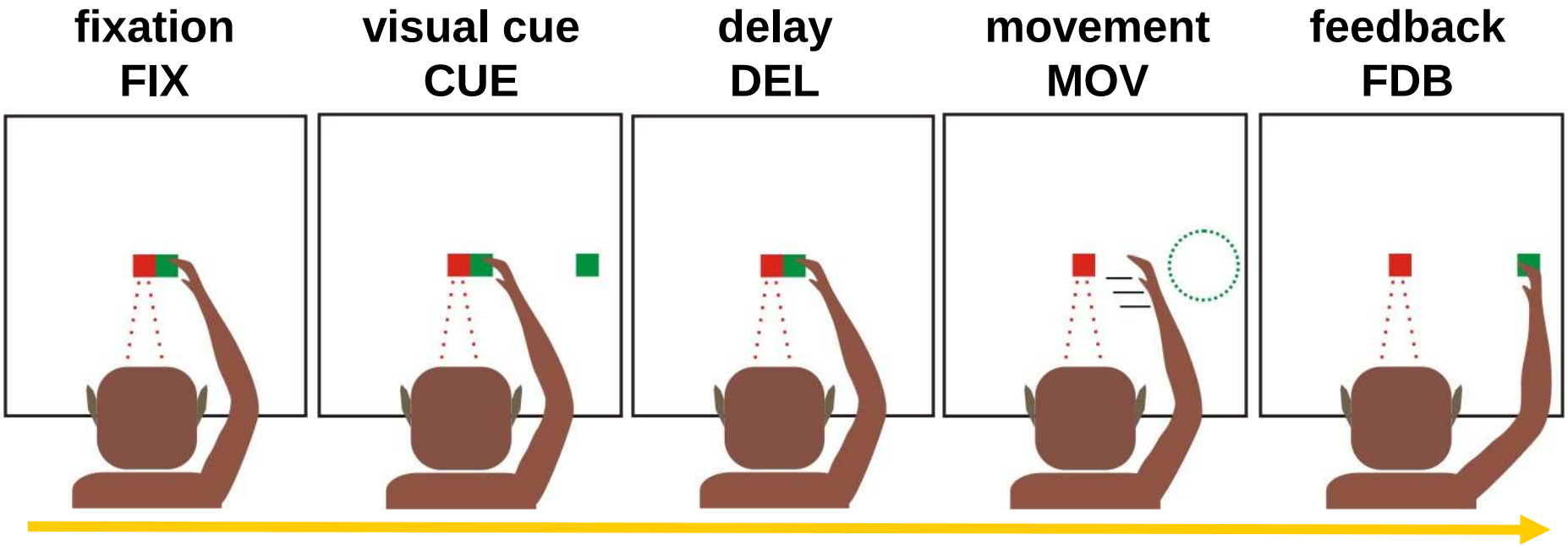


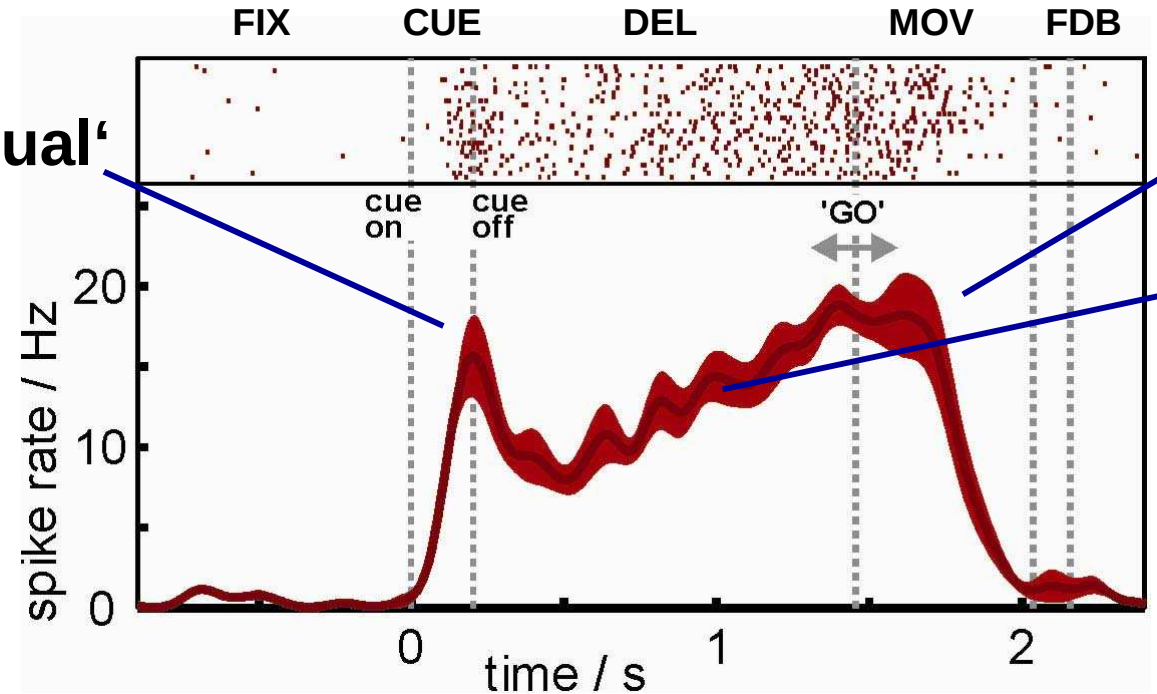
Battaglia-Mayer et al. 2003 Cerebral Cortex

Multi-channel microelectrode recordings in the parietal reach region (PRR)



Identifying movement plans – Step 1: Sustained activity during instructed delay





‘visual‘

‘motor‘

delay-activity

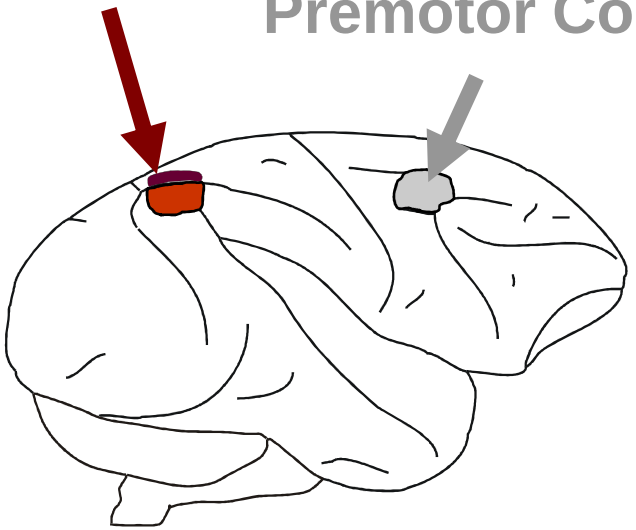
- **visual memory?**
- **movement planning?**

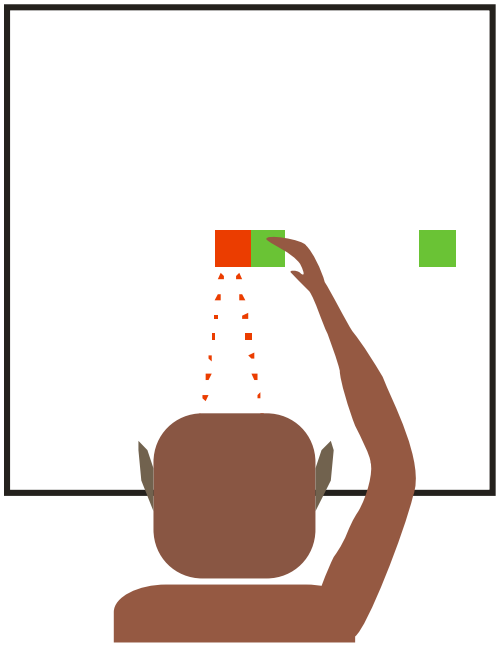
Selectivity for the direction of arm movements

Posterior parietal cortex

Parietal Reach Region

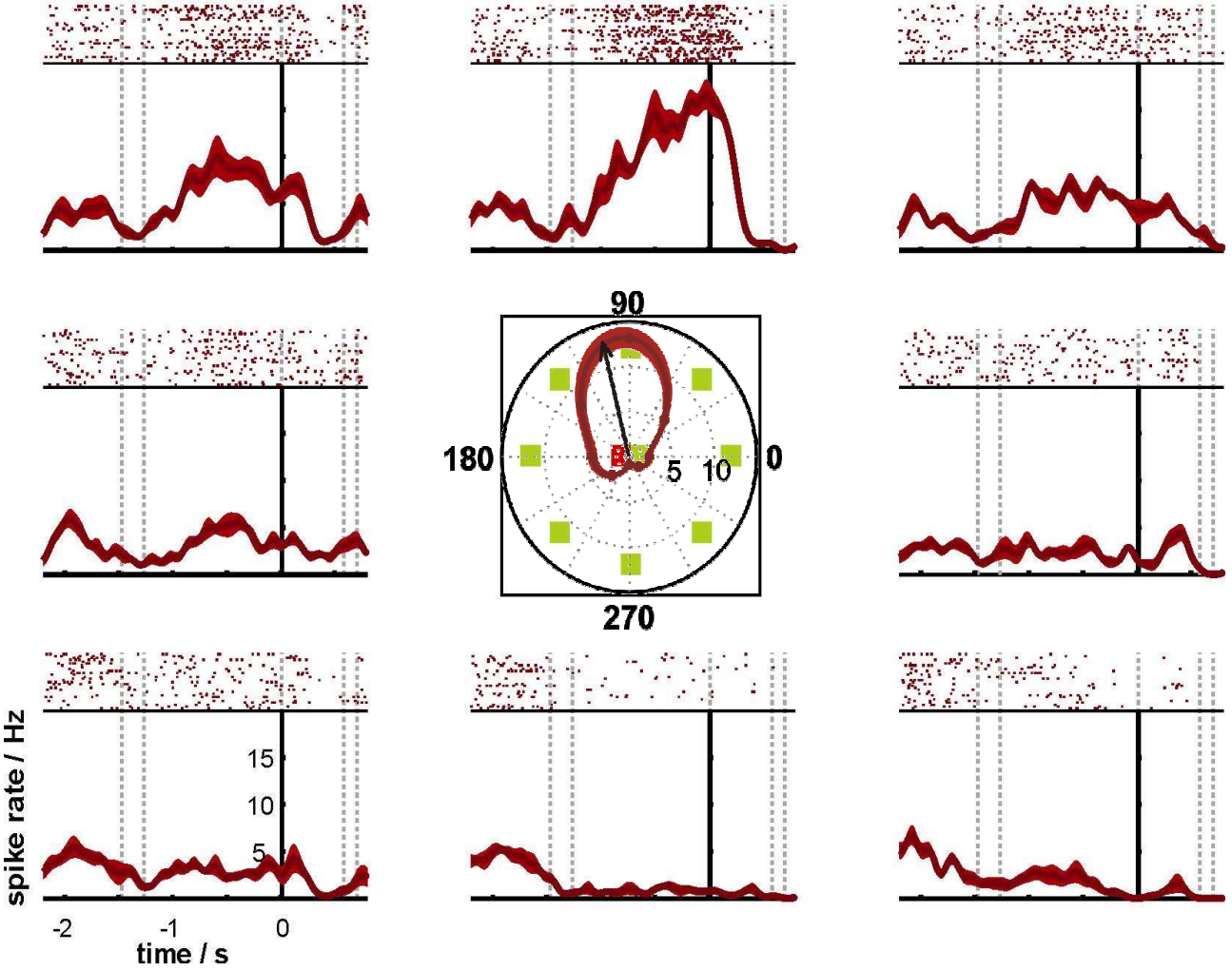
Dorsal Premotor Cortex



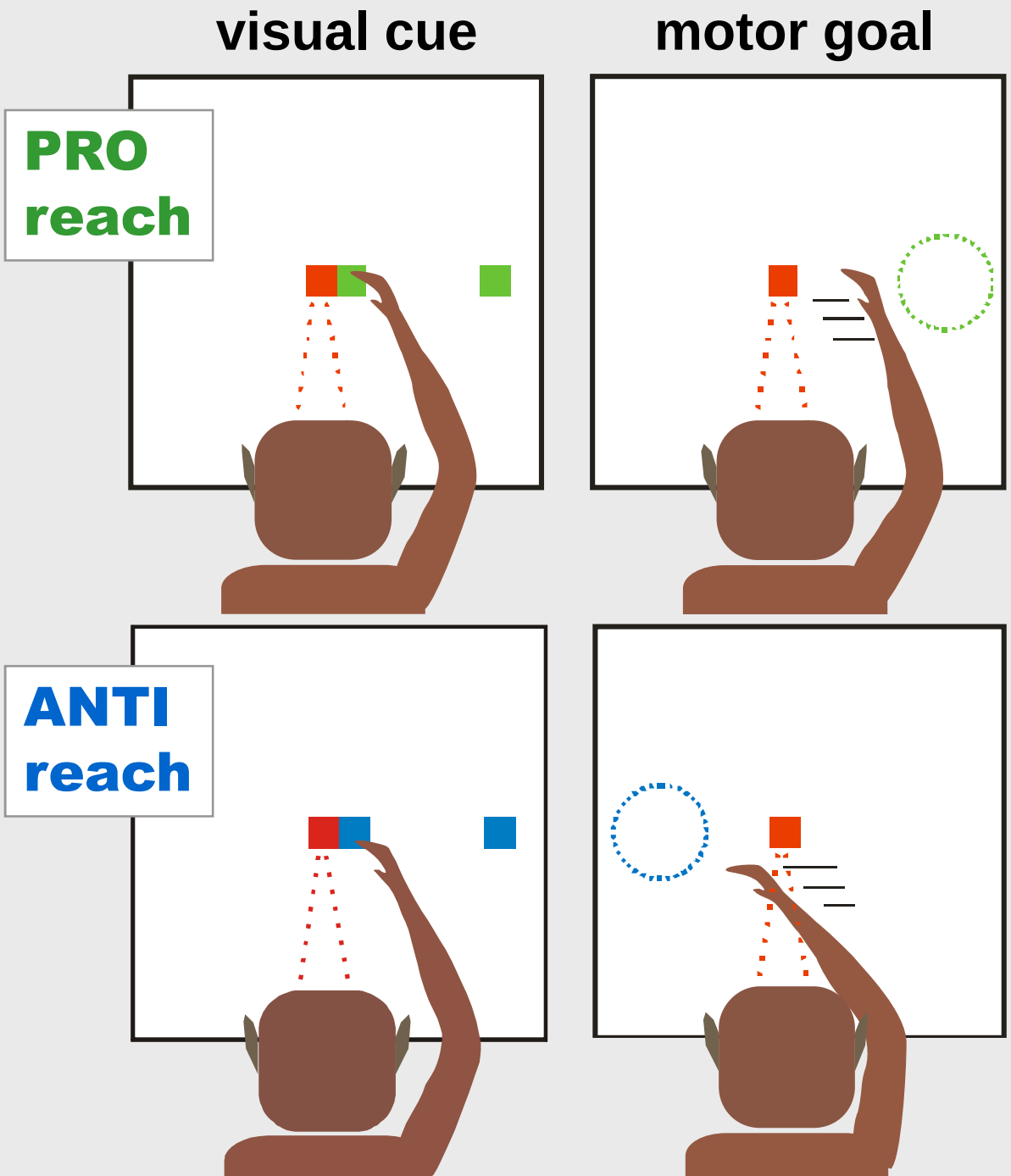


Single PRR neuron

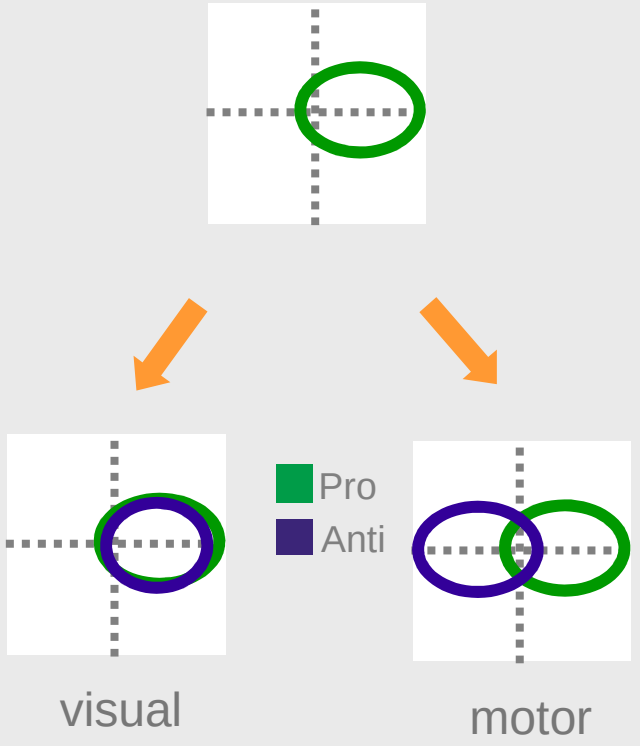
visual cue *movement*



Identifying movement plans – Step 2: Memory-guided ANTI-reach task



- visual or motor?

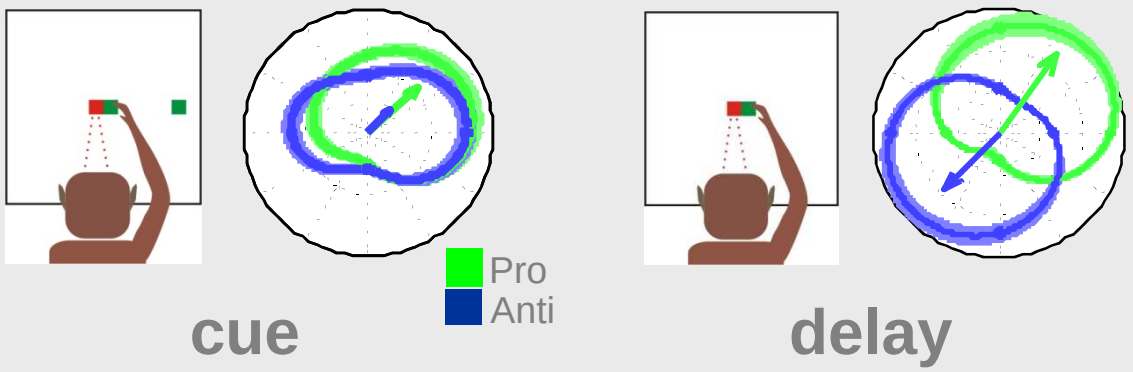


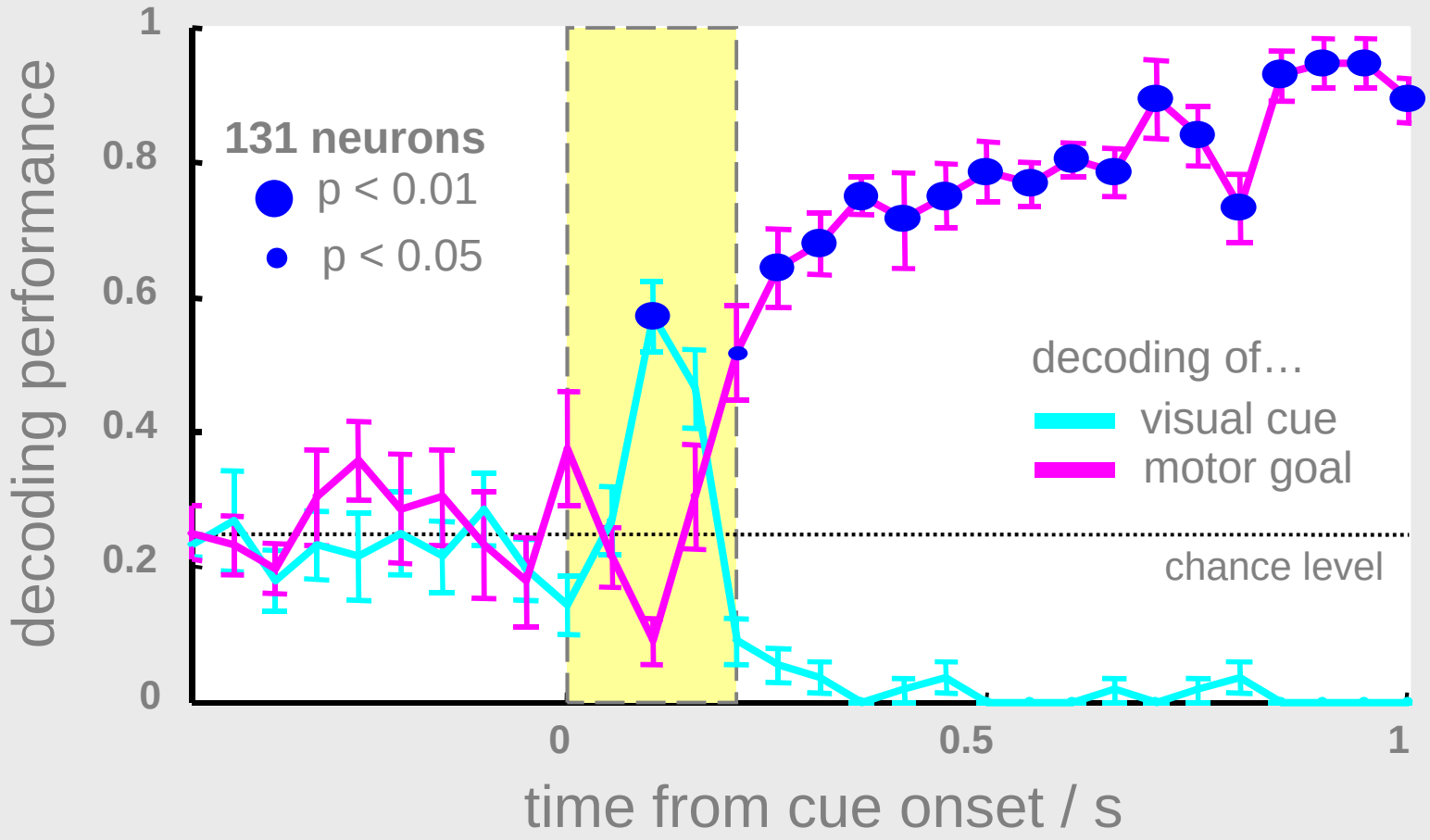
- rule-based motor goals:
  space + context = goal

PRR encodes motor-goal location during the planning phase of an arm movement

Single neuron tuning

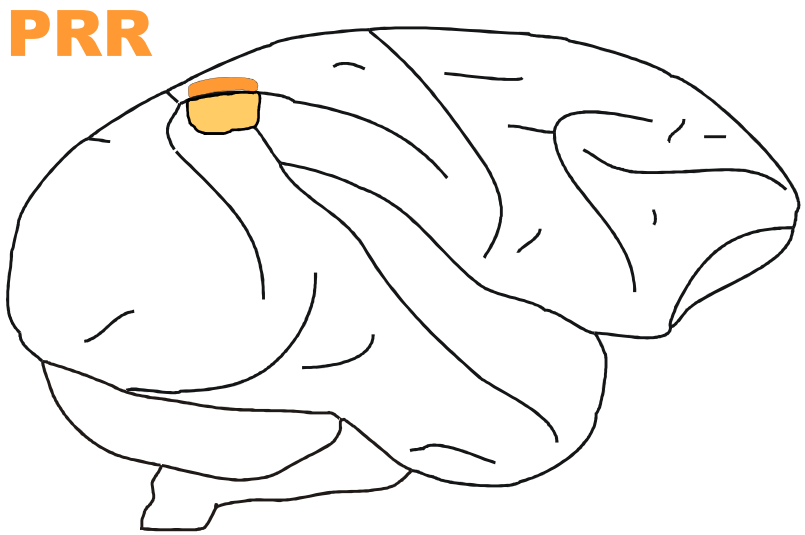
Population decoding





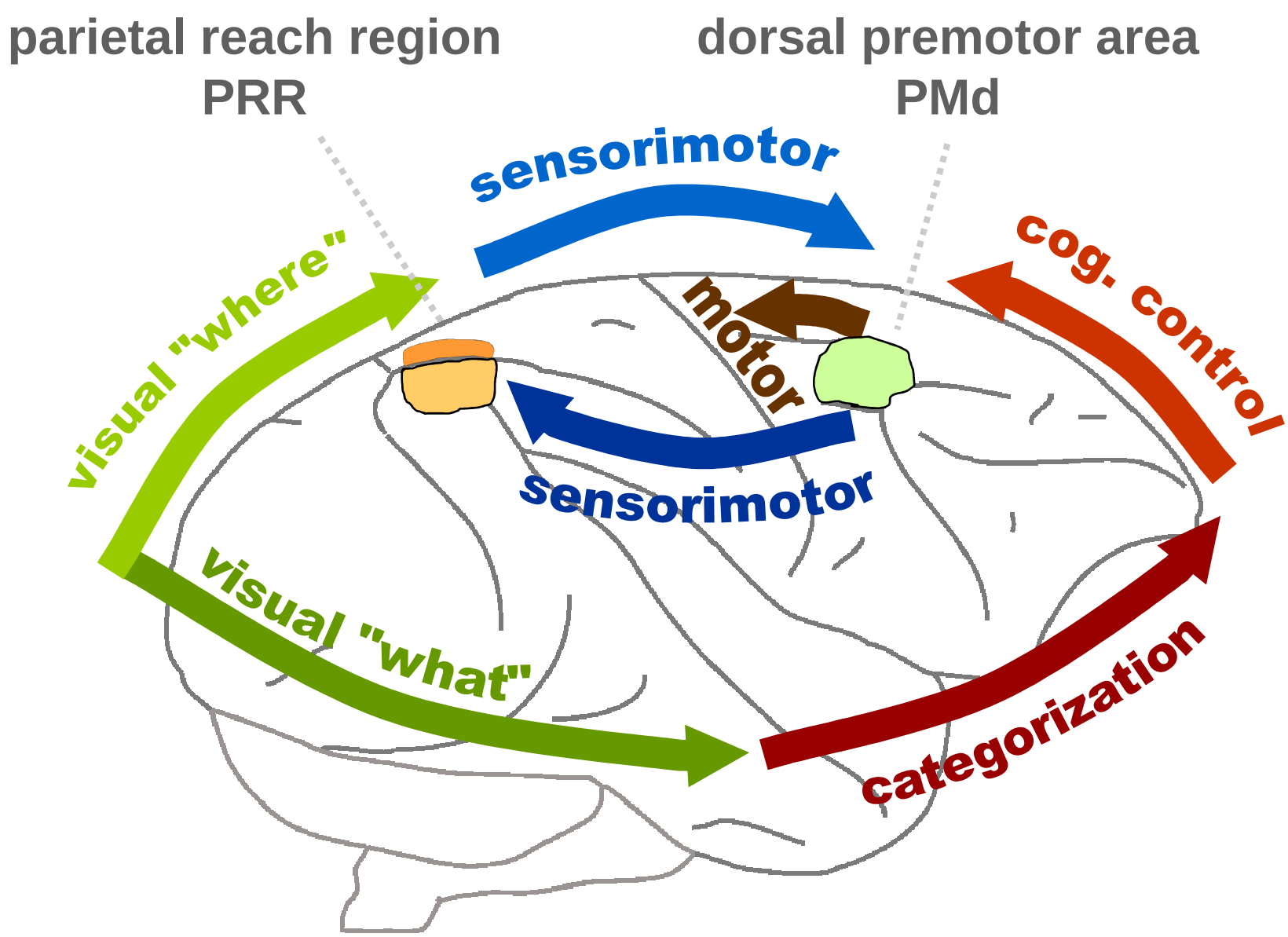
Gail & Andersen 2006 J Neurosci

Summary & Conclusion I
Rule-based motor-goal encoding in PRR

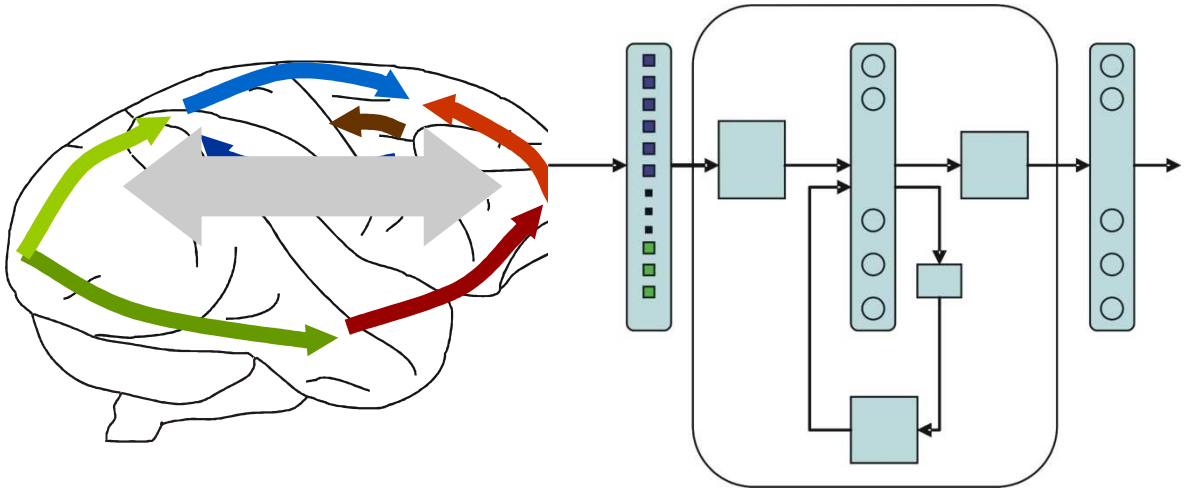


- Cue- and **motor-goal related** information are dynamically encoded in **PRR**, partly by the same neurons
- ***PRR reflects integrated knowledge about the visuo-spatial environment combined with the current behavioral context***
- ***PRR reflects rule-based motor goals***

Feedback pathways for goal-directed reaching



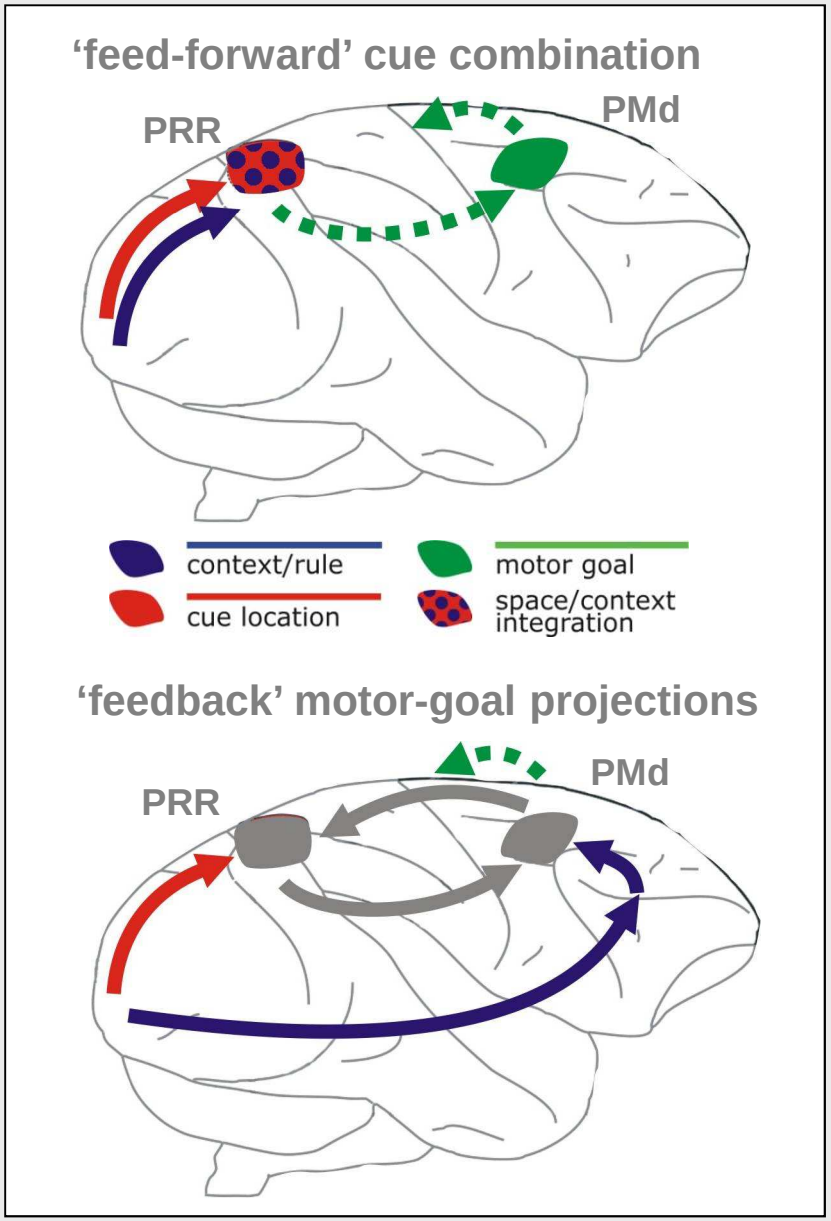
Mechanisms of space and context integration – Neural network simulations



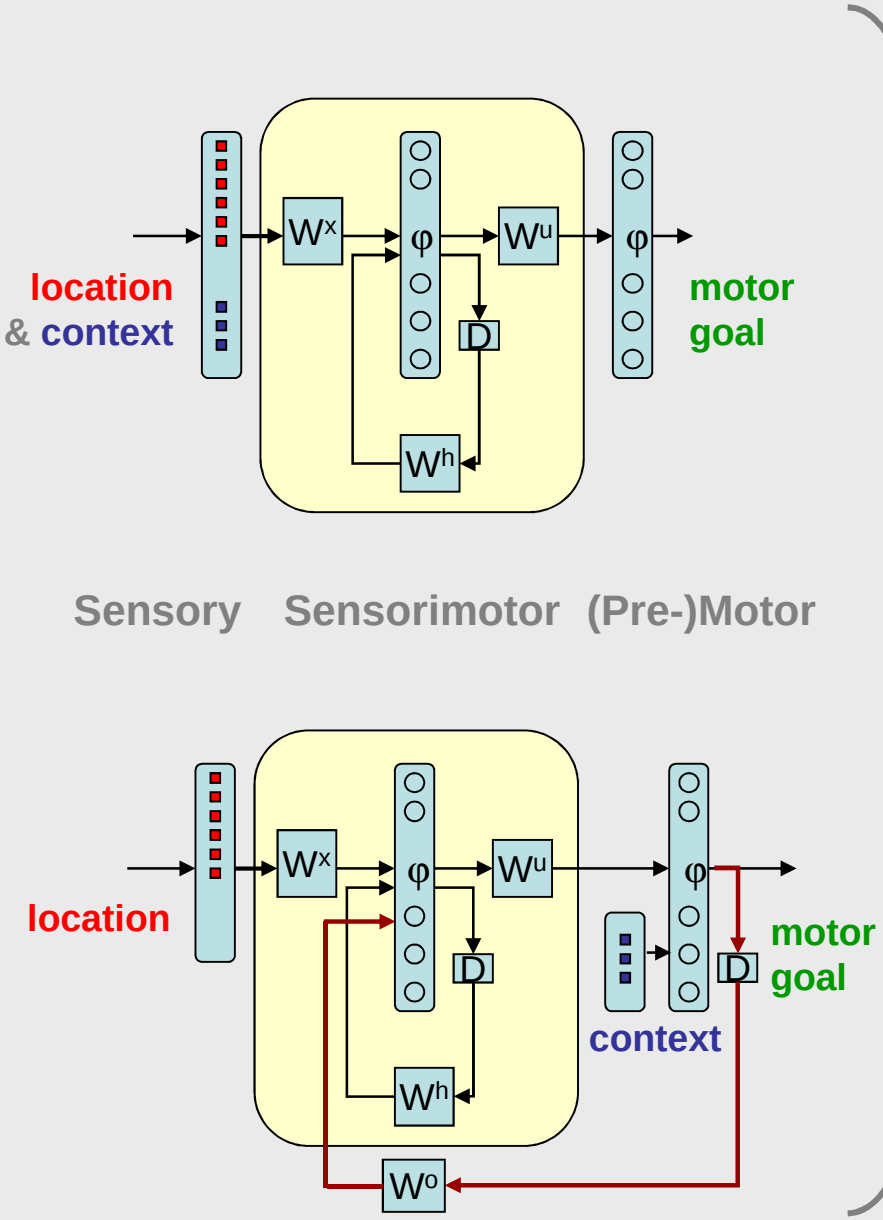
- **Can rule-based reach goal representations be explained by feedback from motor-like structures (computationally)?**

Recurrent neural network models: The role of top-down projections

Hypotheses



Neural network models

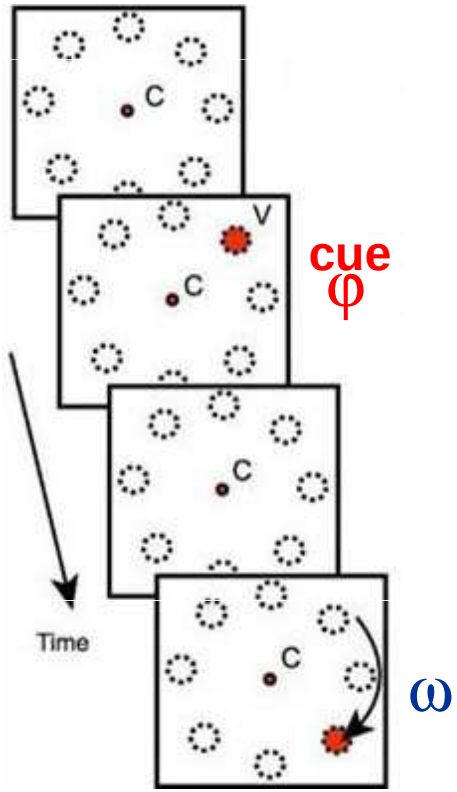


Tuning in sensori-motor layer?

Brozovic, Gail* & Andersen 2007 J Neurosci*

Spatial tuning in the sensorimotor layer depends on the network architecture

visuomotor rotation task
variable cue-response mapping

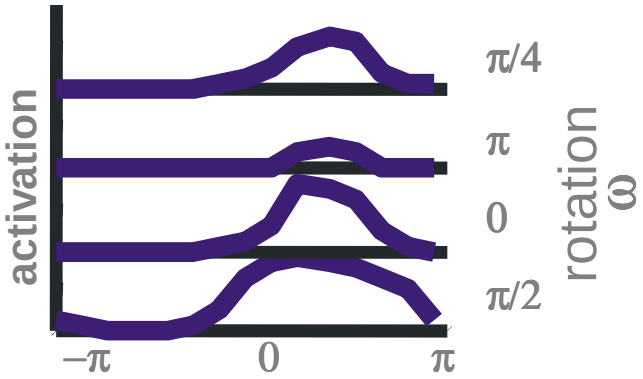


cue location = direction φ

context/rule = rotation ω

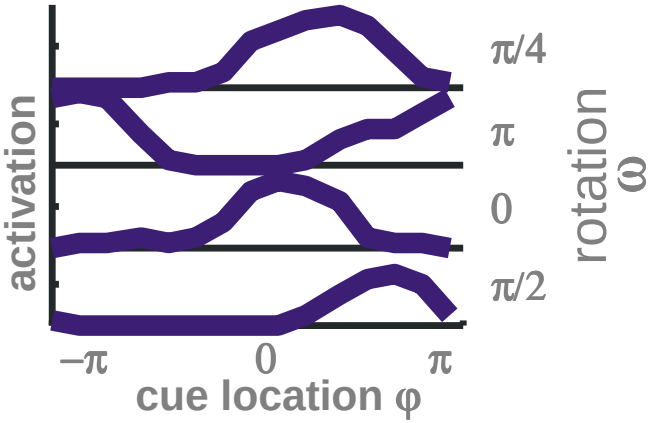
PRO: ω = 0
ANTI: ω = π

hidden layer tuning
example unit



feed-forward network

→ **gain-modulated visual tuning**

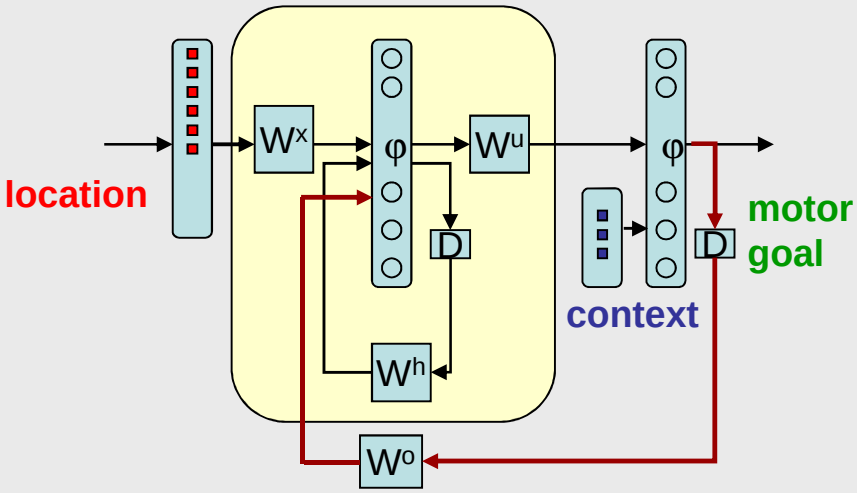


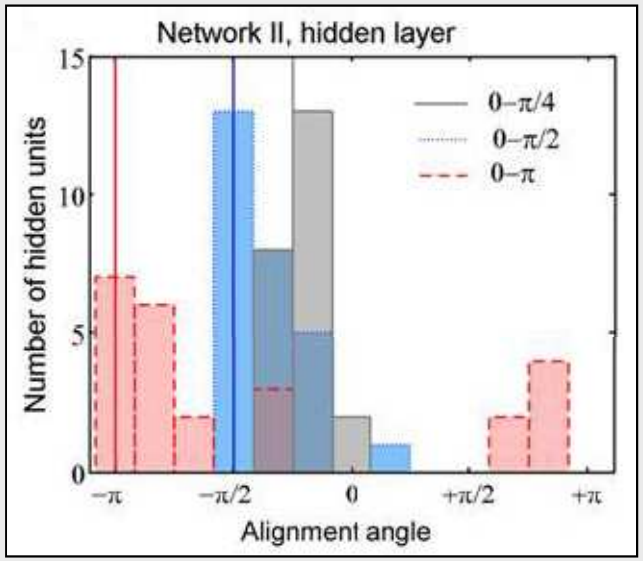
feedback network

→ **gain-modulated motor-goal tuning**

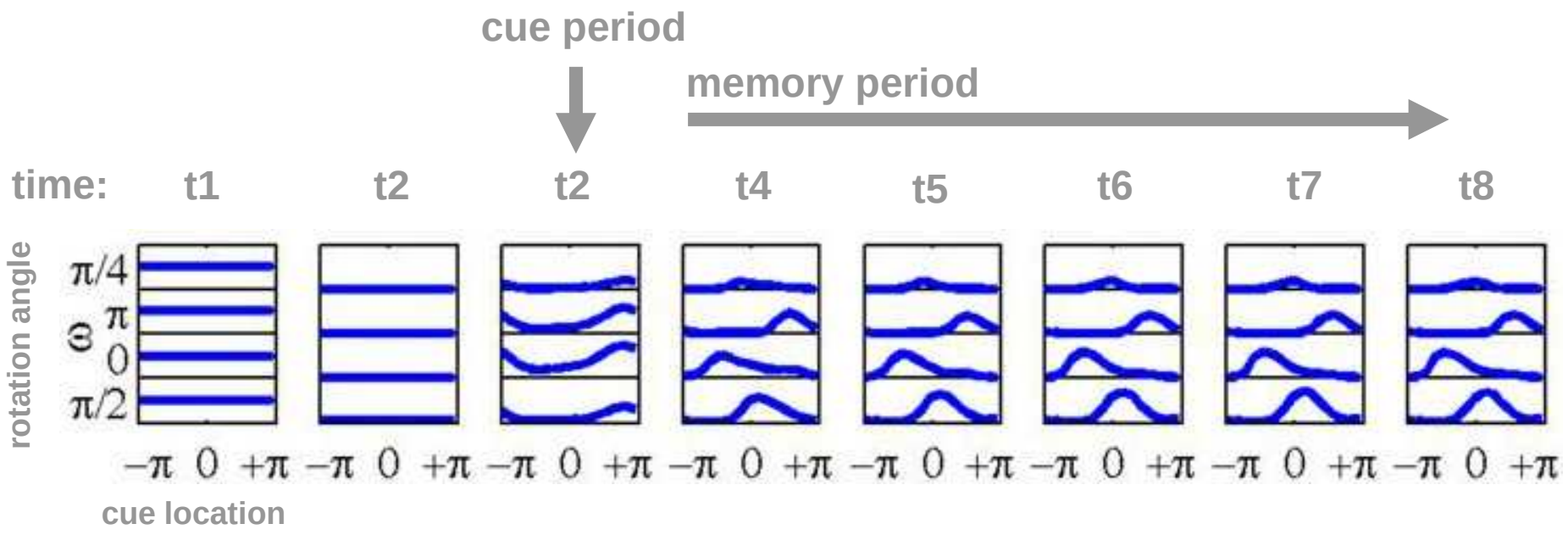
Brozovic, Gail* & Andersen 2007 J Neurosci*

Gain-modulated motor-goal tuning in the hidden layer of the feed-back network





Hidden layer tuning

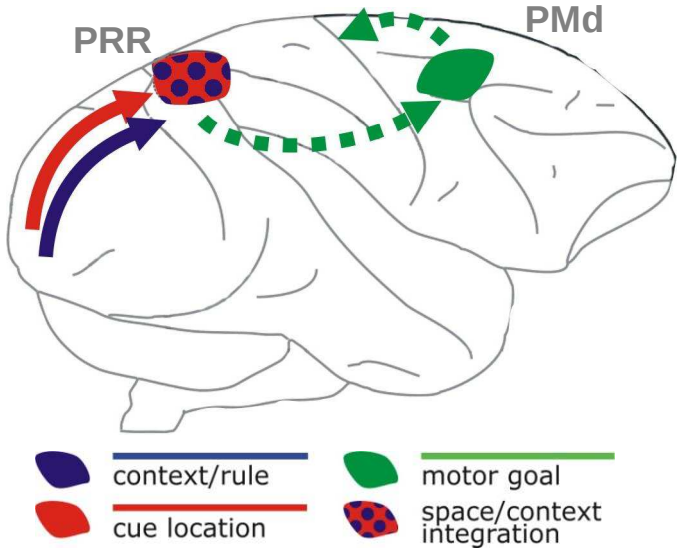


Brozovic, Gail* & Andersen 2007 J Neurosci*

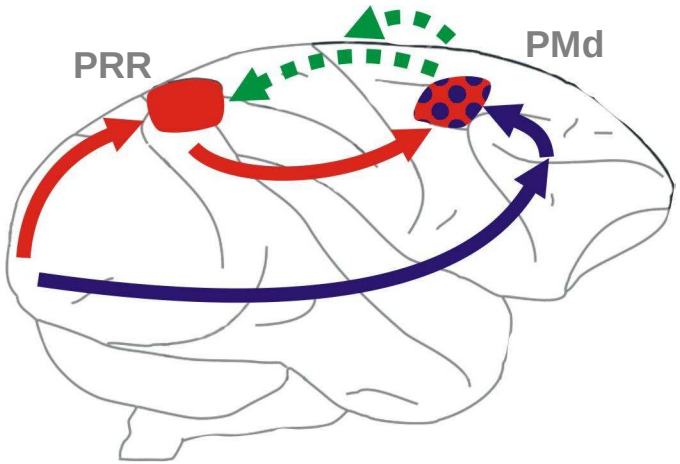
Hidden layer motor-goal tuning only via strong top-down projections

Hypotheses

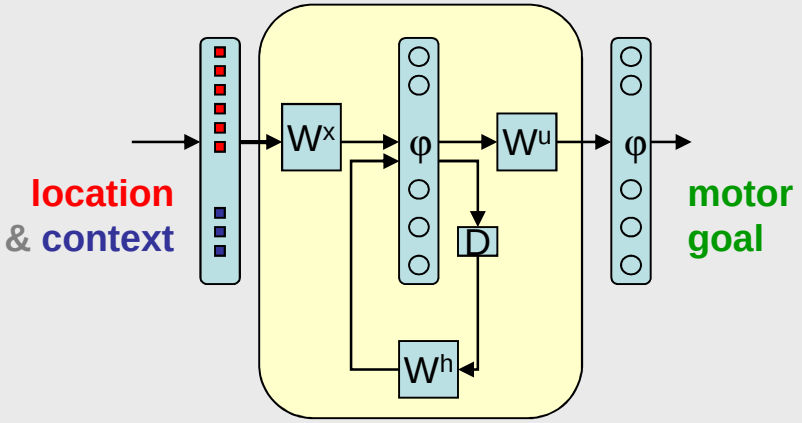
‘feed-forward’ cue combination



‘feedback’ motor-goal projections



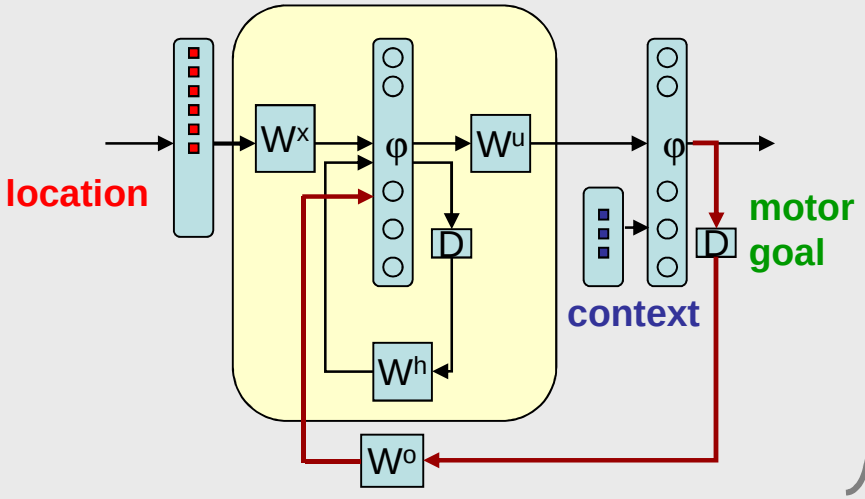
Neural network models



☹ gain-modulated visual tuning

Sensori-motor layer

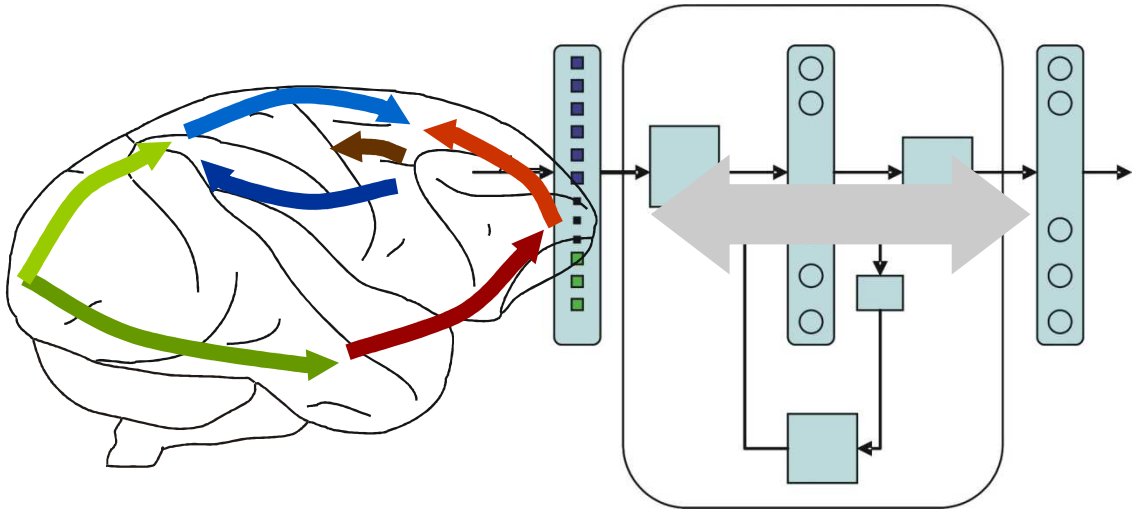
Sensory Sensorimotor (Pre-)Motor



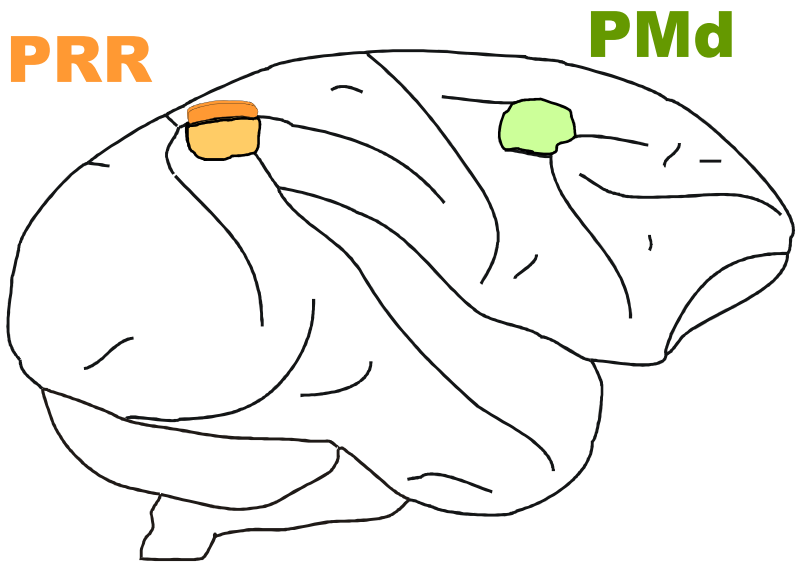
☺ gain-modulated motor goal tuning

Brozovic, Gail* & Andersen 2007 J Neurosci*

Summary & Conclusion II
Network simulations of rule-based visuomotor mapping



- Motor-goal tuning in sensorimotor areas (like PRR) could be the result of **top-down projections** from motor-tuned structures
- Rule-based visuomotor remapping could be achieved via **gain-modulation** of spatial representations

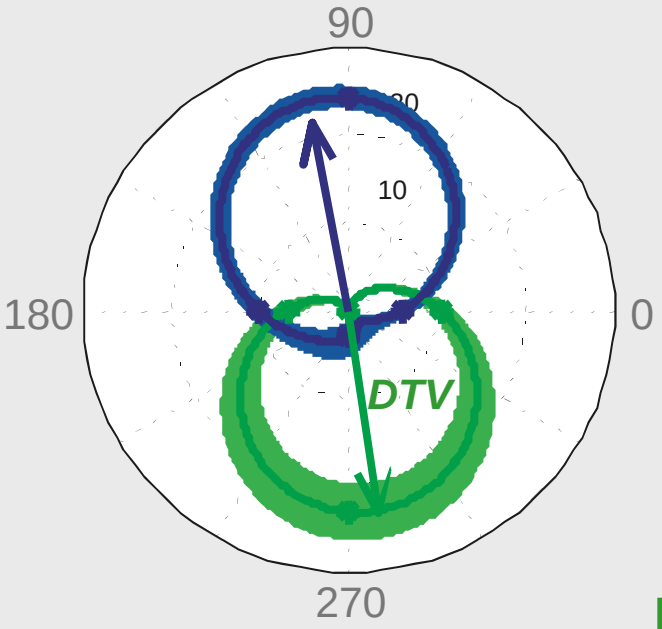


Are rule-based reach goal representations in PRR/PMd gain-modulated by the rule?

Contextual gain modulations
of motor-goal representations during movement planning

‘classical’ motor tuning
independent of context

monkey S, PMd

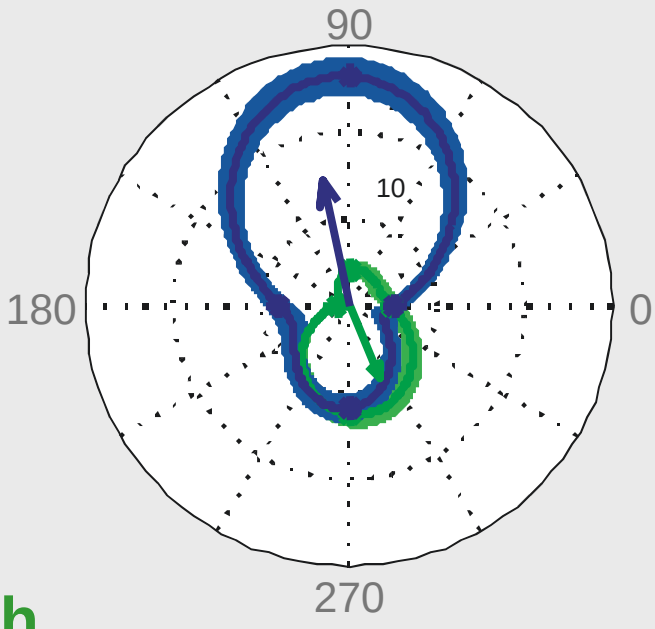


response relative to
cue position

PRO reach
ANTI reach

gain-modulated motor tuning
dependent on context

monkey A, PRR

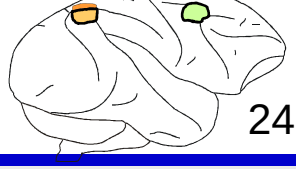


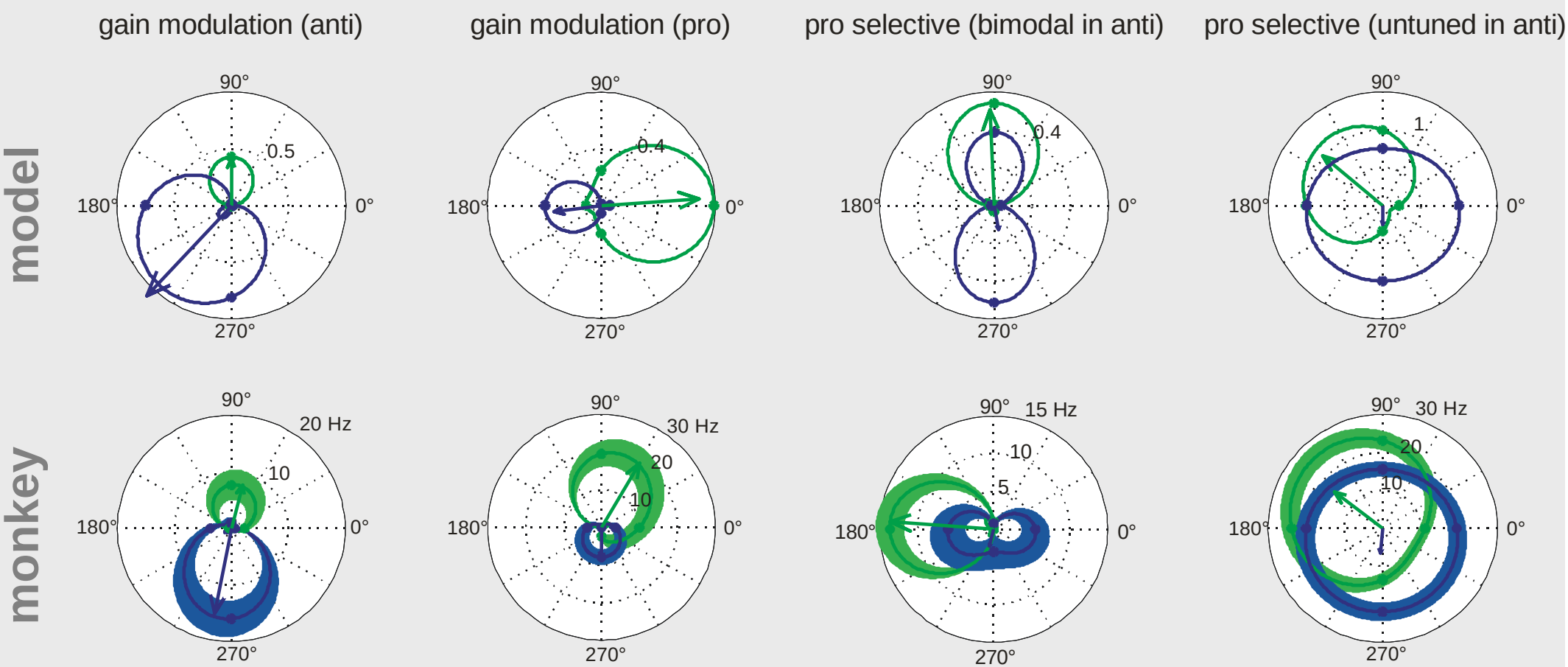
response relative to
cue position

Gail et al. 2009 J Neurosci

Contextual gain and selectivity modulations

similarity between model and neural data



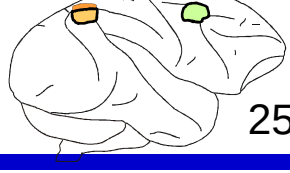


PRO reach

ANTI reach

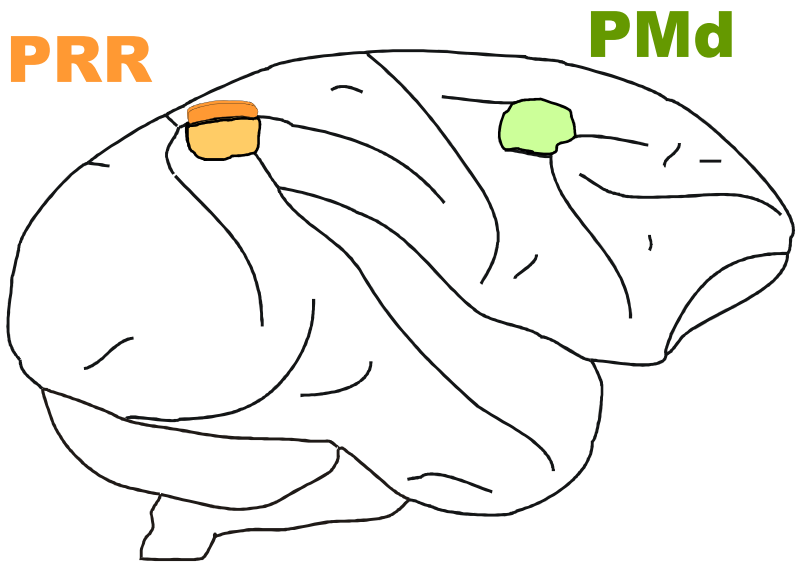
Gail et al. 2009 J Neurosci

Summary & Conclusion III
Contextual gain-modulation in PRR and PMd



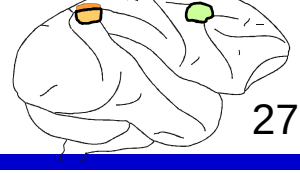
- context affects motor-goals in PRR and PMd by …
  - strong gain-modulation
  - spatial selectivity modulations
- anti- compared to pro-reaches induce …
  - increased gain in PMd
  - reduced selectivity in PRR

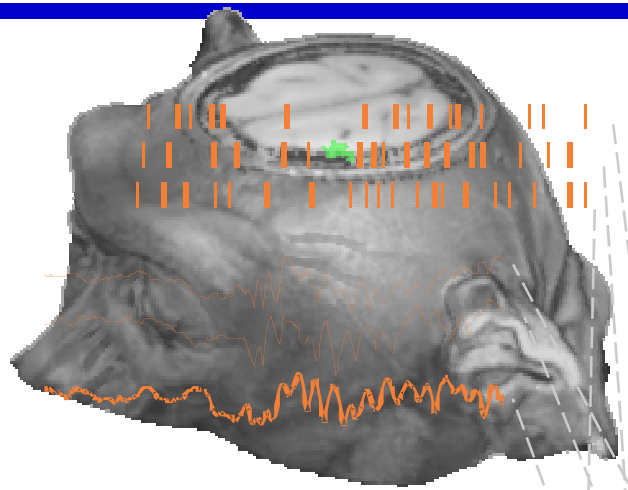
- ***gain modulation for contextual remapping***
- ***preferred encoding of …***
  - ***… spatially inferred motor-goals in PMd?***
  - ***… directly cued motor-goals in PRR?***

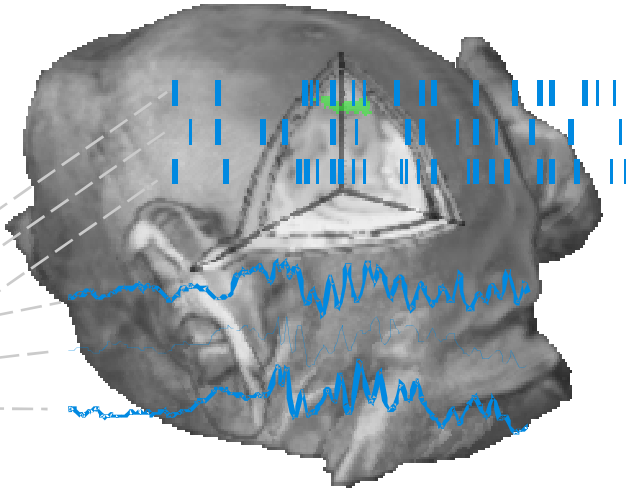


Are rule-based reach goals represented earlier in PMd than PRR?

Simultaneous multi-channel recordings in areas PMd and PRR







touch-screen

fixation spot

reach target

micro-electrodes

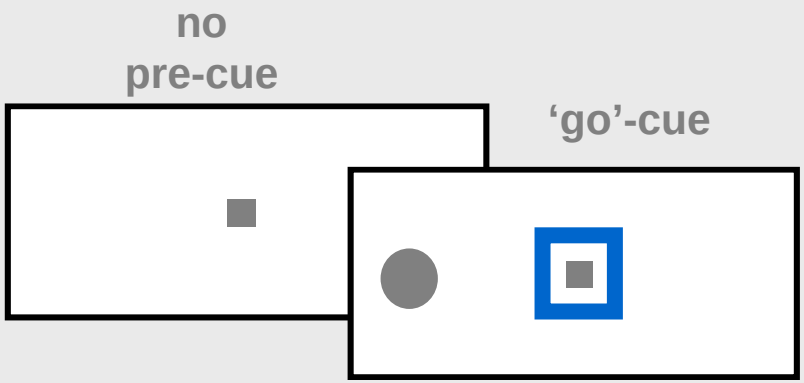
reward

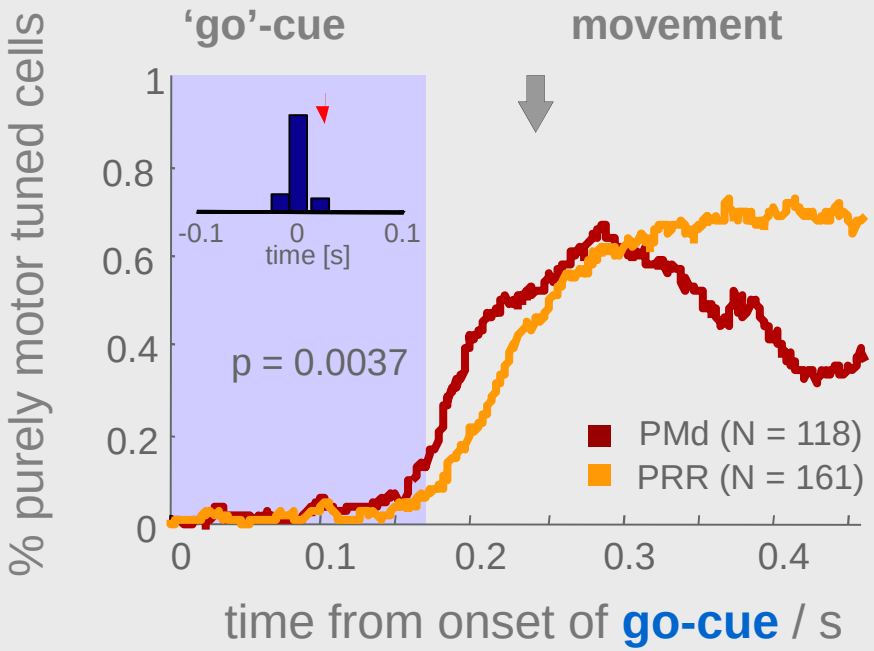
compare motor-goal latencies

Motor goals are earlier in PMd than in PRR

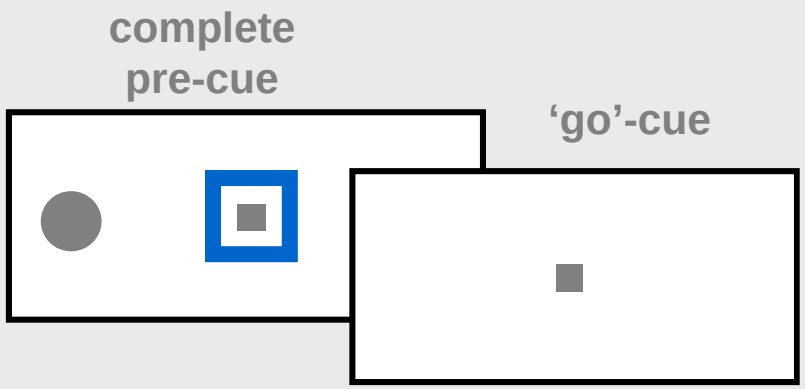
independent of a motor command

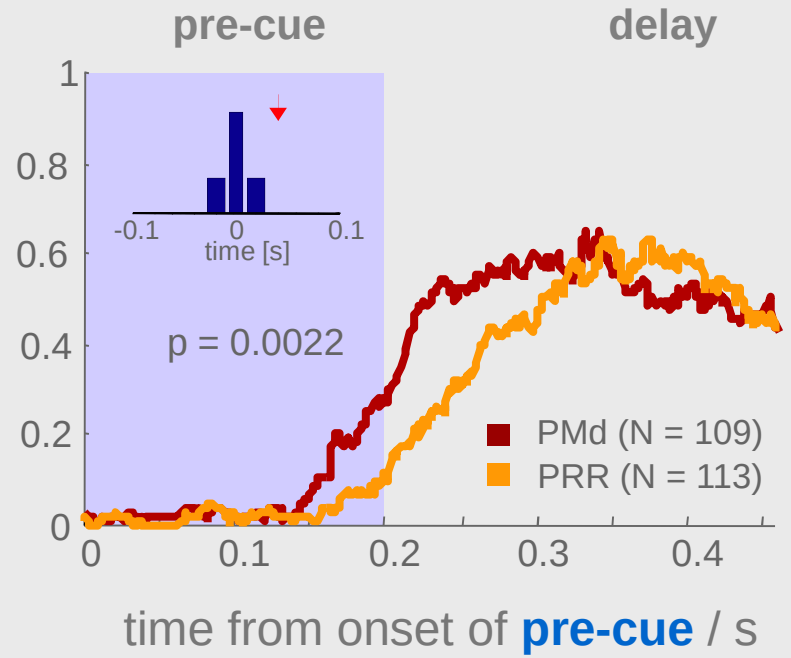
Reaction-time reach





Memory-guided reach



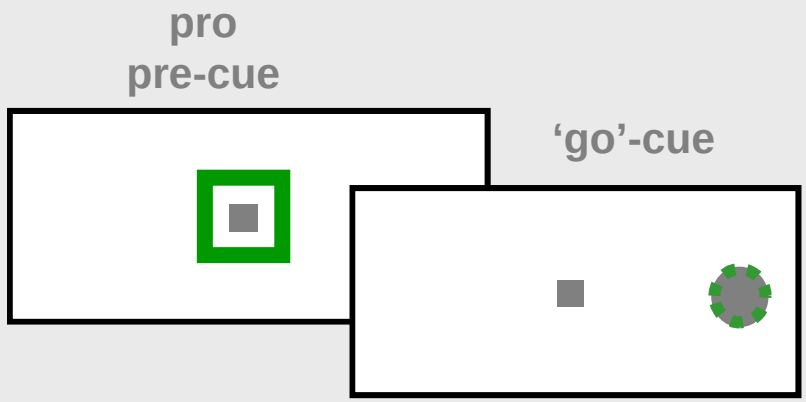


Westendorff et al. 2010 J Neurosci

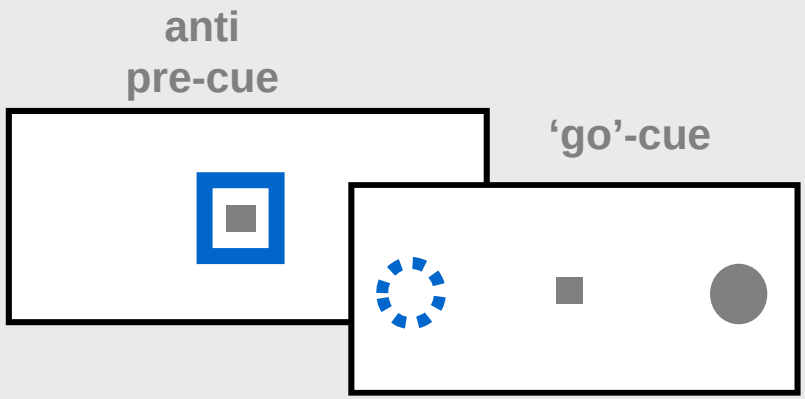
Motor goals are earlier in PMd than in PRR

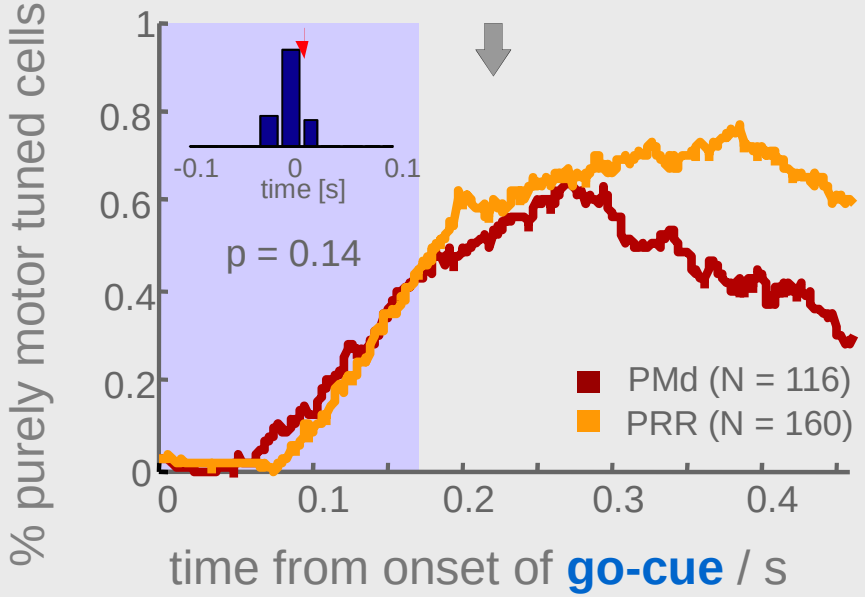
but only for inferred (ANTI) reaches

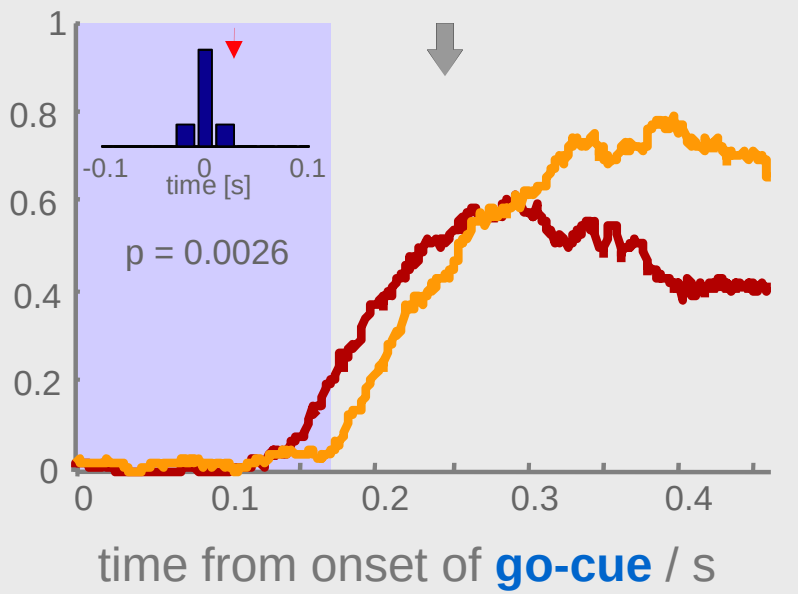
PRO reaches



ANTI reaches





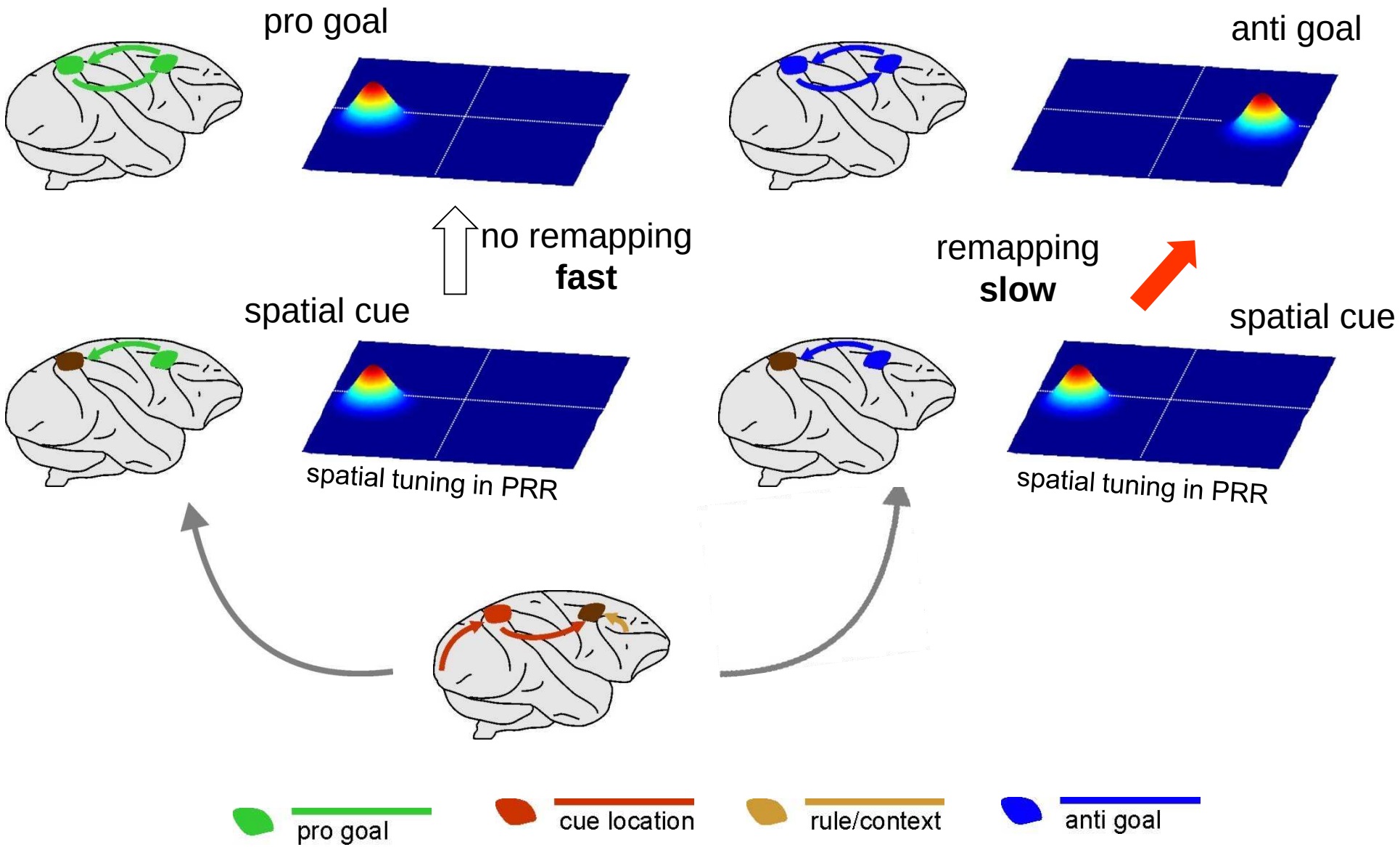


Westendorff et al. 2010 J Neurosci

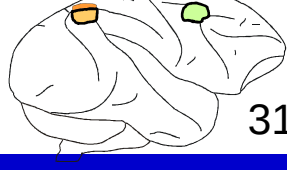
Dynamic remapping could explain latency

PRO reaches

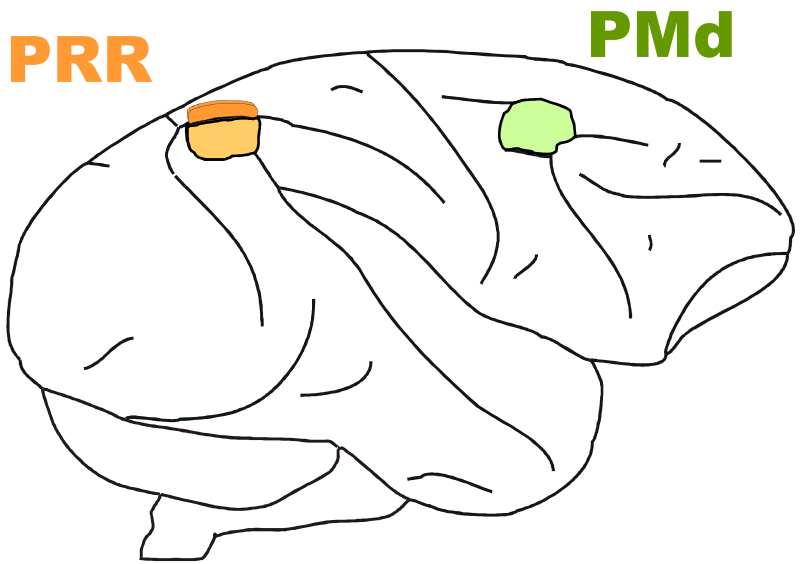
ANTI reaches



Summary & Conclusion IV
Motor-goal latencies in PRR vs. PMd



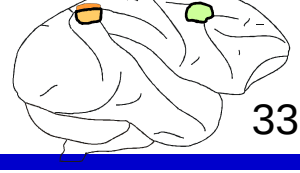
- rule-based motor-goal tuning **earlier in PMd** than PRR
  - for inferred motor-goals (anti-reaches)
  - independent of motor command (instructed delay)
- ***frontoparietal latency differences***
  - ***are not dependent on corollary discharge***
  - ***are probably induces by the slow dynamics of remapping parietal spatial representations***
- ***fronto-parietal projection***
  - ***might trigger updating of spatial motor-goal representations in PRR during planning***
  - ***not clear, if also present in tasks without updating***

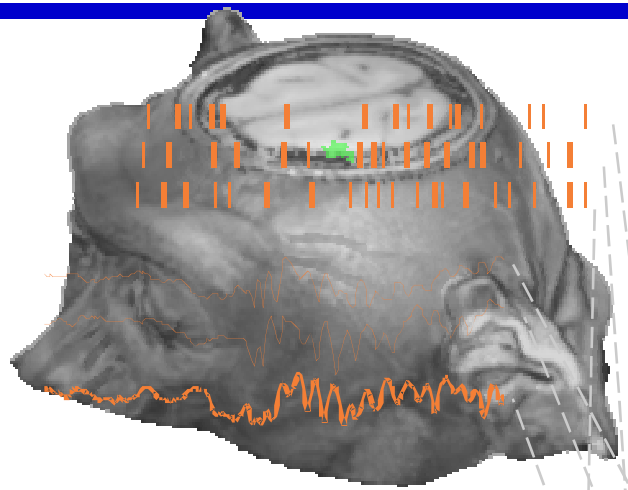


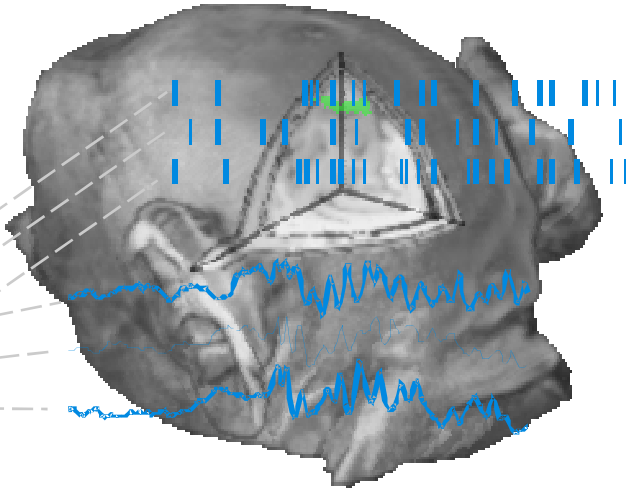
Are there frontoparietal projections effective even when there is no latency difference?

(Annette Witt, Demian Battaglia, Fred Wolf)

Simultaneous multi-channel recordings in areas PMd and PRR







touch-screen

fixation spot

reach target

micro-electrodes

reward

test functional effective connectivity

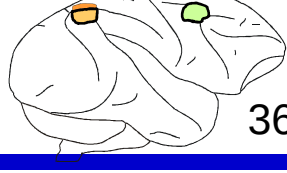
Parieto-frontal and fronto-parietal projections in different frequency bands and trial periods

[removed]

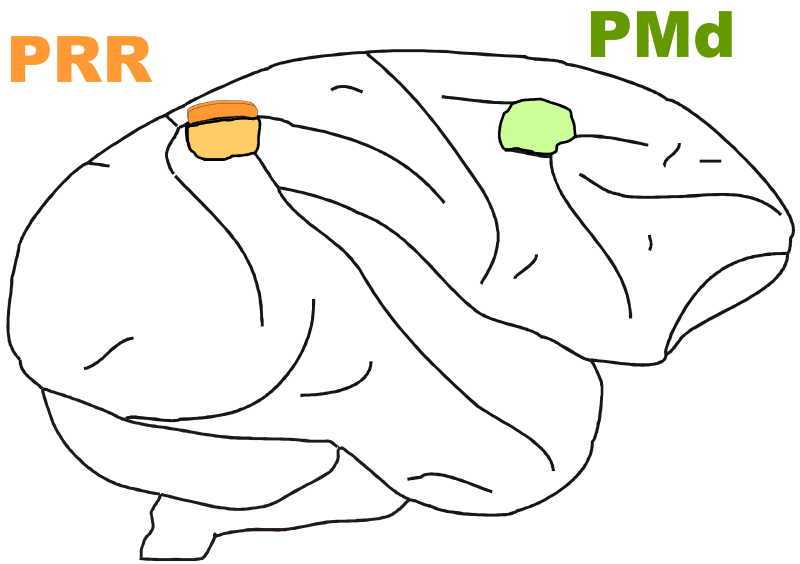
Parieto-frontal and fronto-parietal projections in different frequency bands and trial periods

[removed]

Summary & Conclusion V
Effective connectivity between PRR and PMd

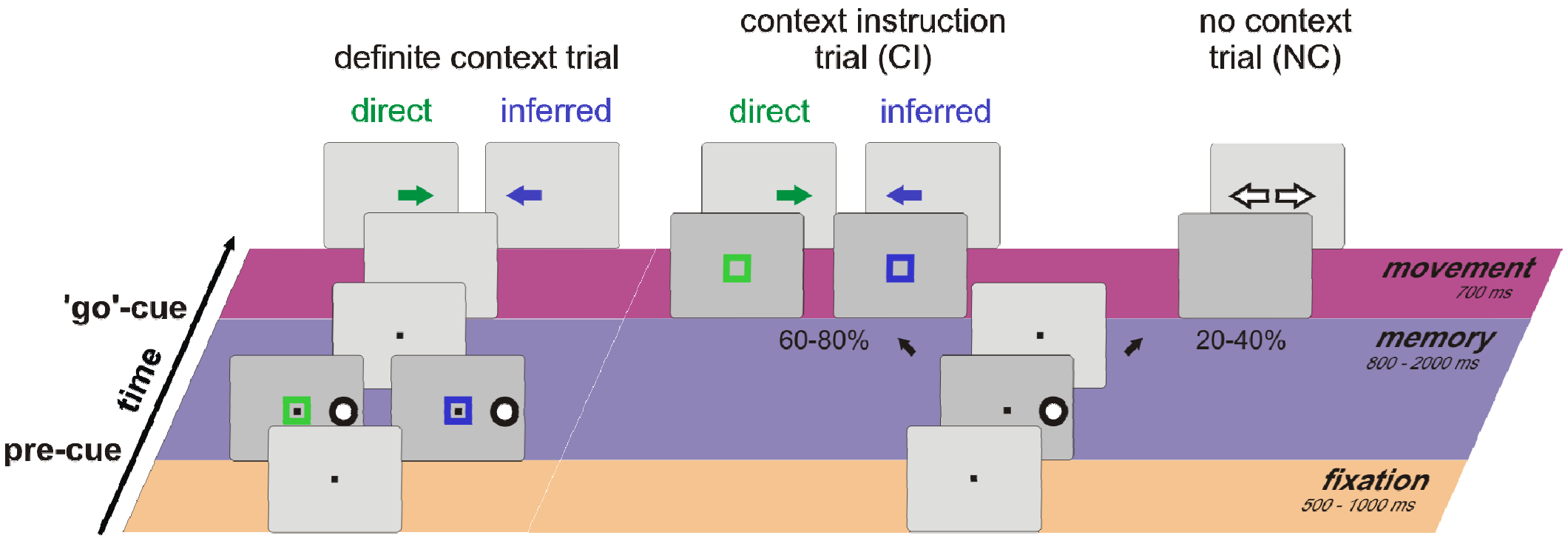


- effective connectivity between PMd and PRR exists in both directions in PRO and ANTI trials
  - at different time periods and frequency bands
    - PMd to PRR briefly around cue onset at low frequencies (<15 Hz)
    - PRR to PMd during delay in beta/lower gamma range (20-35 Hz)
- ***frontoparietal projections during motor-goal acquisition/decision*** ***(Pesaran et al. 2008)***
- ***parieto-frontal projections during planning***
- ***independent communication channels***



Does PRR simultaneously represent optional rule-based motor goals?

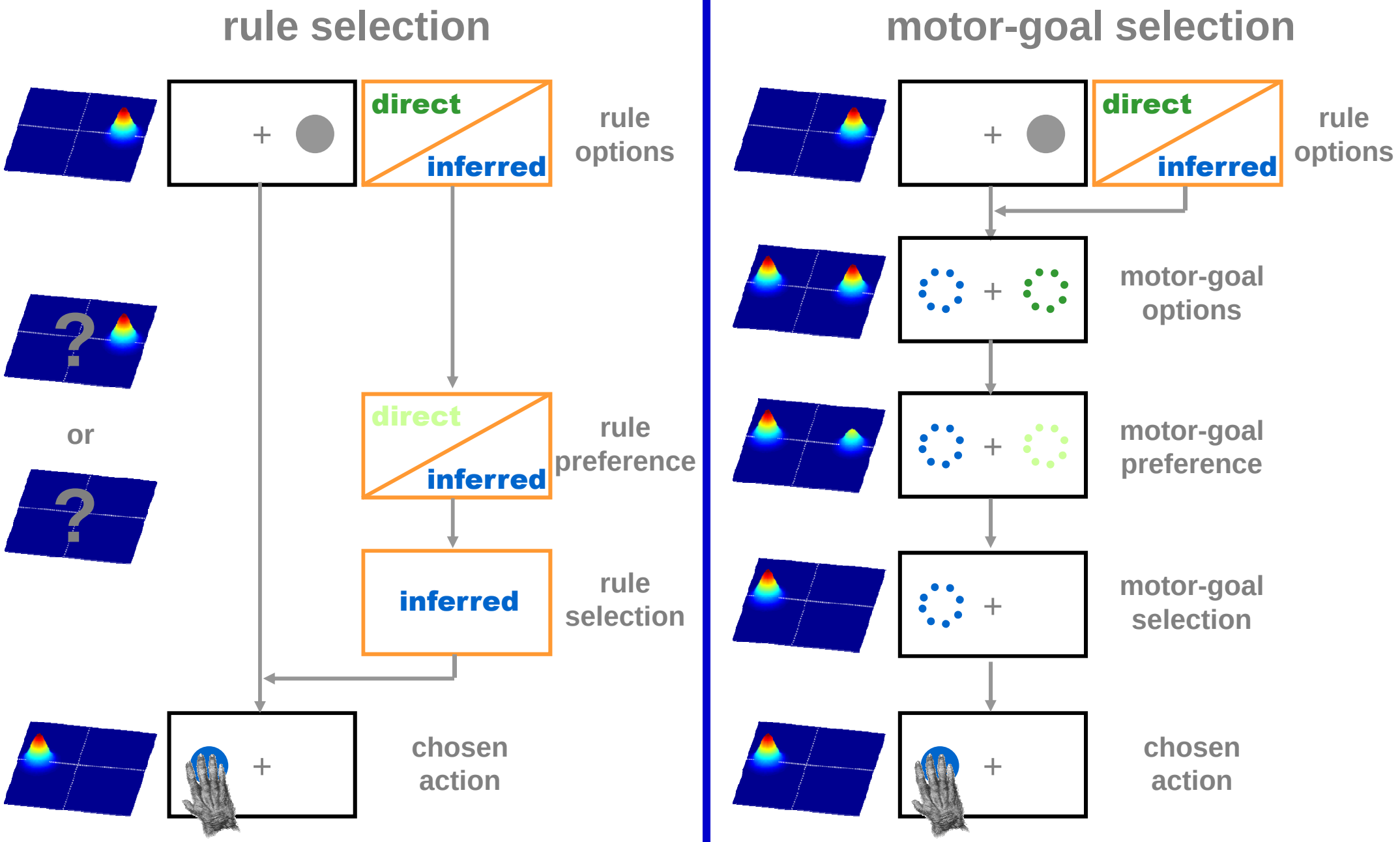
The potential motor goal experiment



Definite motor goal
(during planning)

Two potential motor goals
(during planning)

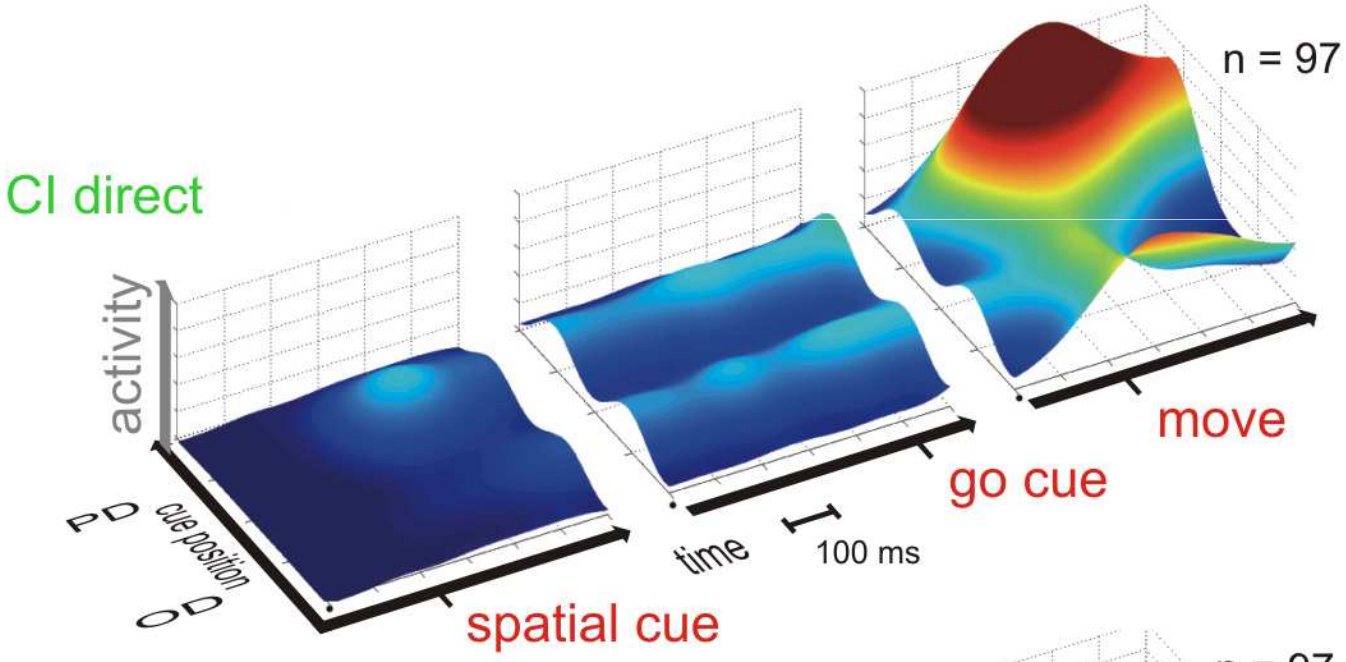
Selecting rules or goals?

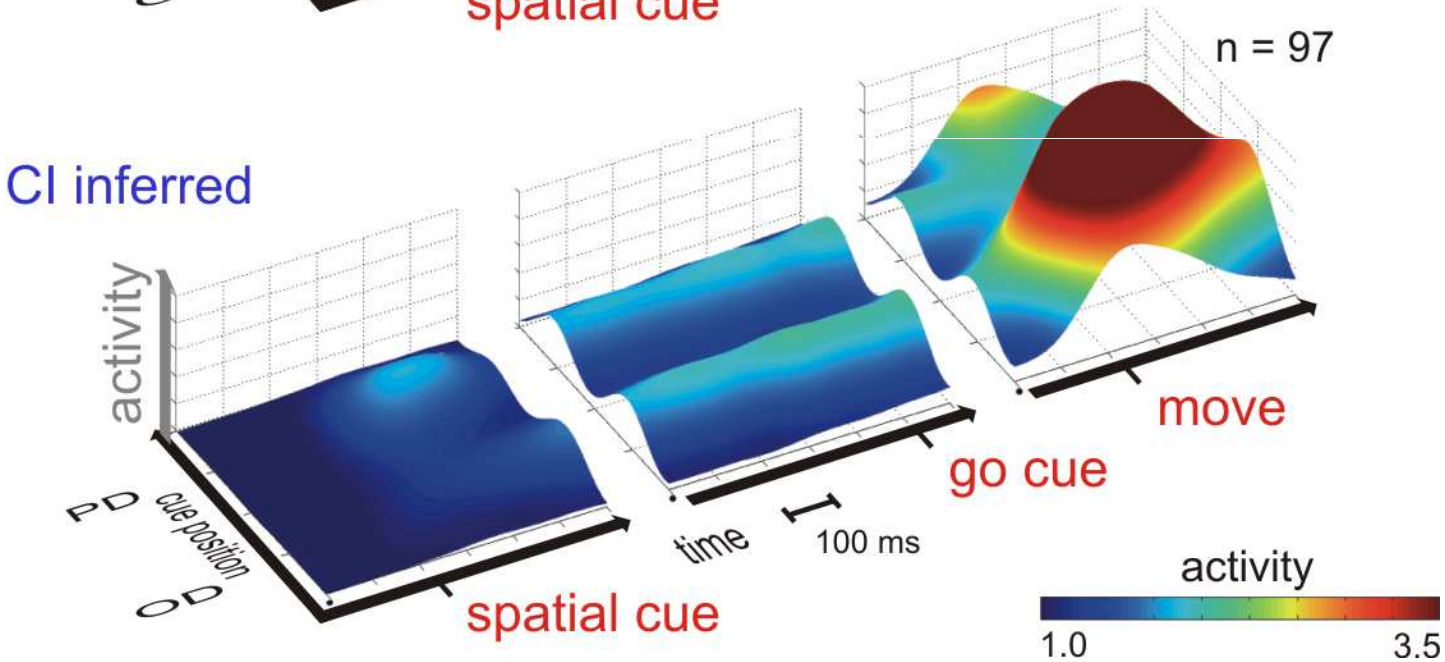


Balanced behavior: Bimodal tuning

Population activity

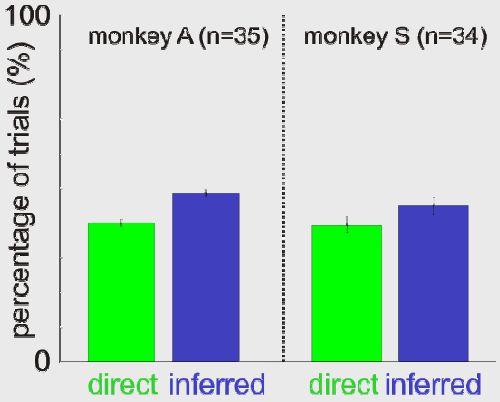
Population activity



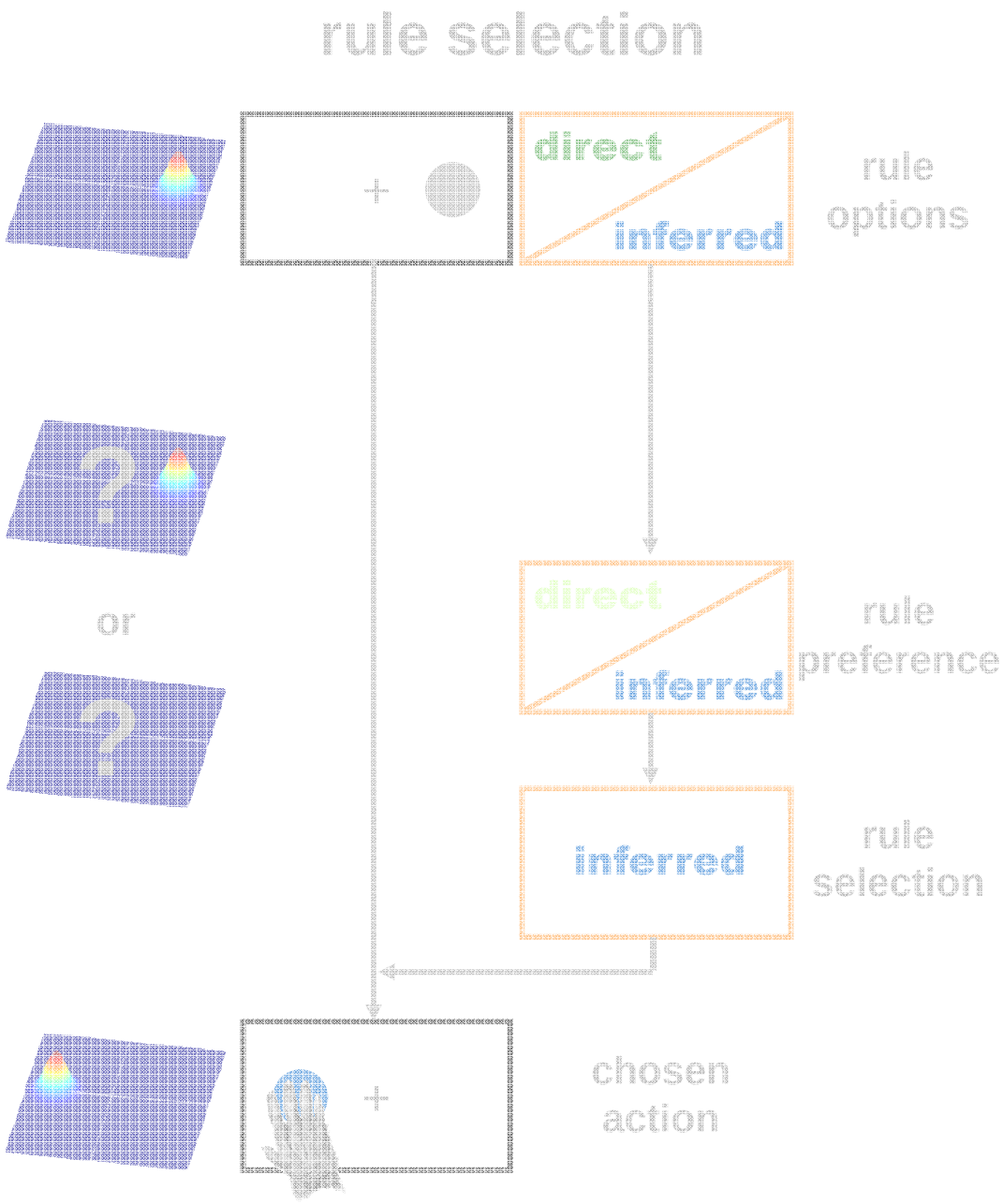


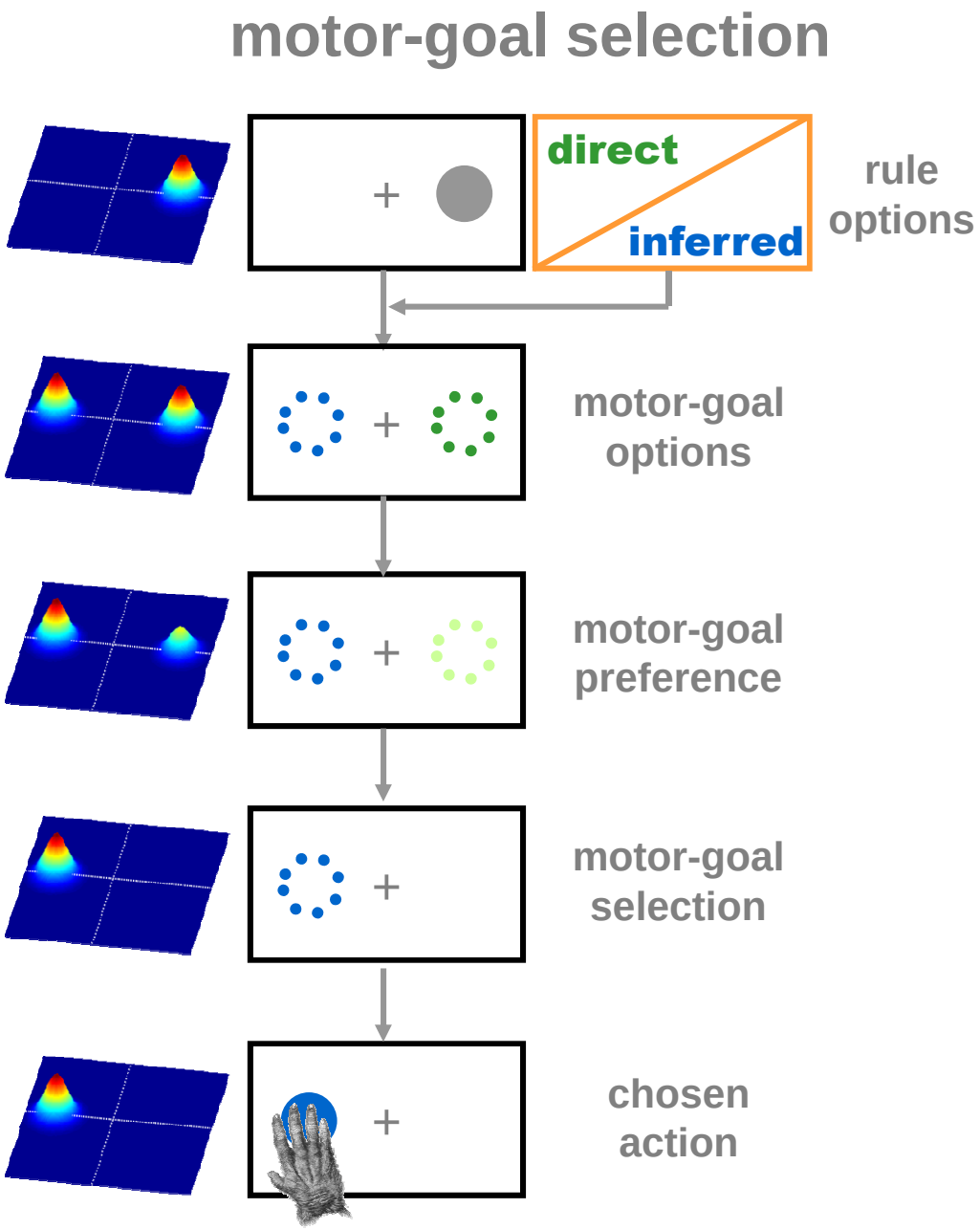
Behavior

balanced dataset



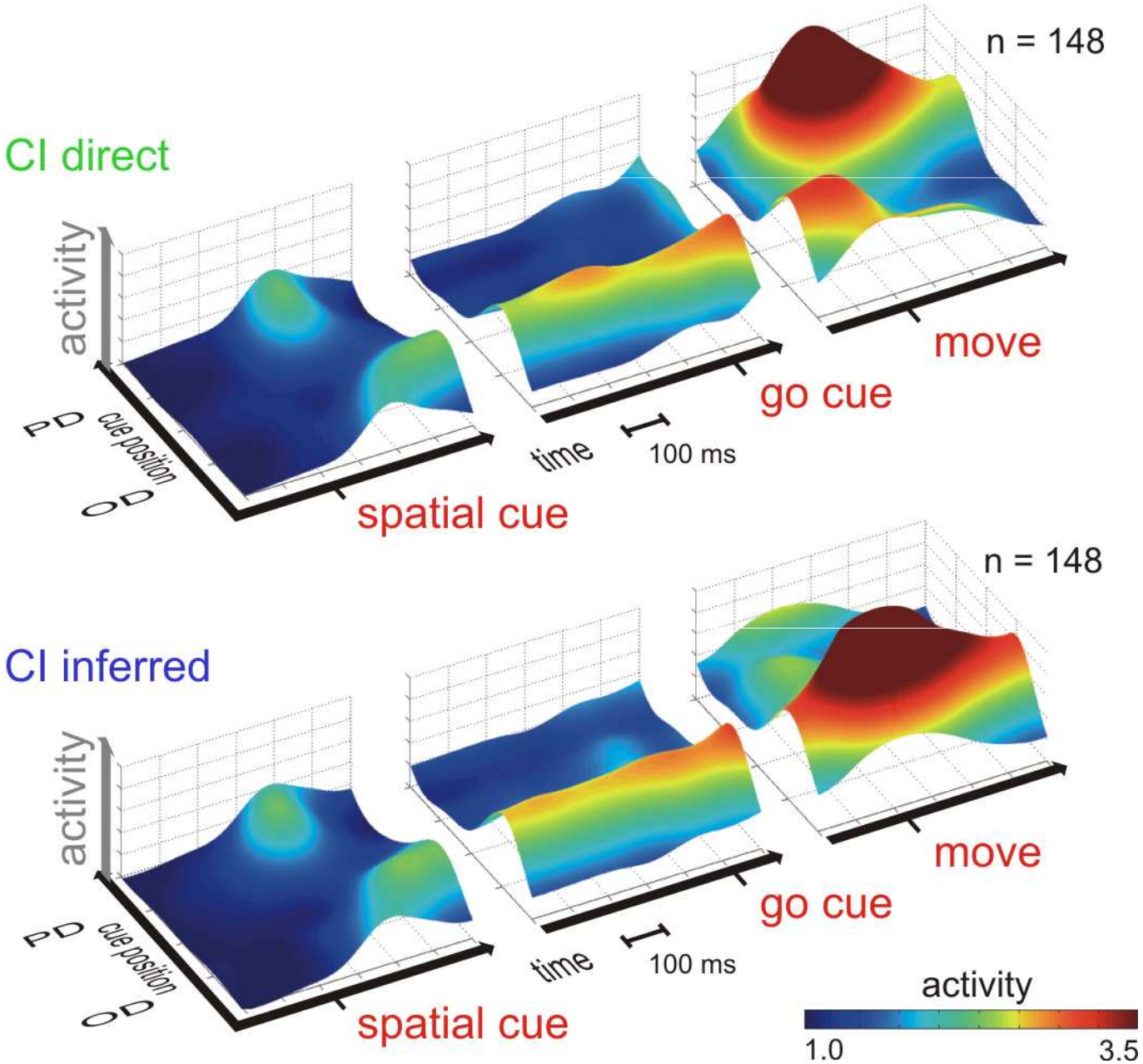
Selecting among weighted goals





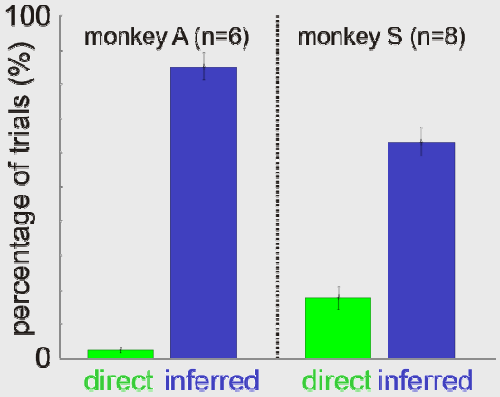
Biased behavior: Inferred-goal tuning

Population activity

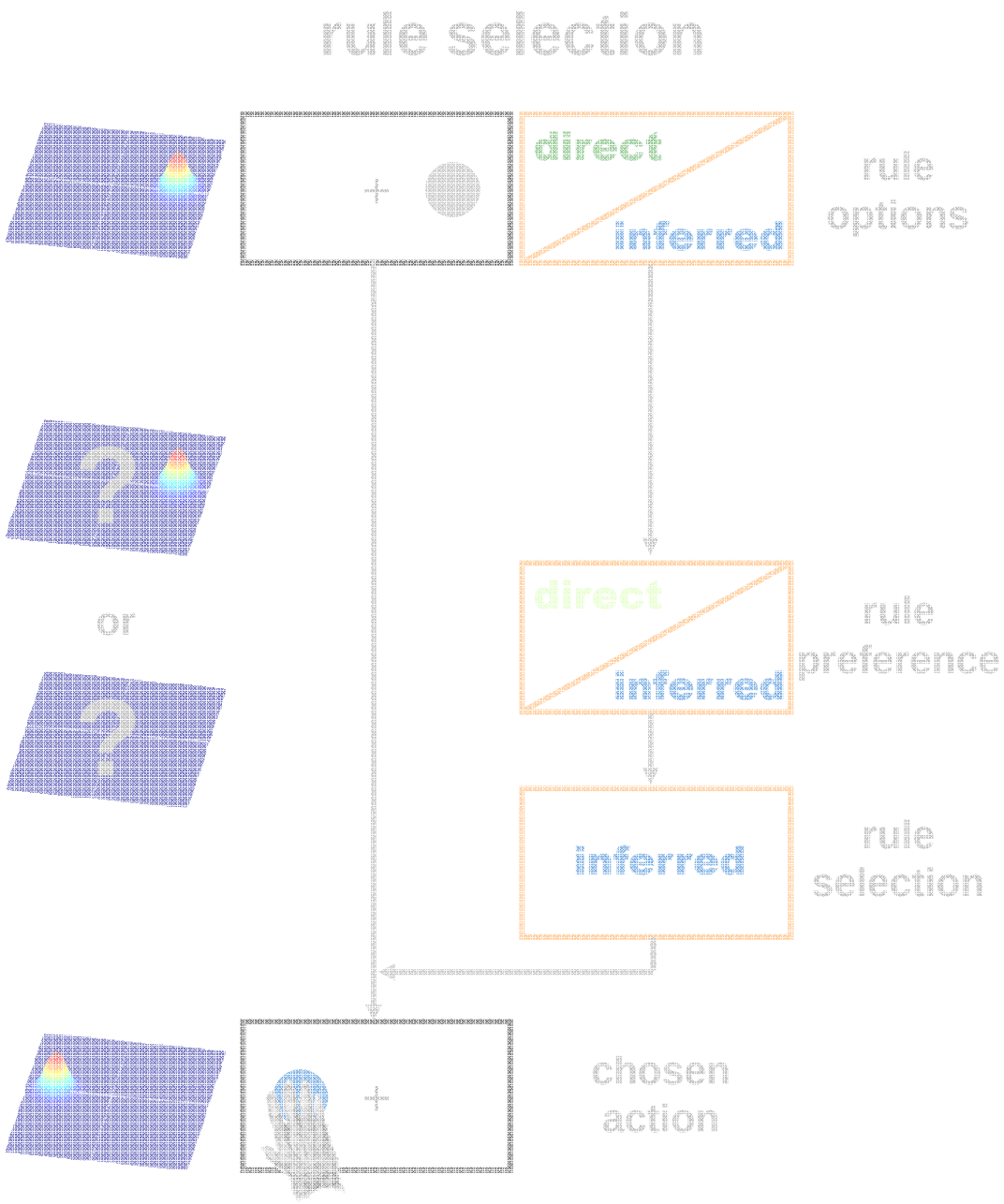


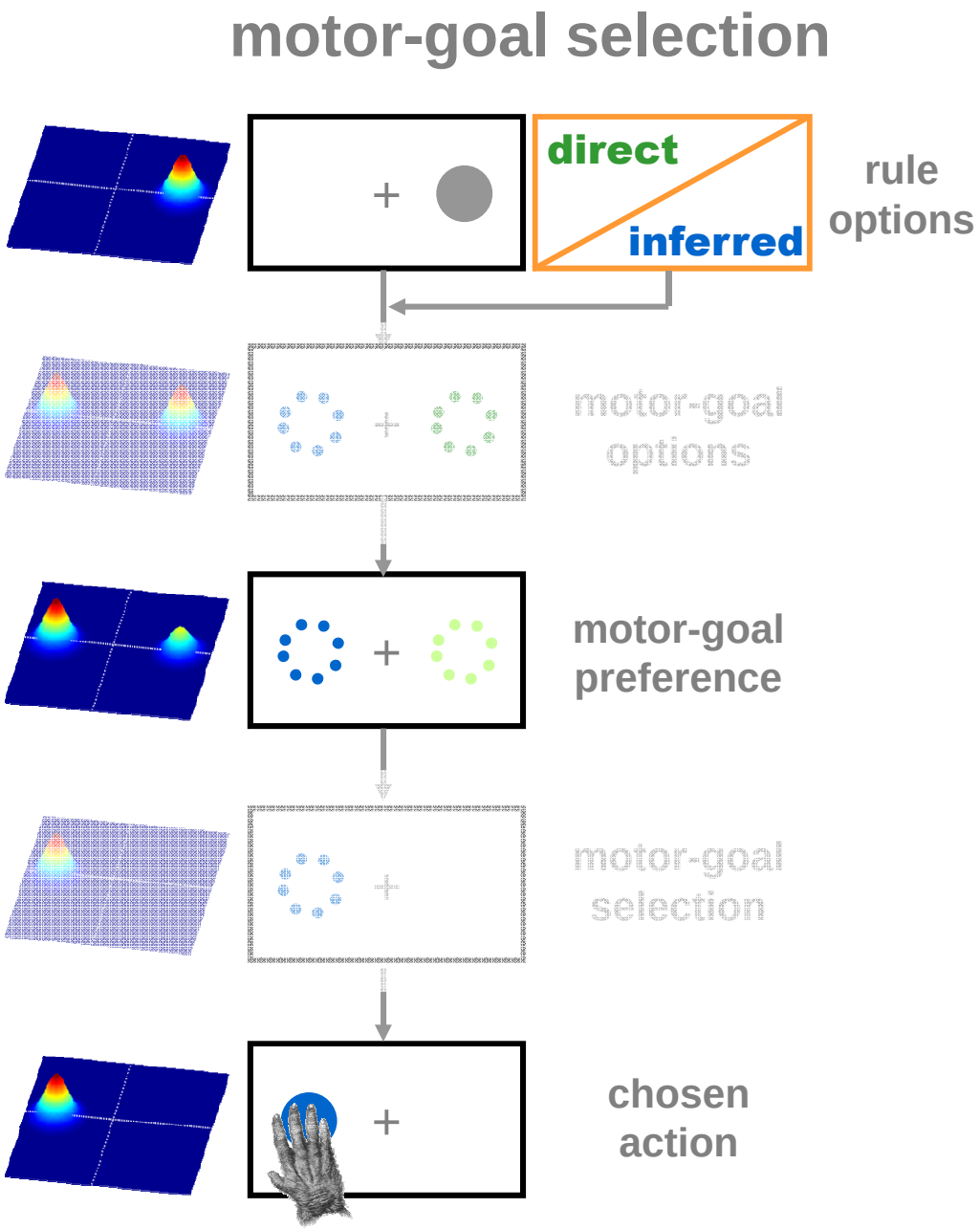
Behavior

biased dataset



Selecting among weighted goals





Summary & Conclusion VI
Deciding among rule-based motor goals in PRR

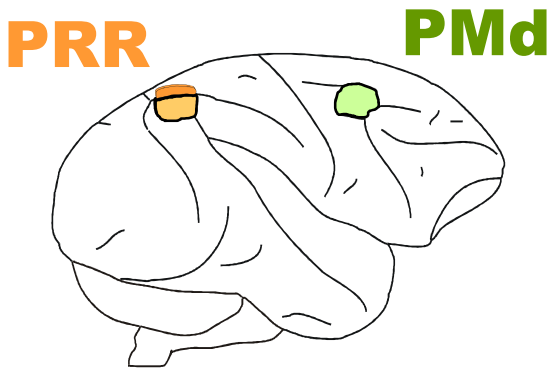
- Alternative rule-based motor goals can be encoded simultaneously in PRR

- ***The sensorimotor system can implement rule-based decision as competition between alternative motor goal representations***

- Motor-goal representations in PRR during planning …
  - depended on the probability with which the monkey on average selected the corresponding goal
  - mostly did not depend on the immediate final choice of the monkey

- ***PRR reflects preferences, not options or preliminary selections***

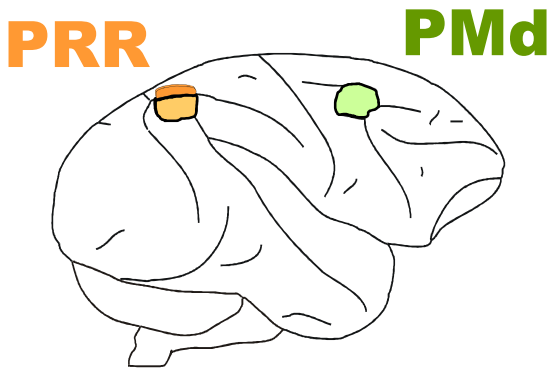
Rule-based motor goals



- Are rule-based reach goals represented in parietal cortex?
- Can rule-based reach goal representations be explained by feedback from motor-like structures (computationally)?
- Is there empirical evidence for fronto-parietal projections?
  - based on motor goal latency?
  - based on effective functional connectivity?
- Are optional reach goals represented in parietal cortex?

YES

Rule-based motor goals



- **Motor goal representations in PRR exist during planning of definite and optional movements, independent of execution**
- **They are likely the consequence of fronto-parietal projections**
- ***Fronto-parietal projections***
  - ***might trigger updating of spatial motor-goal representations in PRR during planning***
  - ***might be needed for a prospective (not only predictive) forward model computation during open loop reach planning***

Thank you!