

# Flexible representations of tactile motion with the hand

**Fourth – year Lunch Talk**  
**Brain and Cognitive Sciences Department**

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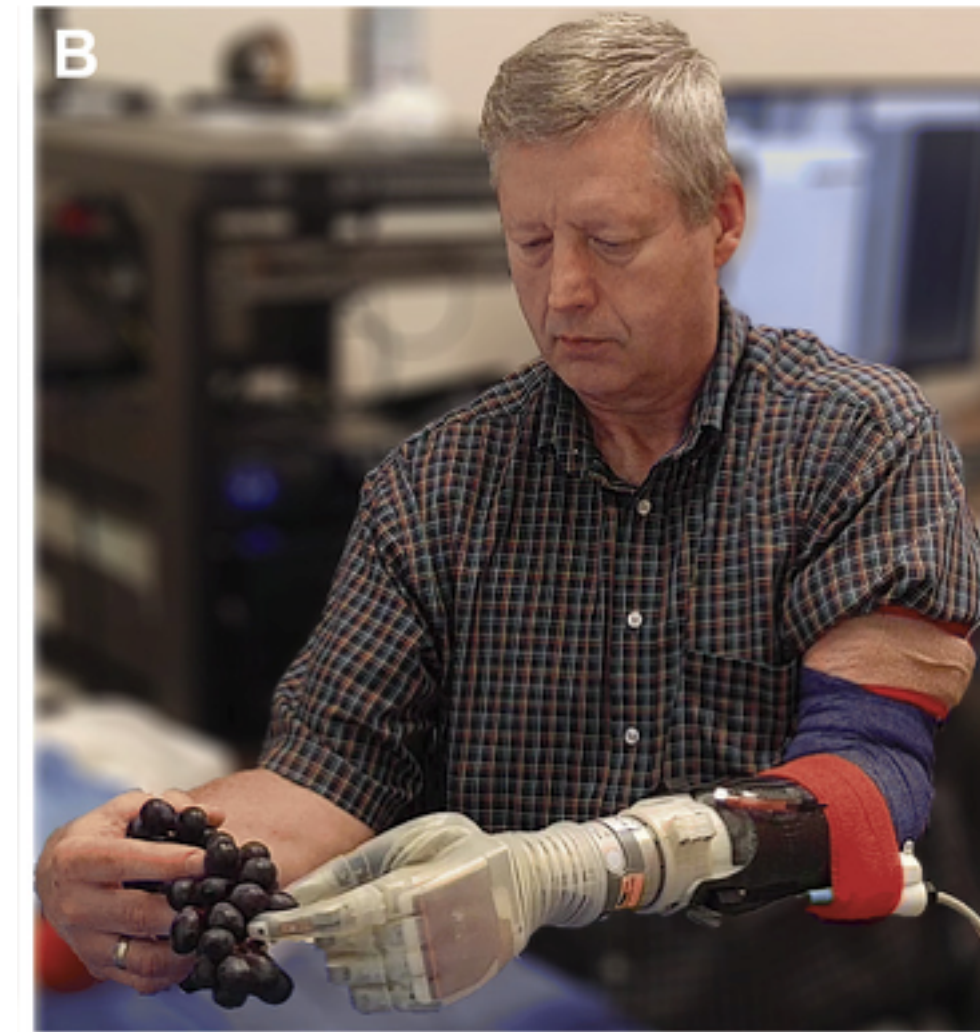
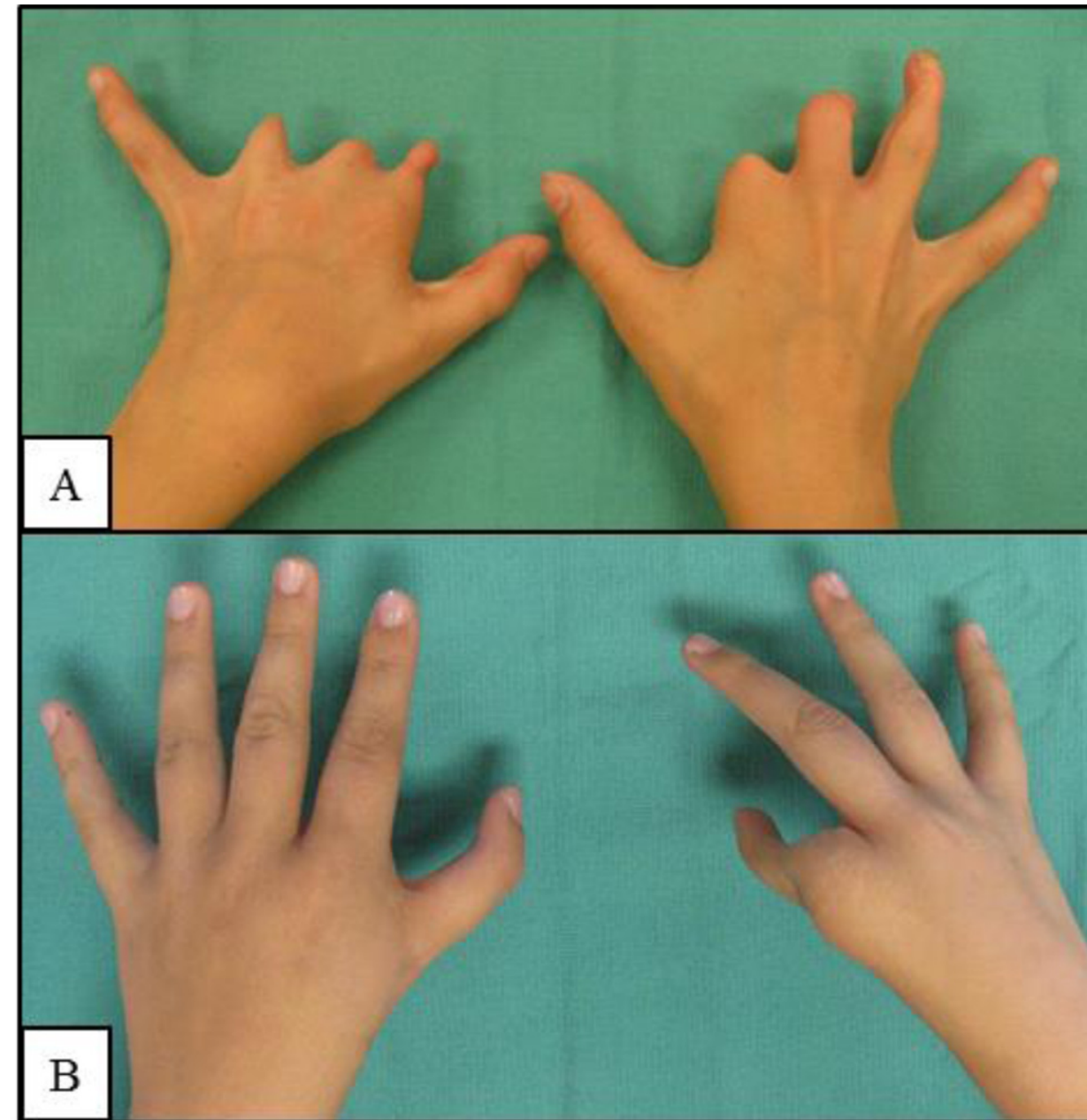
PI: Manuel Gomez-Ramirez

November 1st, 2023

Motivation



# A first-hand experience



Wolff, Aviva. 2020. "Chapter 2 - Hand Function: Typical Development." In *Pediatric Hand Therapy*, edited by Joshua M. Abzug, Scott H. Kozin, and Rebecca Neiduski, 13–23. Elsevier.

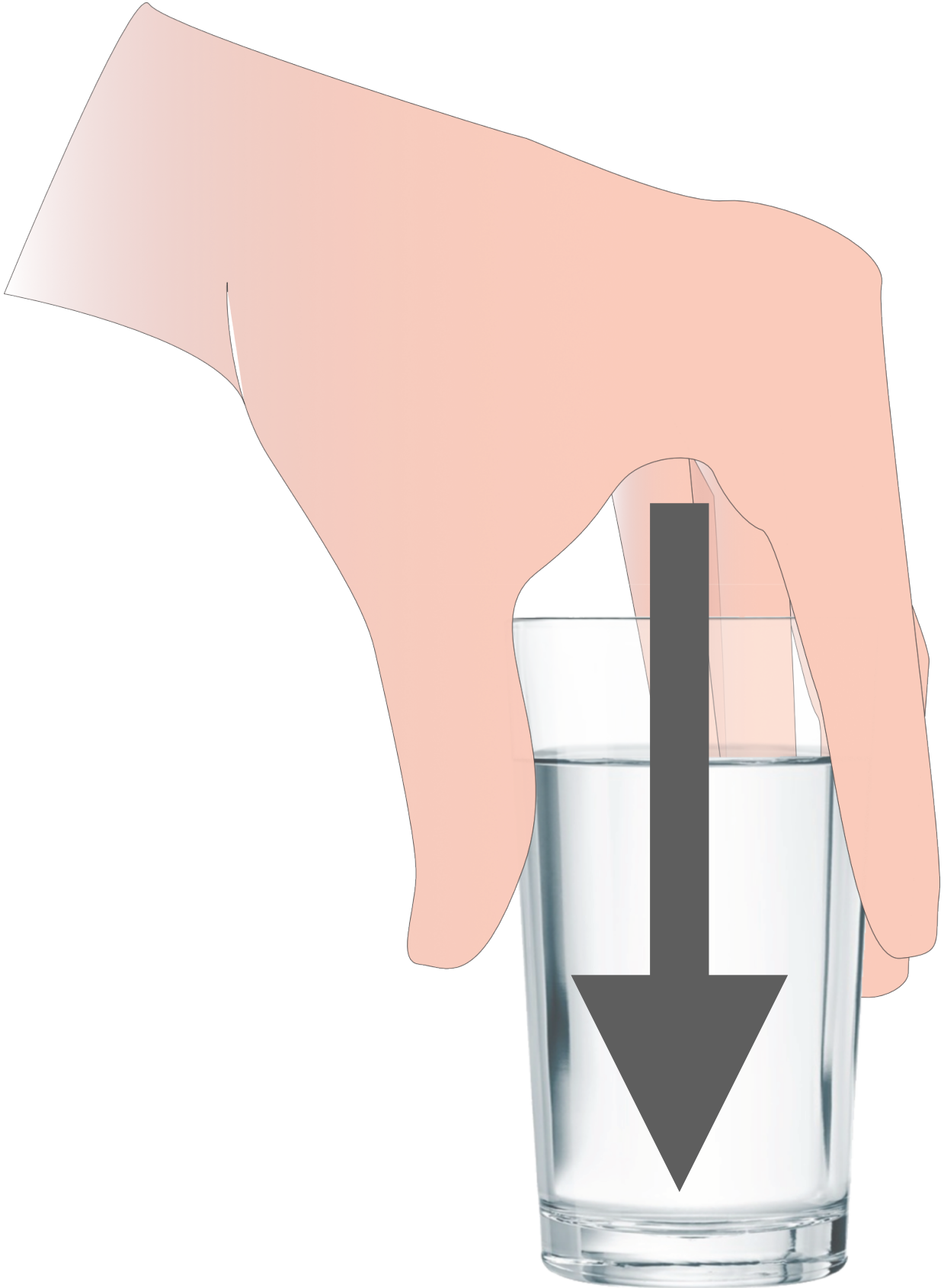
Franzblau, Lauren E., Kevin C. Chung, Noelle Carlozzi, Autumn Y. T. Chin, Kate W. Nellans, and Jennifer F. Waljee. 2015. "Coping with Congenital Hand Differences." *Plastic and Reconstructive Surgery* 135 (4)

"Biomimetic Sensory Feedback through Peripheral Nerve Stimulation Improves Dexterous Use of a Bionic Hand | Science Robotics." 2019  
Thomas, Neha, Alexandra J. Miller, Hasan Ayaz, and Jeremy D. Brown. 2023. "Haptic Shared Control Improves Neural Efficiency during Myoelectric Prosthesis Use." *Scientific Reports* 13 (1): 484.

# How does the brain solve the slipping glass problem?

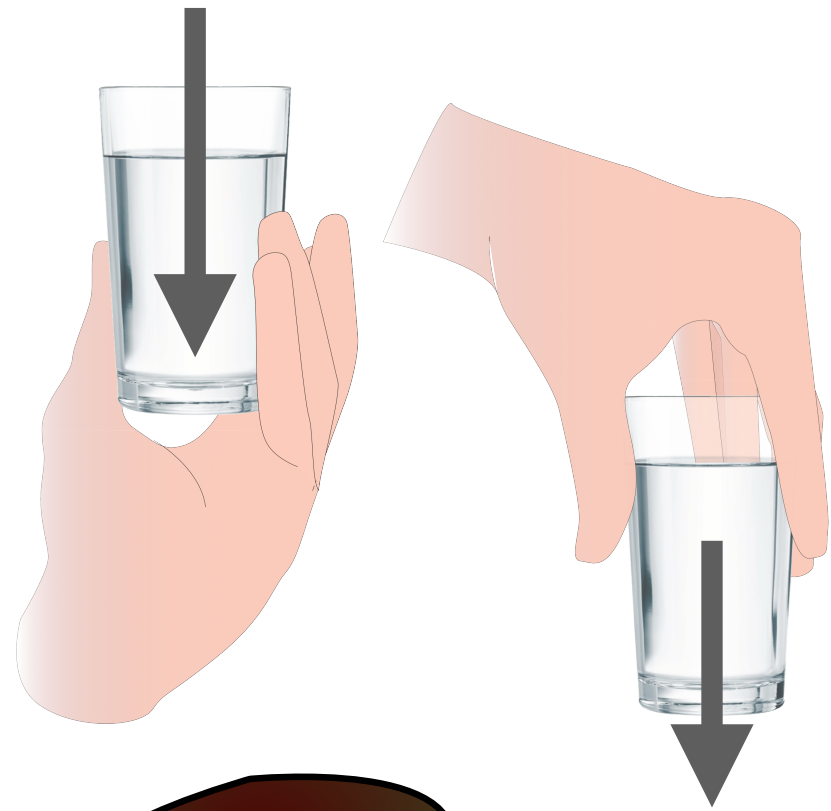


Downwards



Downwards

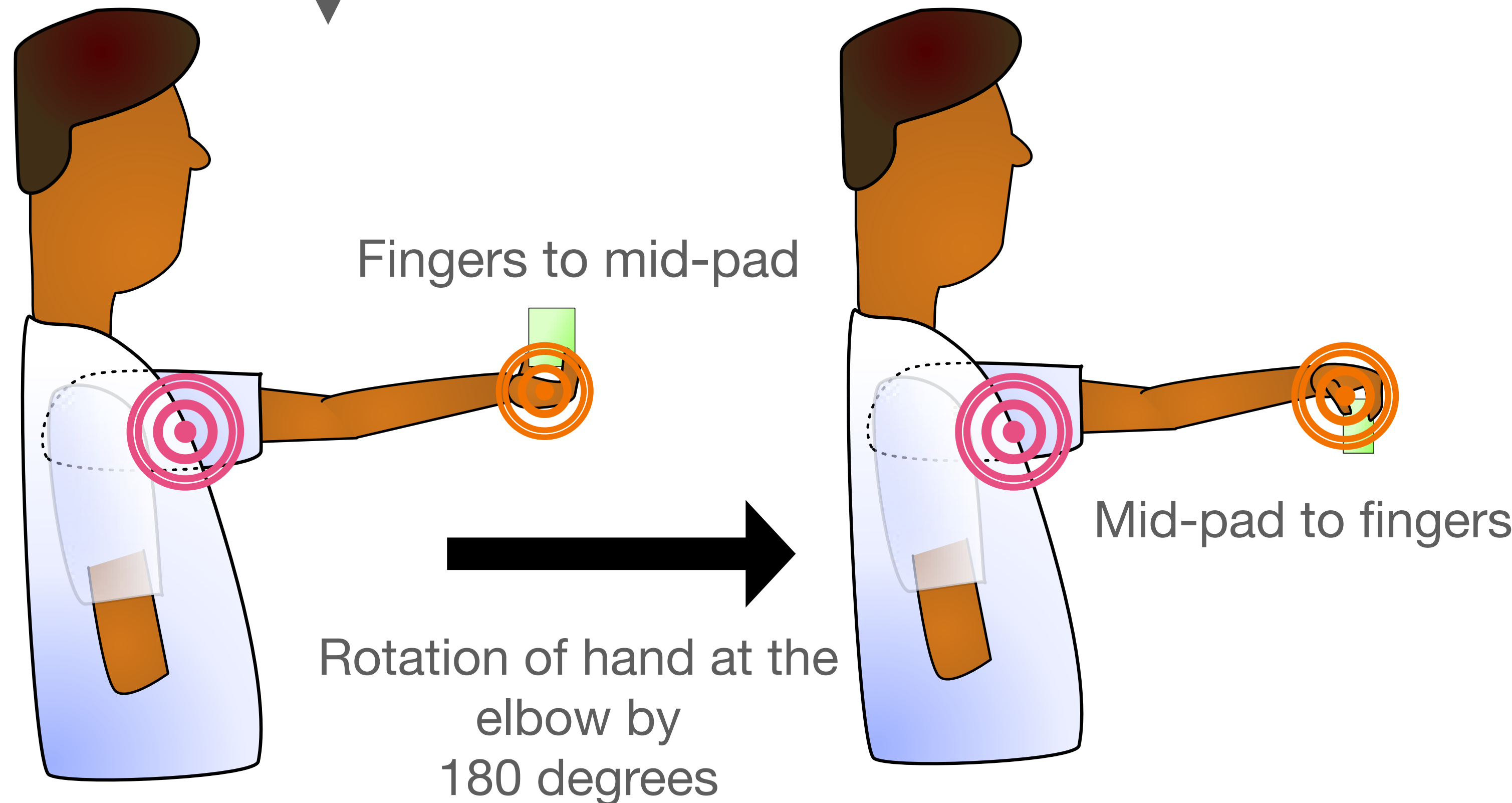
# How does the brain solve the slipping glass problem?



What changes between the two cases?

The posture of the hand  
Motion direction on the fingers  
w.r.t the hand

= Proprioceptive state of the arm  
= Cutaneous motion  
= information



Motion in sternum-centric reference frame stays the same

Motion in finger-centric reference frame changes

# Analogous motion integration mechanisms in vision and tactile domains



*Adelson & Movshon 1982, Nature Vol. 300*  
*YC Pei et. al 2008 PNAS*  
*YC Pei et. al 2011 Neuron*

# Analogous motion integration mechanisms in vision and tactile domains

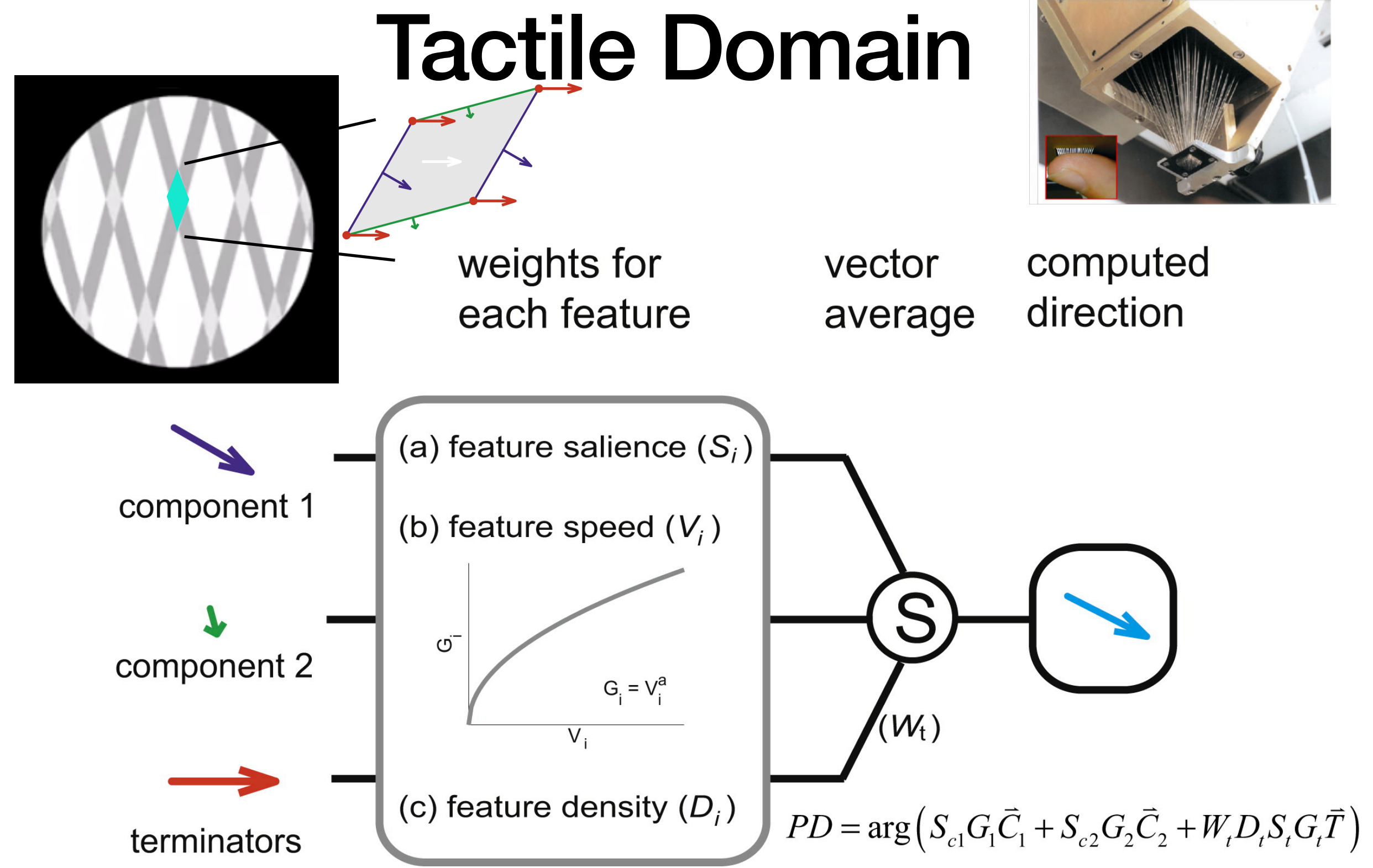
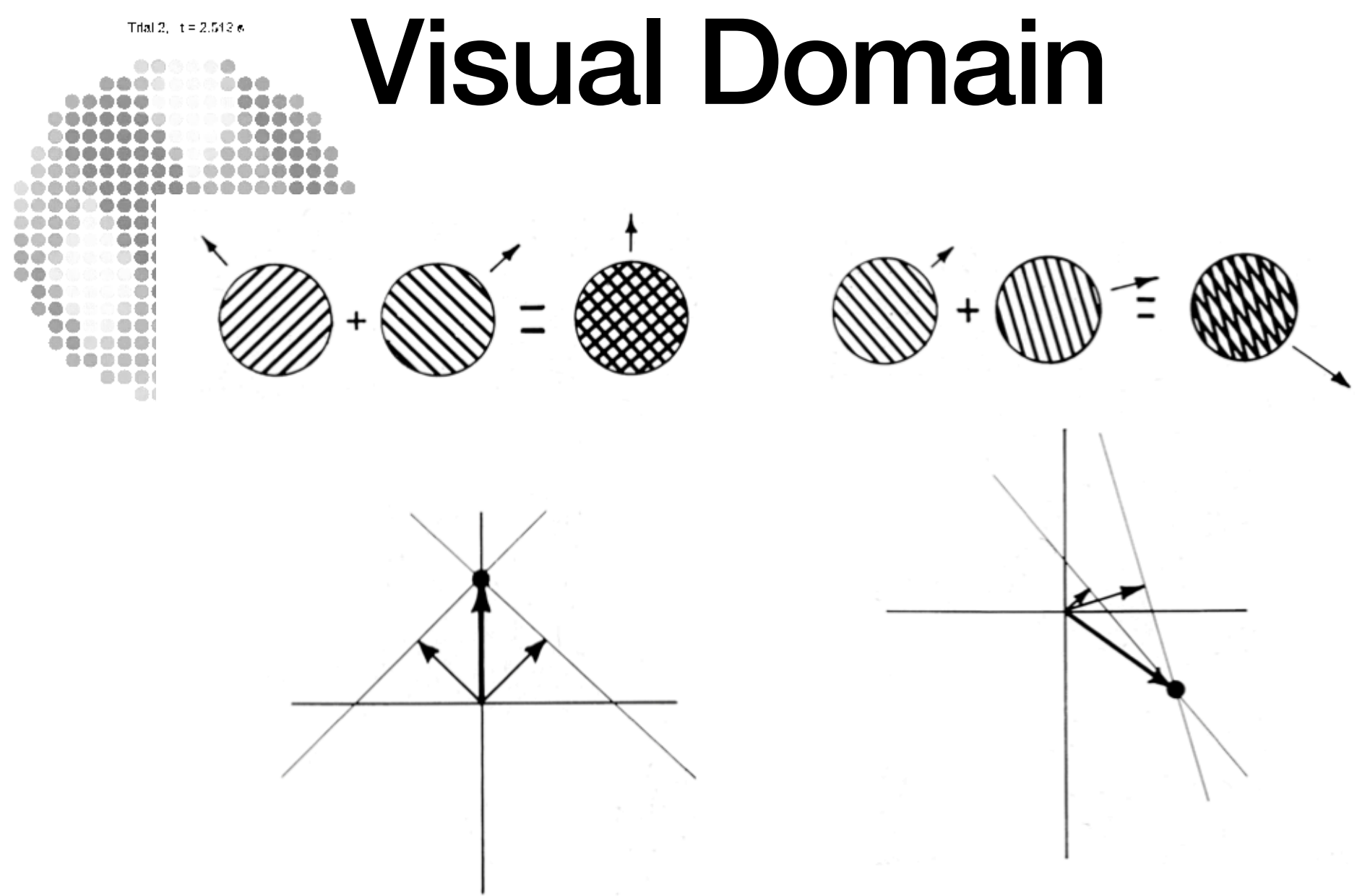
## Visual Domain



## Tactile Domain



# Analogous motion integration mechanisms in vision and tactile domains



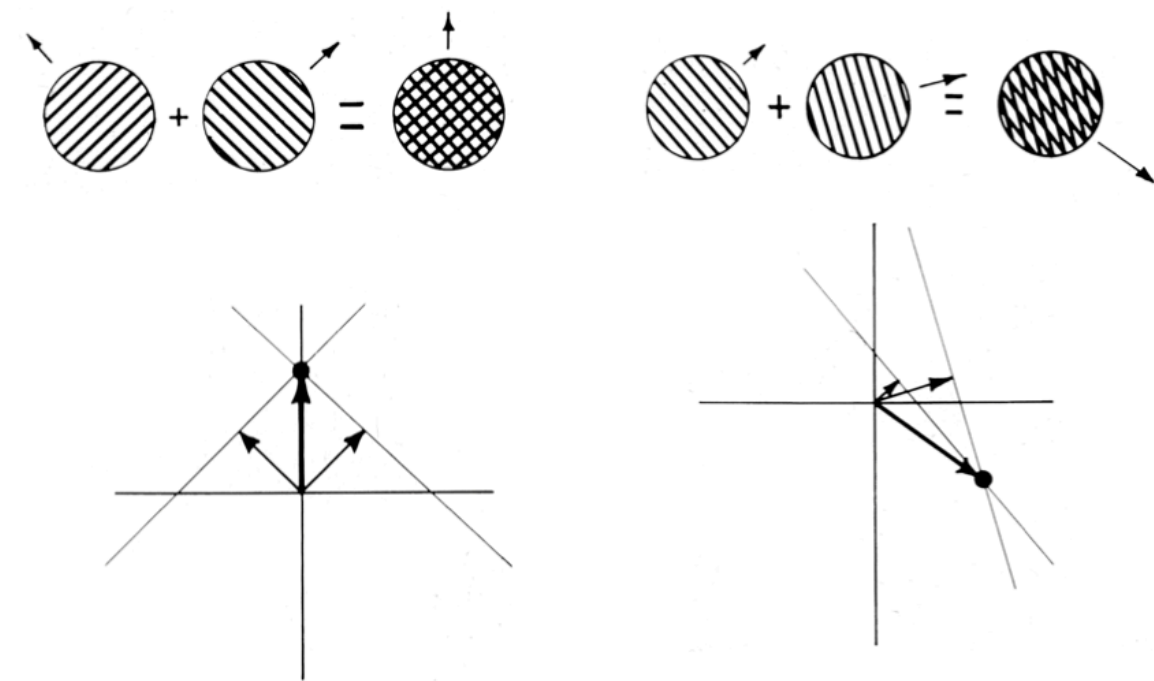
## Intersection of Constraints

## Full-Vector Average model

Adelson & Movshon 1982, Nature Vol. 300  
 YC Pei et. al 2008 PNAS  
 YC Pei et. al 2011 Neuron

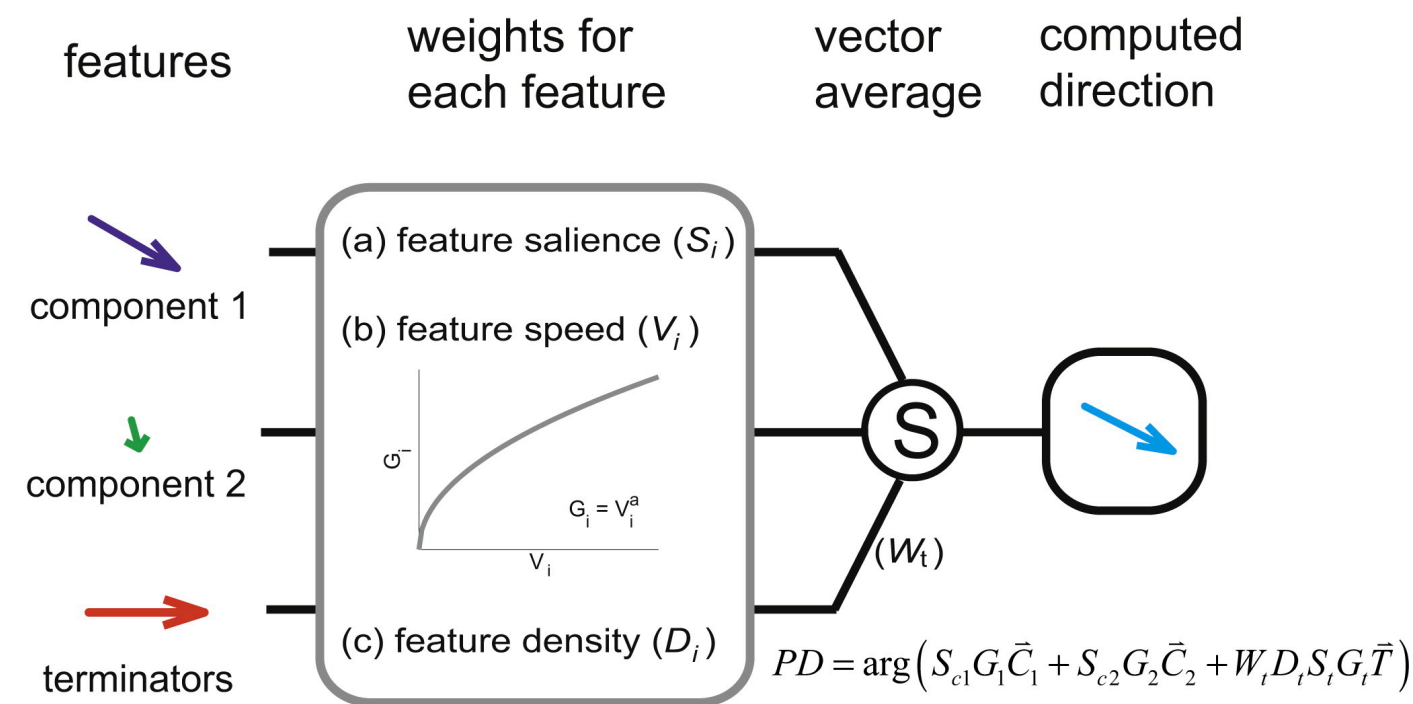
# Analogous motion integration mechanisms in vision and tactile domains

## Visual Domain

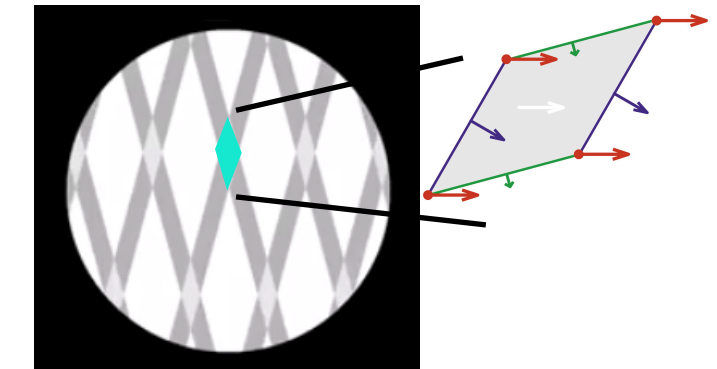


Intersection of Constraints

## Tactile Domain



Full-Vector Average model



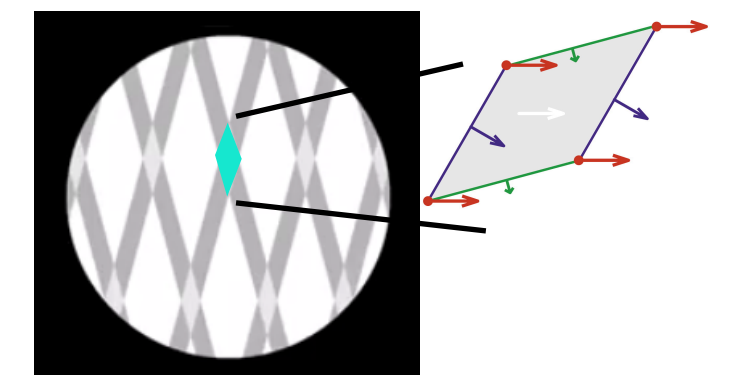
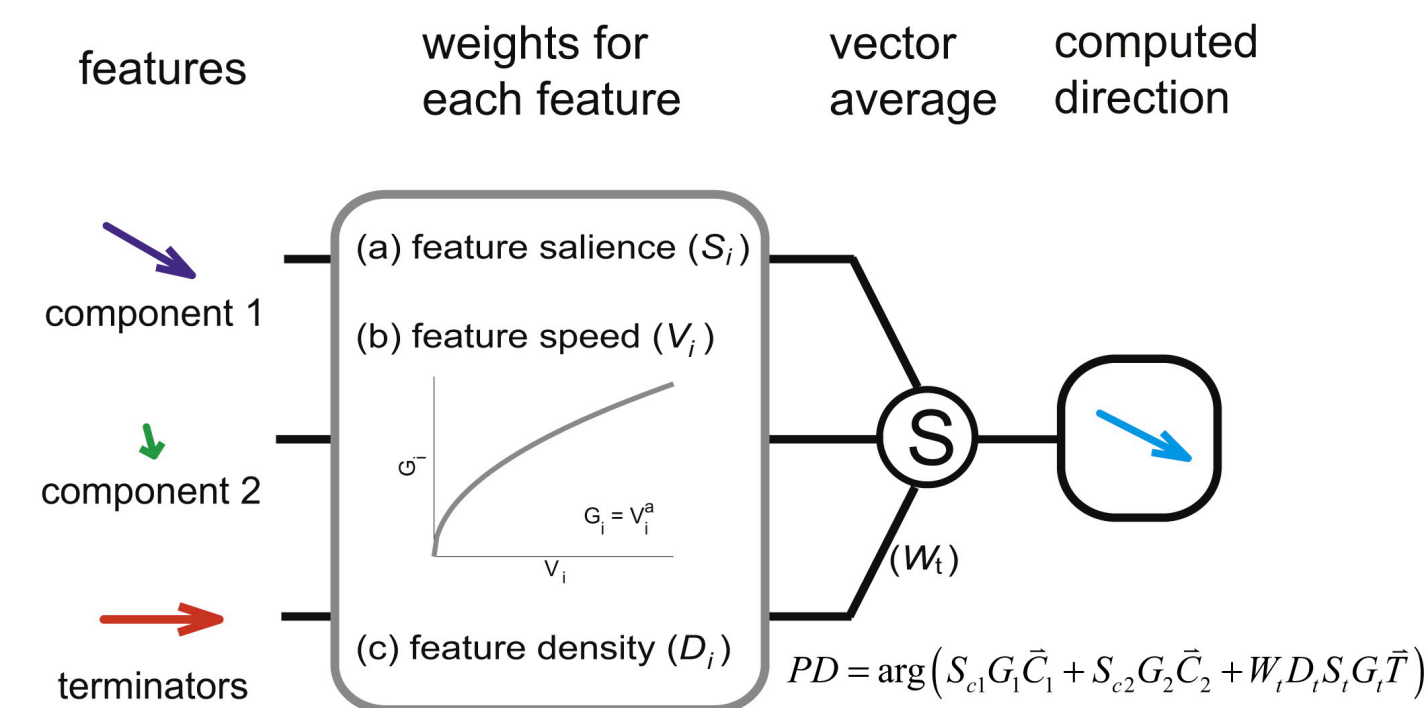
## Pattern neurons in MT

## Pattern neurons in Area 1 of Somatosensory Cortex

# Analogous motion integration mechanisms in vision and tactile domains

- **Tactile motion tuning functions studied with the hand in a fixed posture**
- **Monkey passively experiences the tactile stimuli and does not performing a behavioral report.**

## Tactile Domain

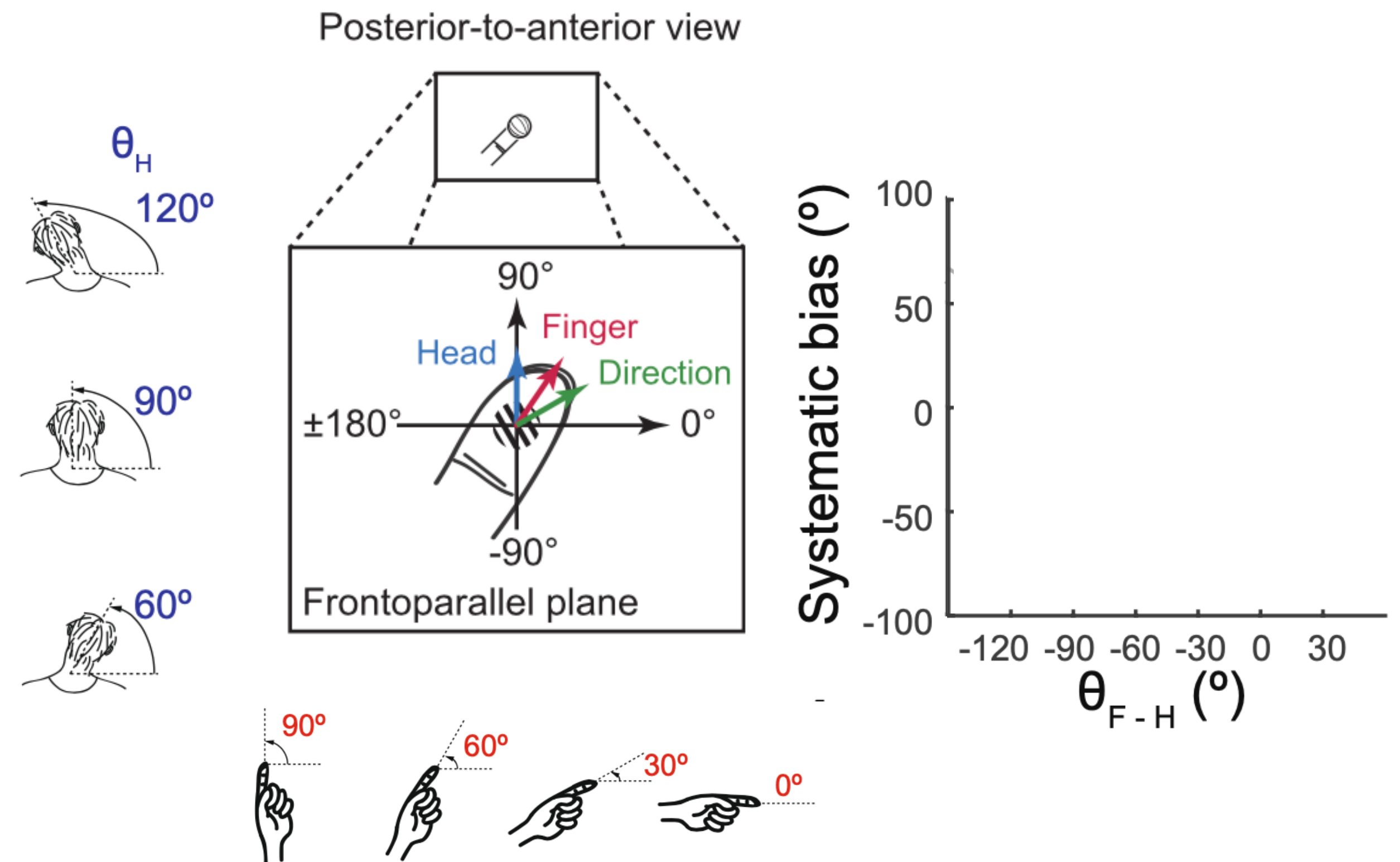


Full-Vector Average model

## Pattern neurons in Area 1 of Somatosensory Cortex

# Proprioceptive state biases tactile motion report

- Proprioception introduces systematic biases in tactile motion perception
- **No explicit reference frame instructed**
- **No theoretical framework for explaining the interaction of posture and tactile motion cues.**

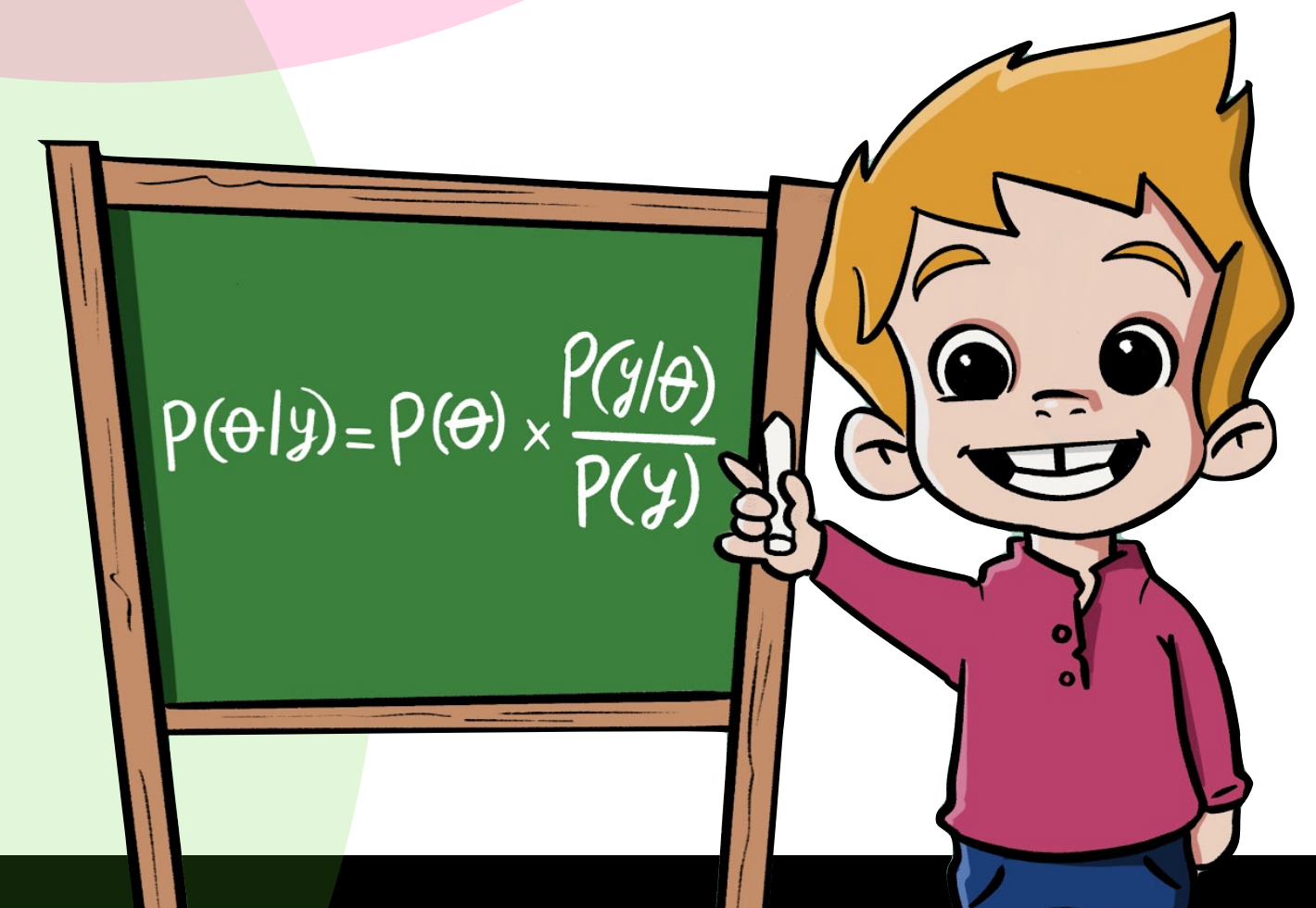


# Research questions of interest

**Goal 1:** Determine if humans can flexibly perceive tactile motion in different proprioceptive states and reference frames?

**Goal 3:** Determine how tactile motion information is modulated by proprioception in the brain?

**Goal 2:** Develop a generalizable computational model that explains human behavioral report.

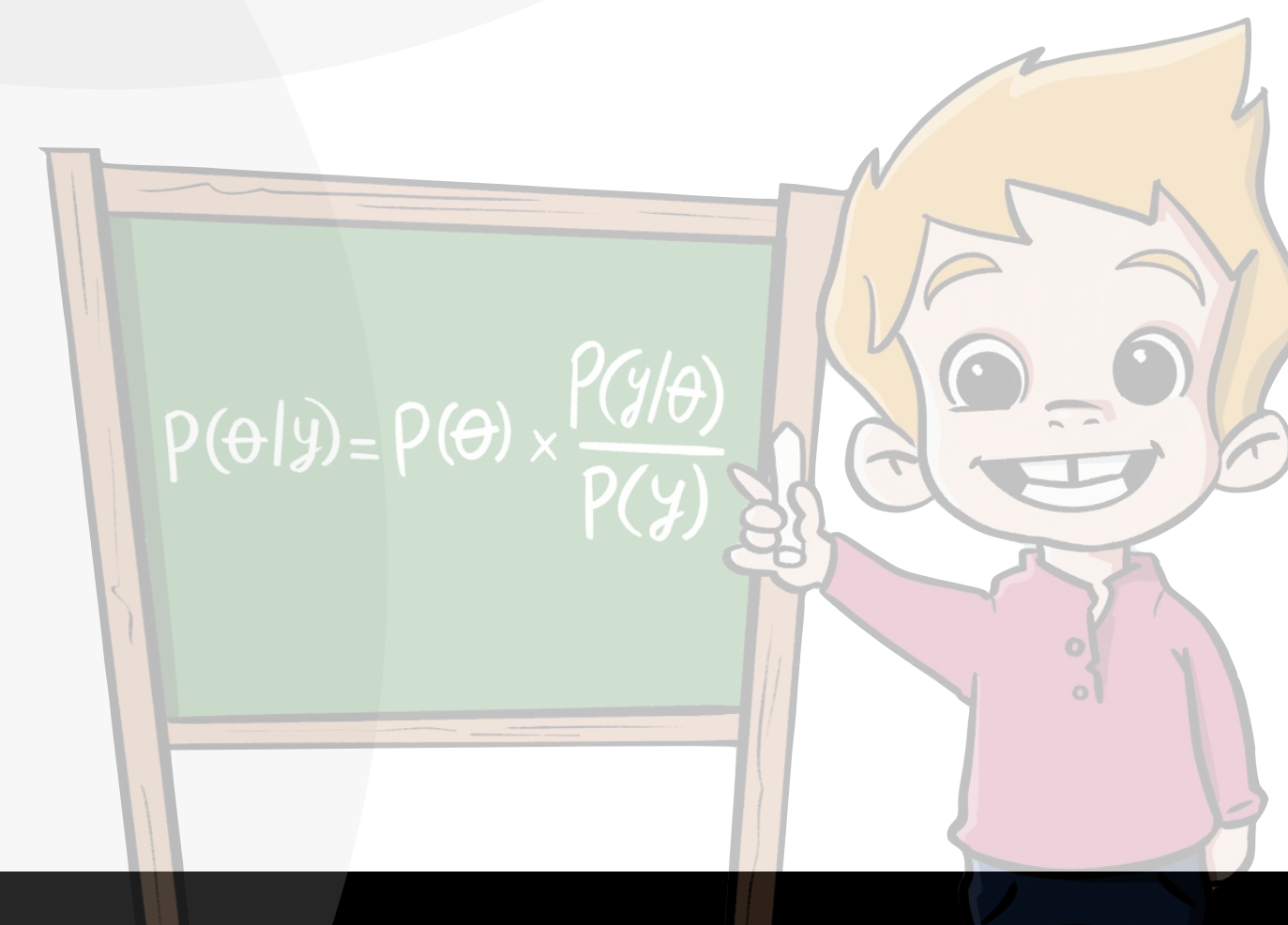
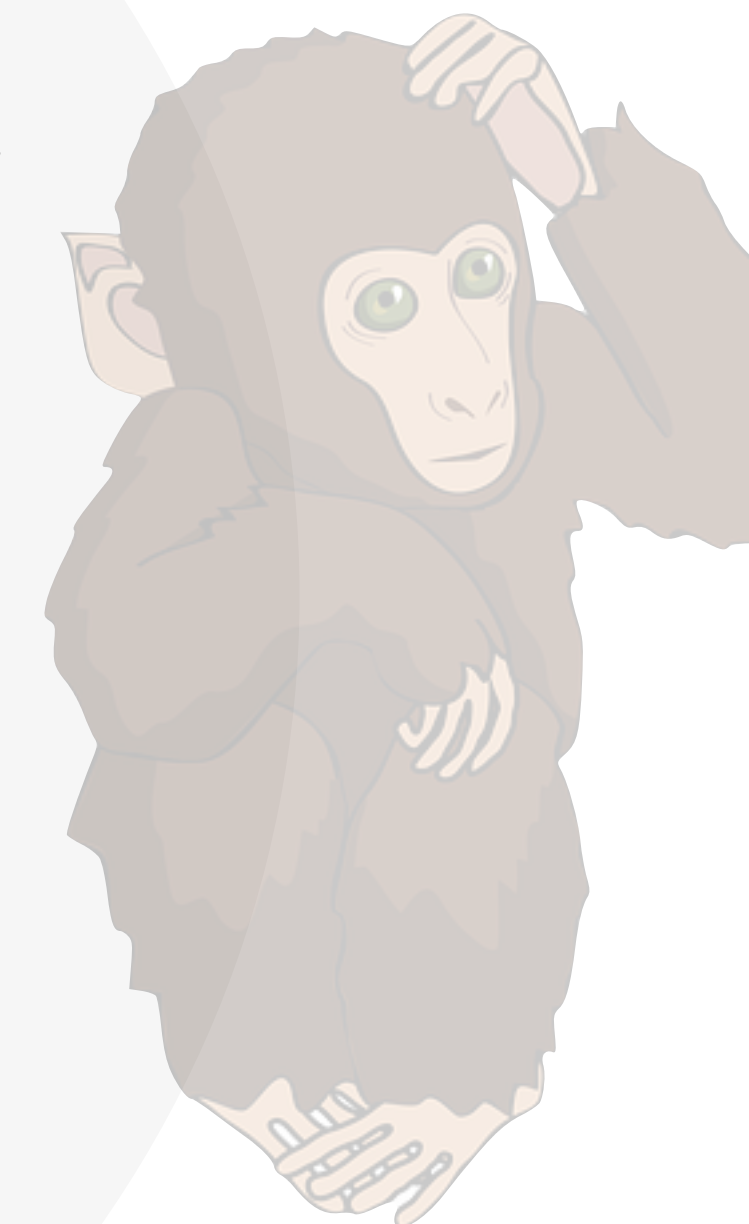


# Research questions of interest

**Goal 1:** Determine if humans can flexibly perceive tactile motion in different proprioceptive states and reference frames?

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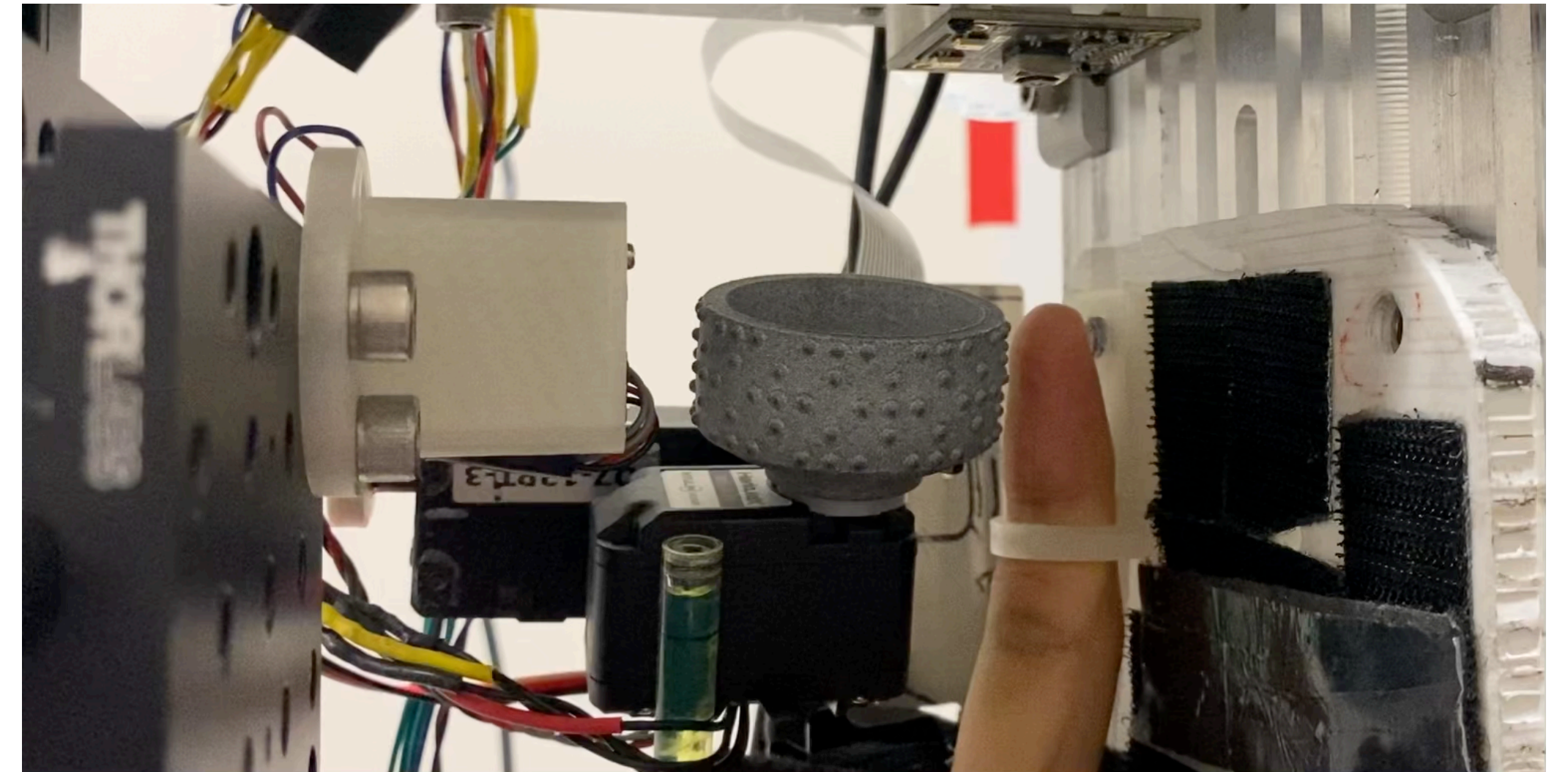
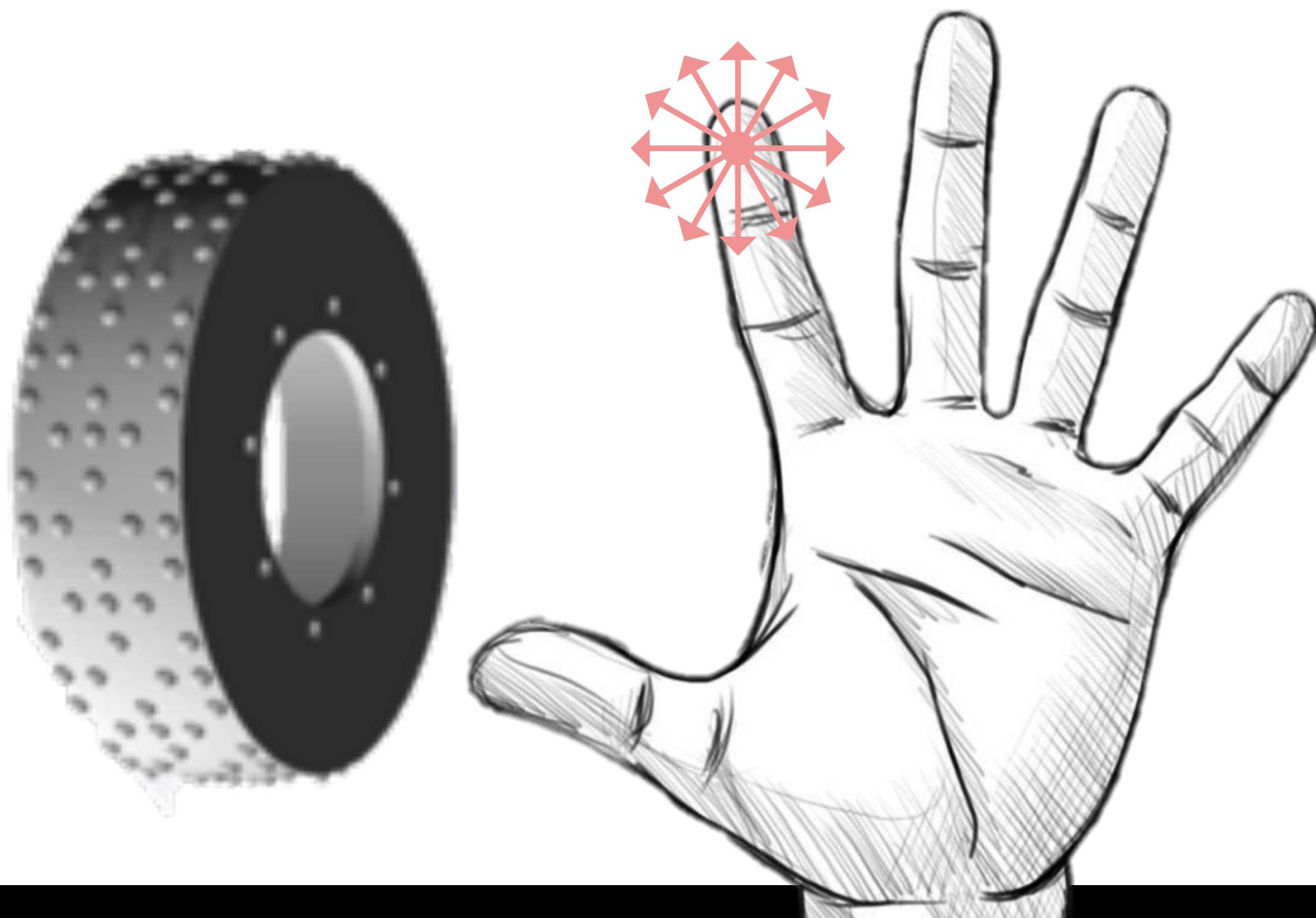


# Experiment Design: Stimulus Properties

## Dot Motion Stimulus

Direction: 0-360°, steps of 30°

Point of Stimulation: Digit 2



# Experiment Design: 2-AFC Motion Direction Discrimination

Two reference frames: Sternum-Centric and Finger-Centric

Two-Alternate Force Choice Motion Direction discrimination

**LEFT vs RIGHT**

w.r.t the center of the body



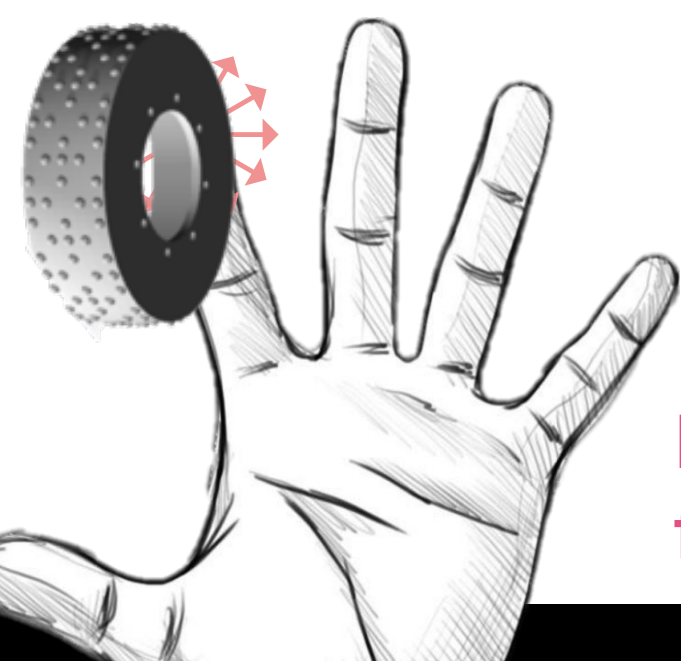
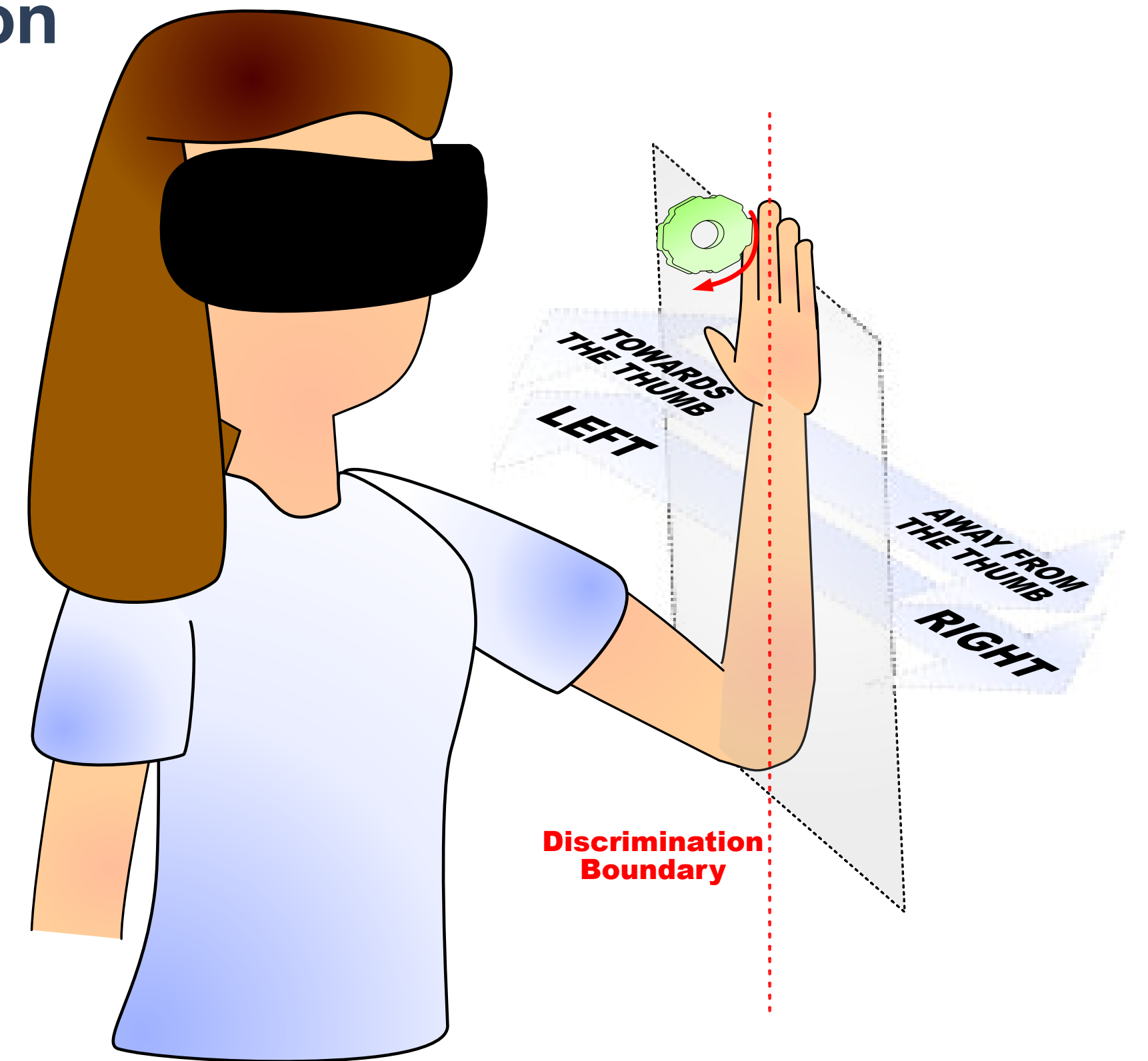
**Sternum-Centric Reference Frame**

**AWAY vs TOWARDS**

the thumb-edge of the palm



**Finger-Centric Reference Frame**



Dot Motion Stimulus at D2  
for 2 seconds, steps of 30 degrees.

# Experiment Design: Three Proprioceptive States

## 2-AFC Motion Discrimination Task



Sternum-Centric Reference Frame

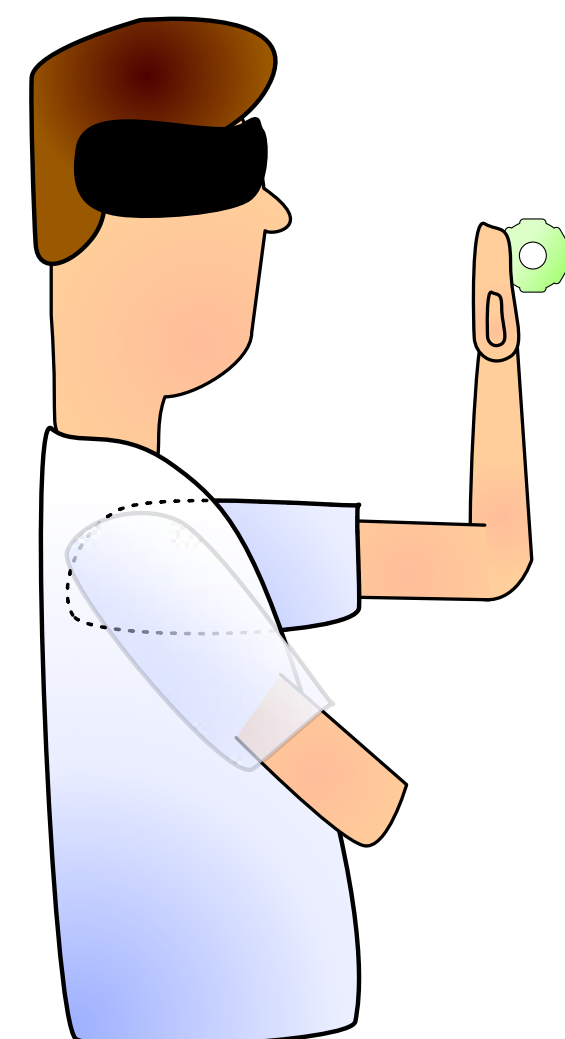
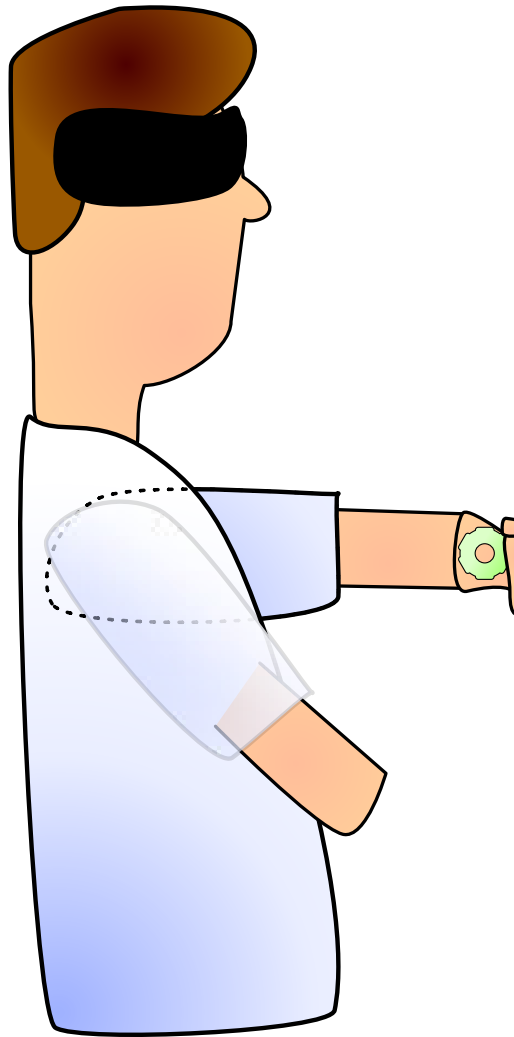
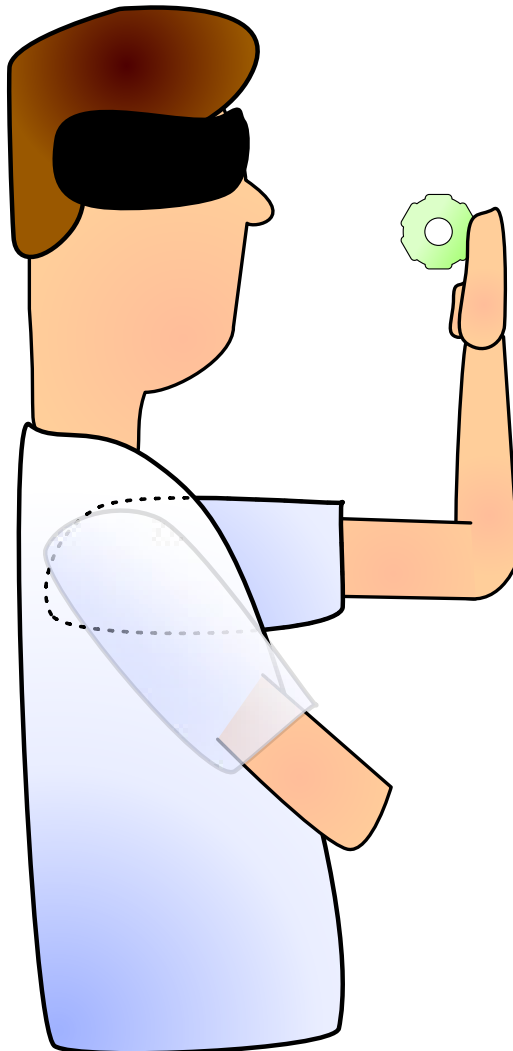


Finger-Centric Reference Frame

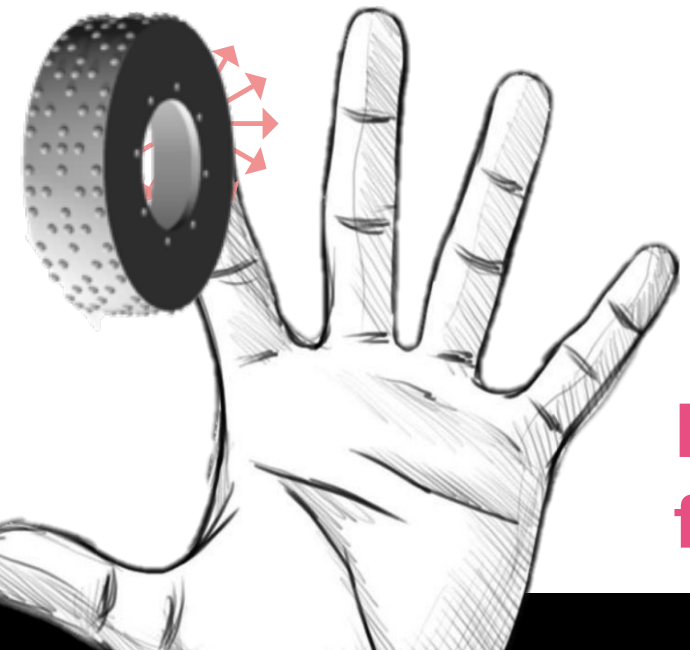
Vertical (V)

Horizontal (H)

Inverted Vertical (I)



Three proprioceptive states (postures)



Dot Motion Stimulus at D2 for 2 seconds, steps of 30 degrees.

# Experiment Design: Trial timeline

## 2-AFC Motion Discrimination Task

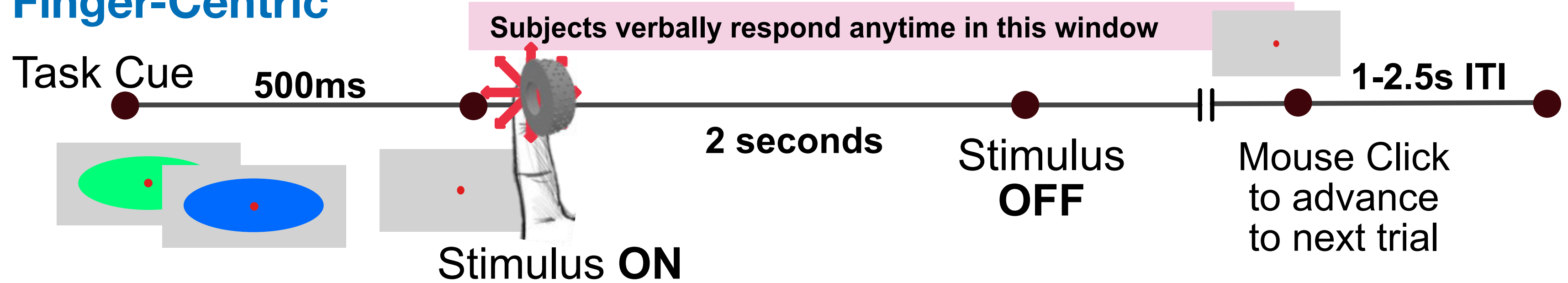


Sternum-Centric Reference Frame

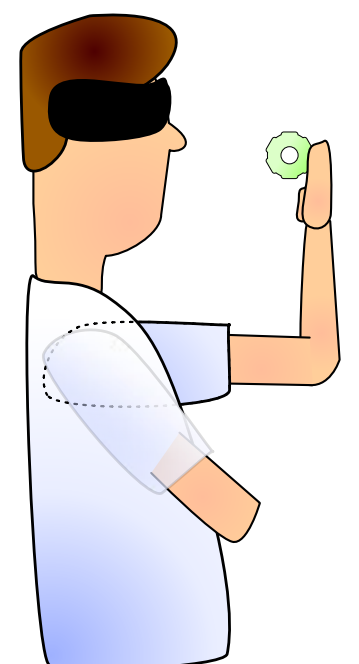


Finger-Centric Reference Frame

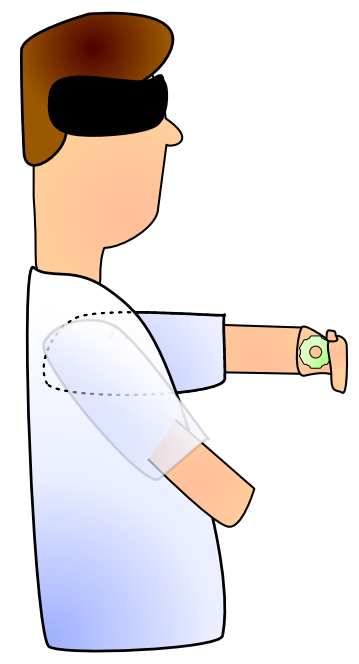
### Sternum-Centric/ Finger-Centric



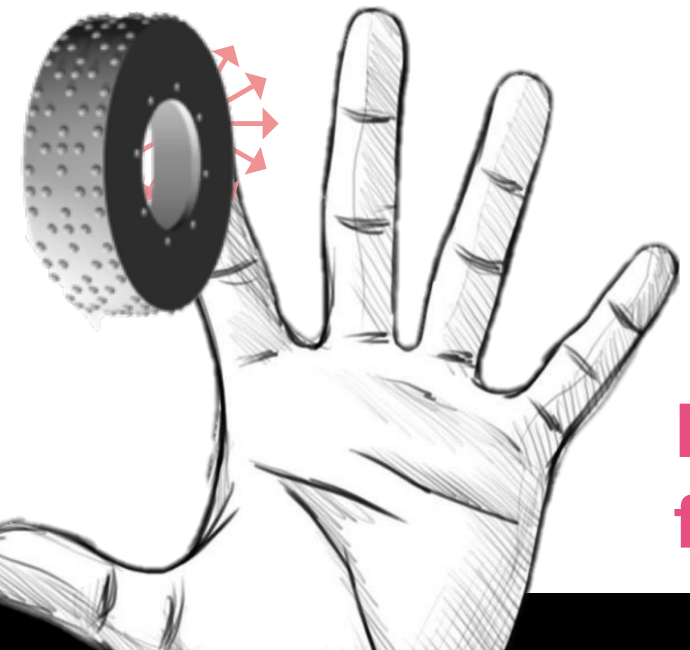
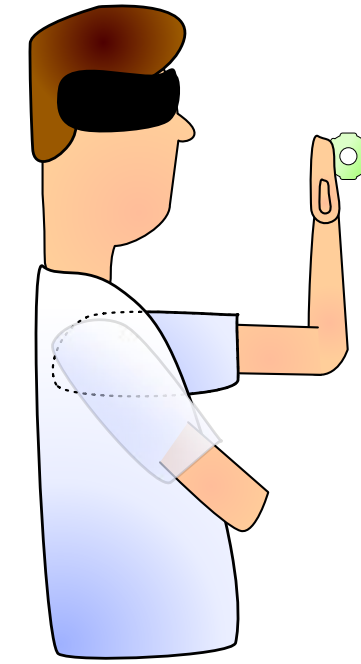
### Vertical (V-O)



### Horizontal (H-O)

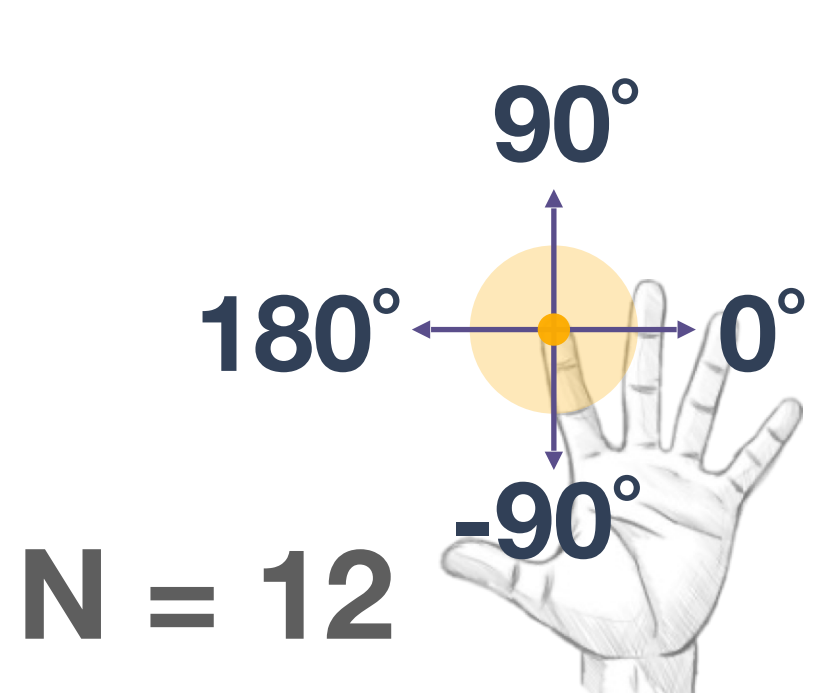
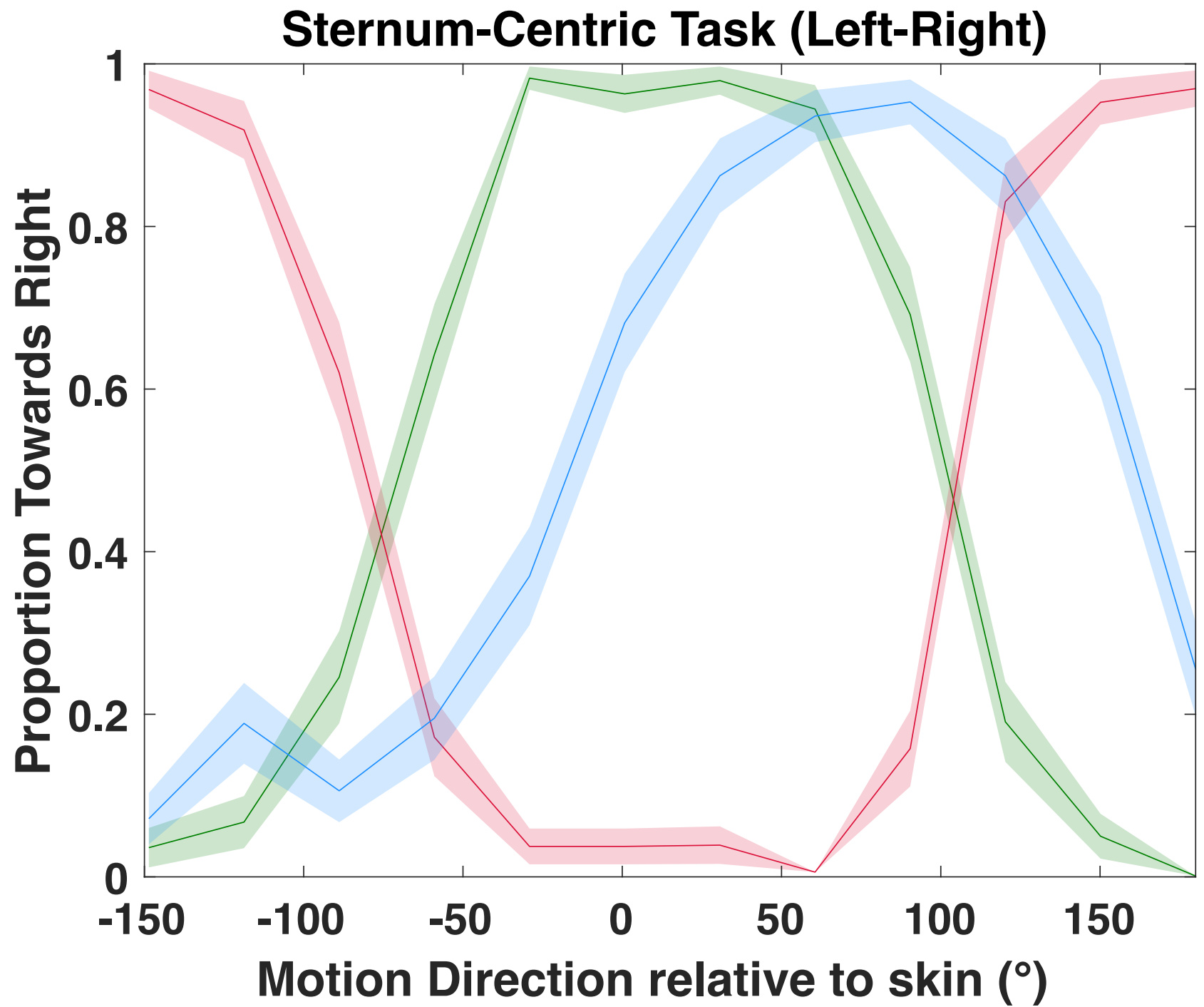
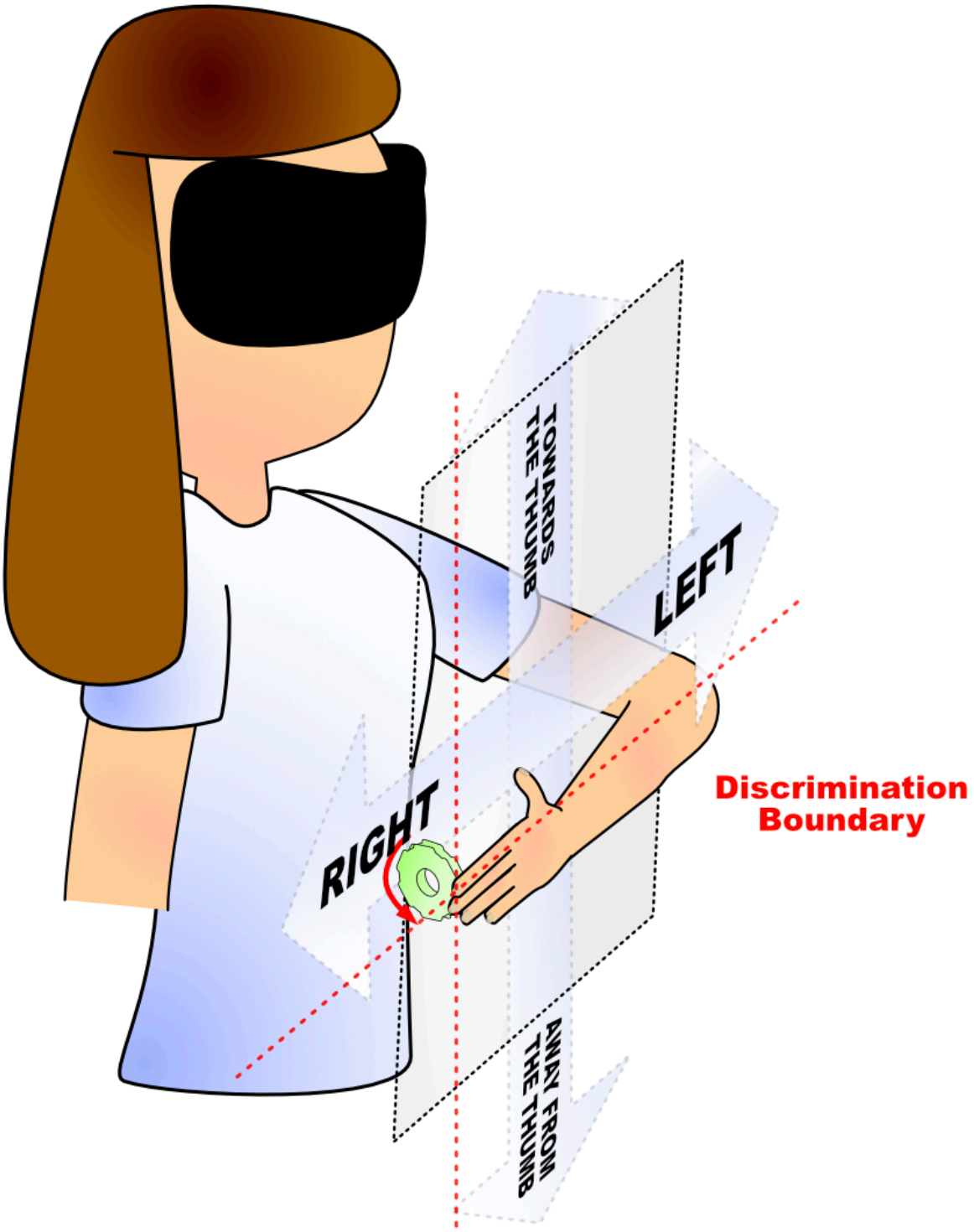
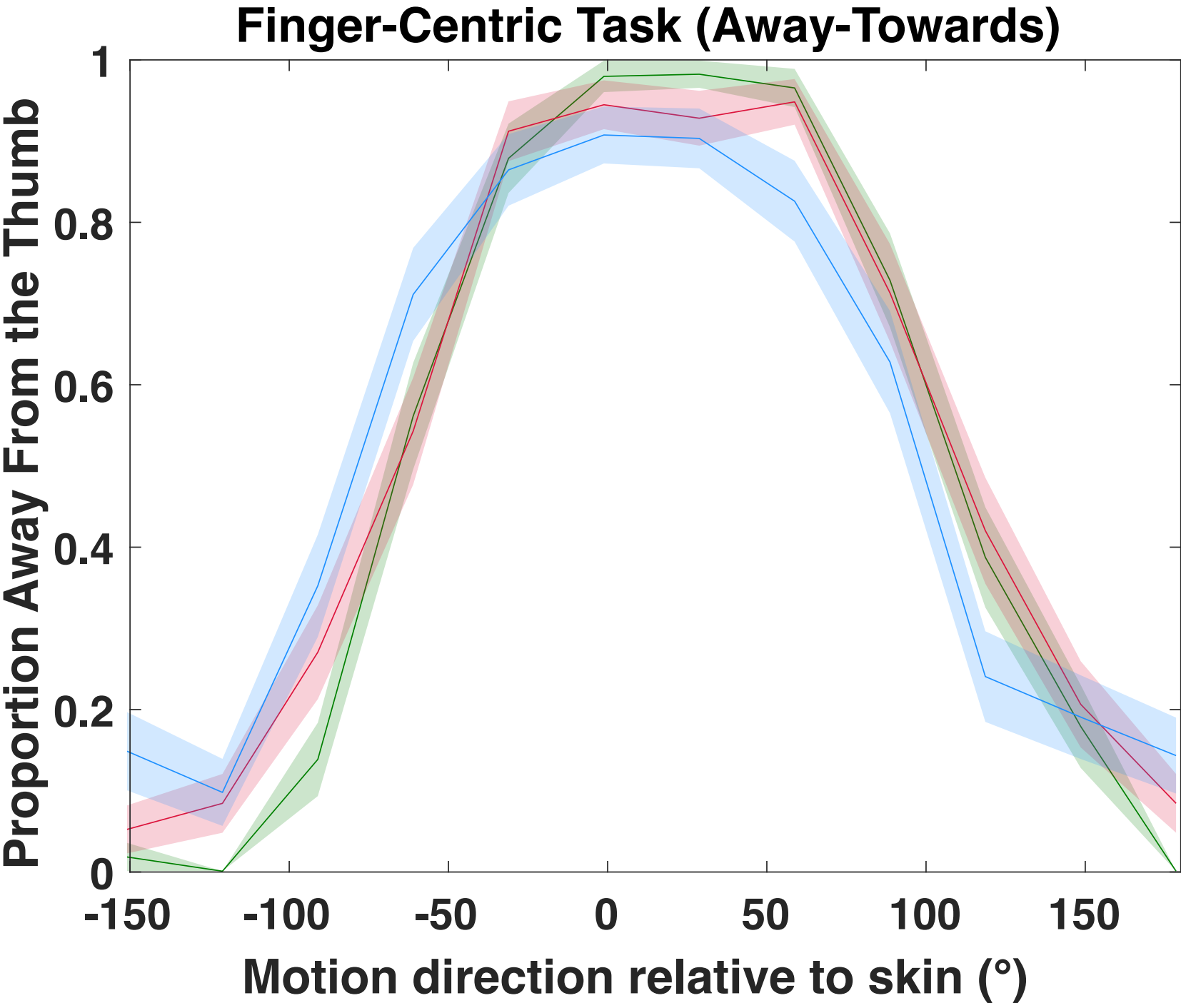


### Inverted Vertical (I-O)

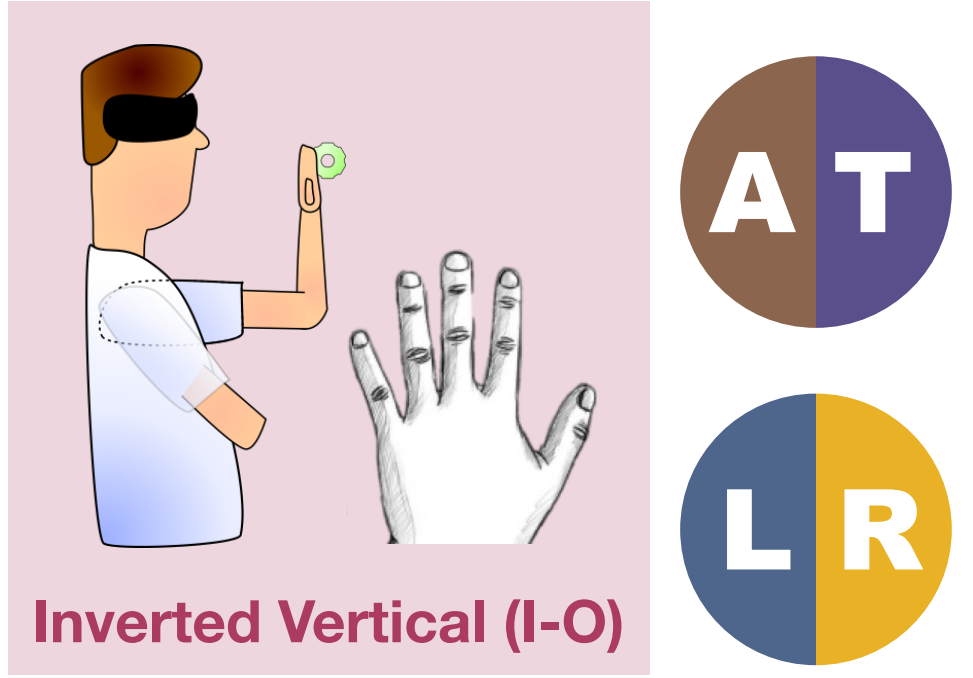
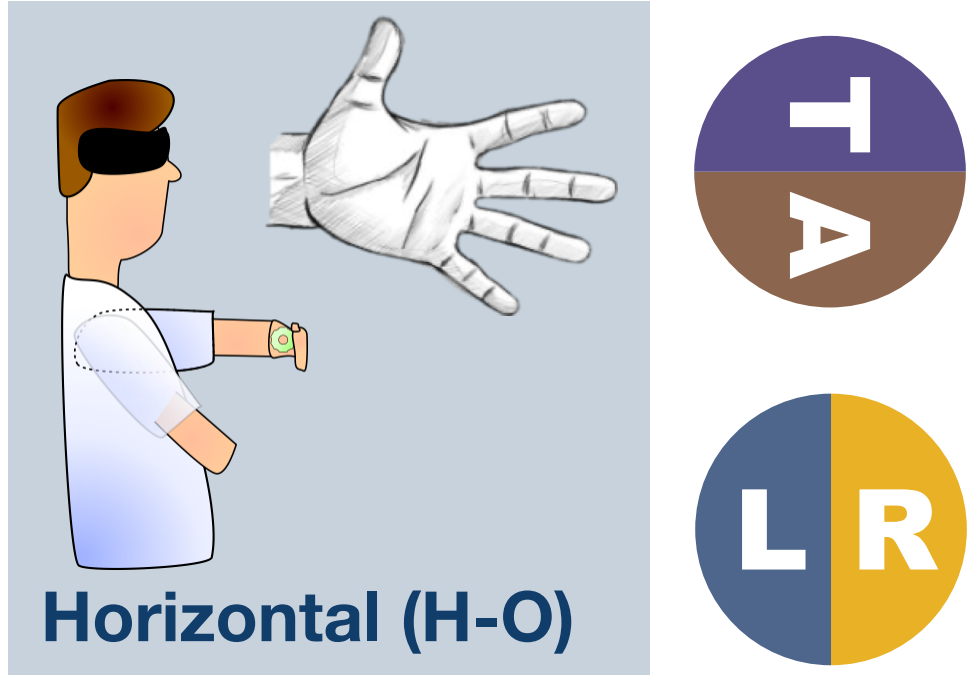
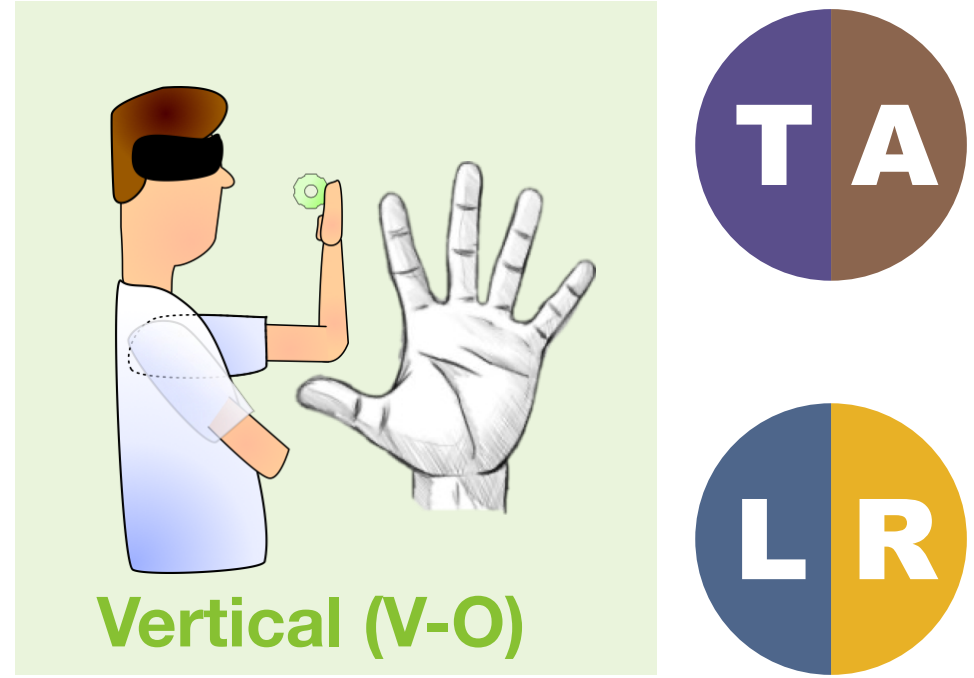


Dot Motion Stimulus at D2 for 2 seconds, steps of 30 degrees.

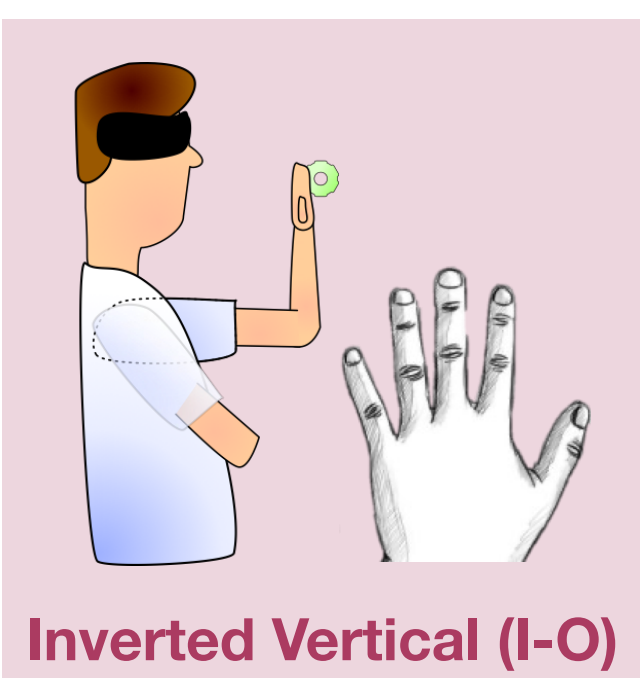
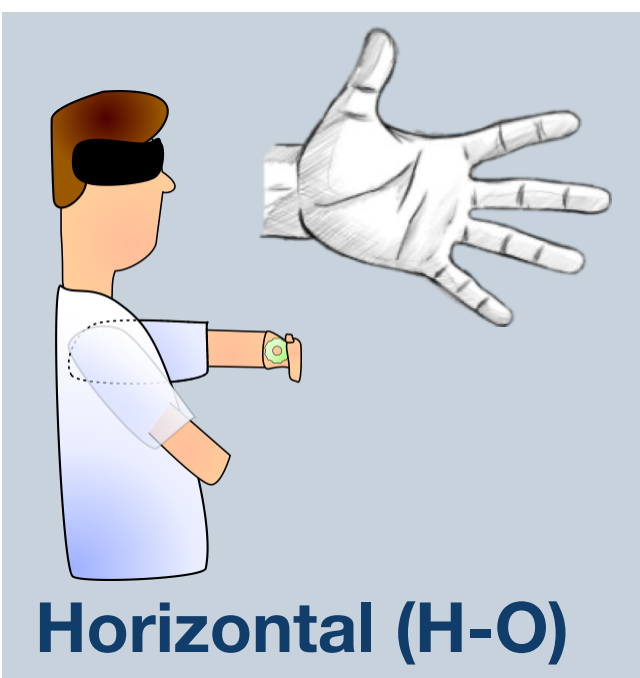
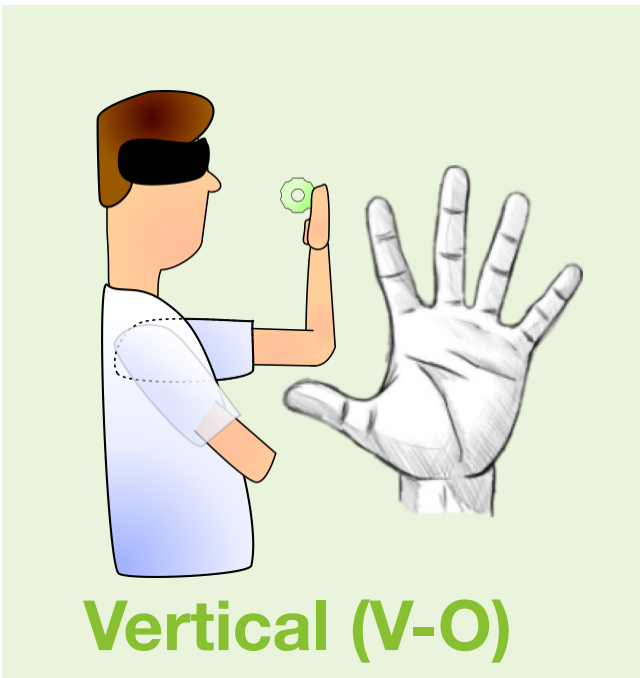
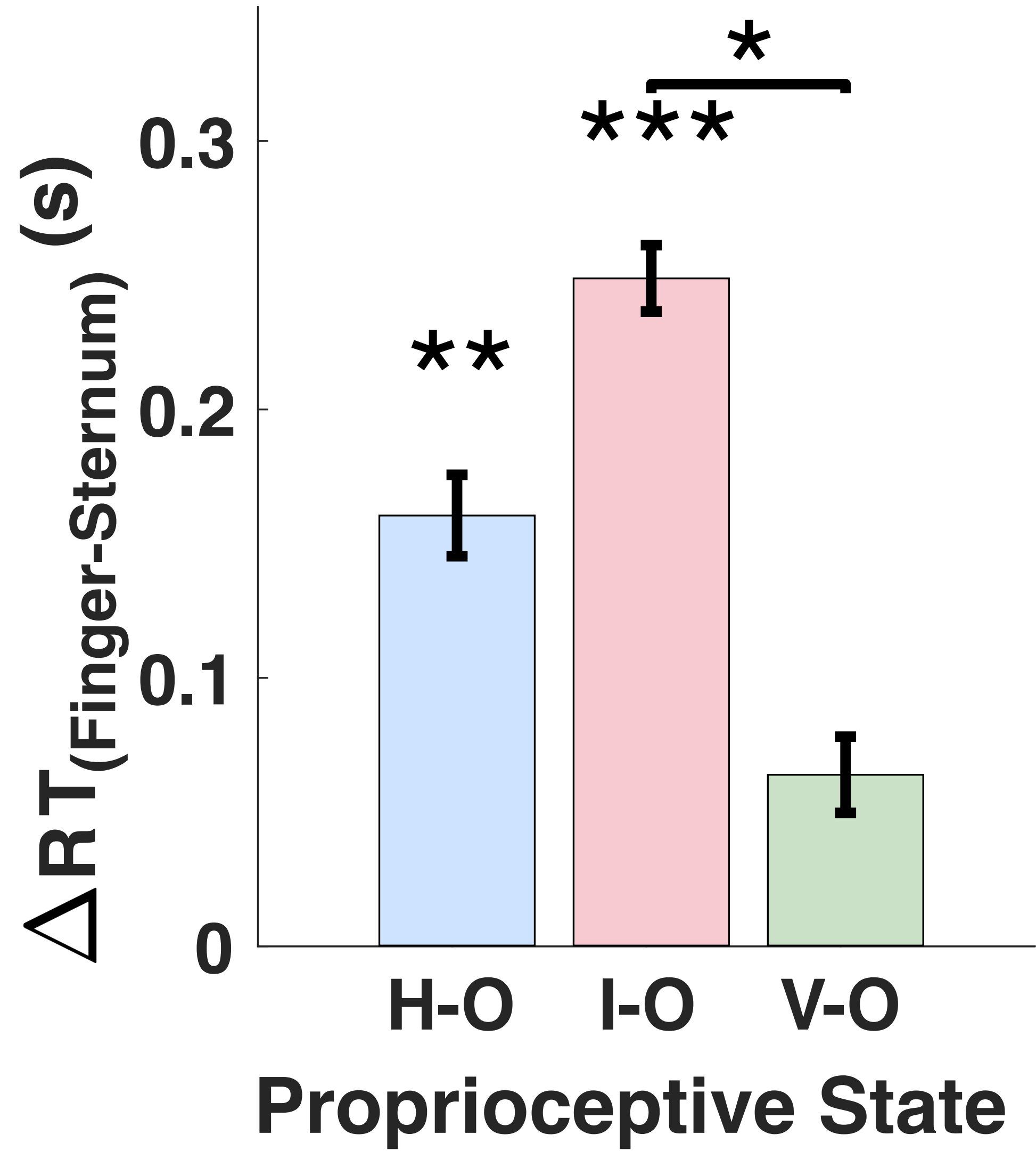
# Subjects flexibly perceive motion in two reference frames



N = 12

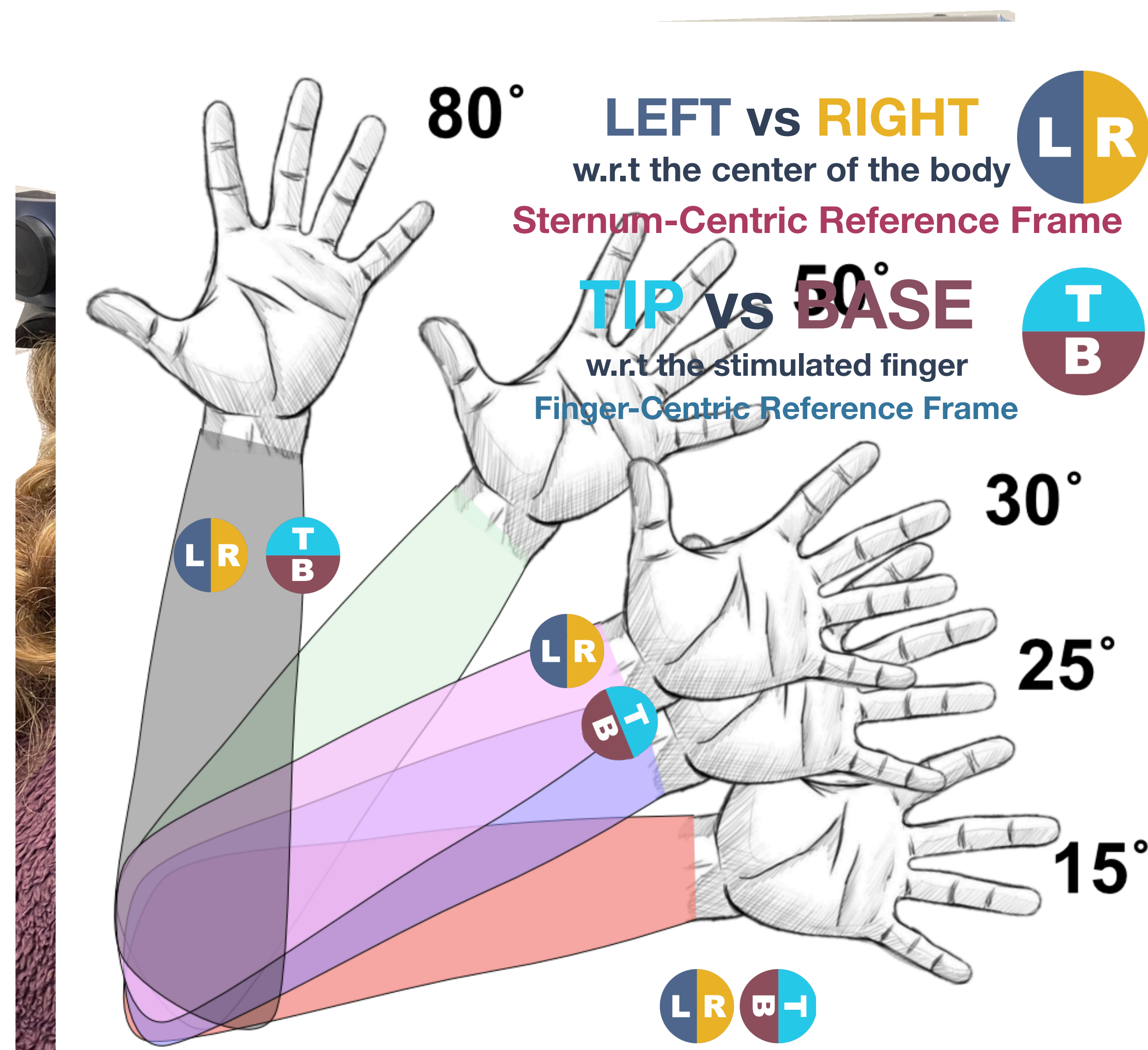


# Sternum-centric motion judgements are readout faster

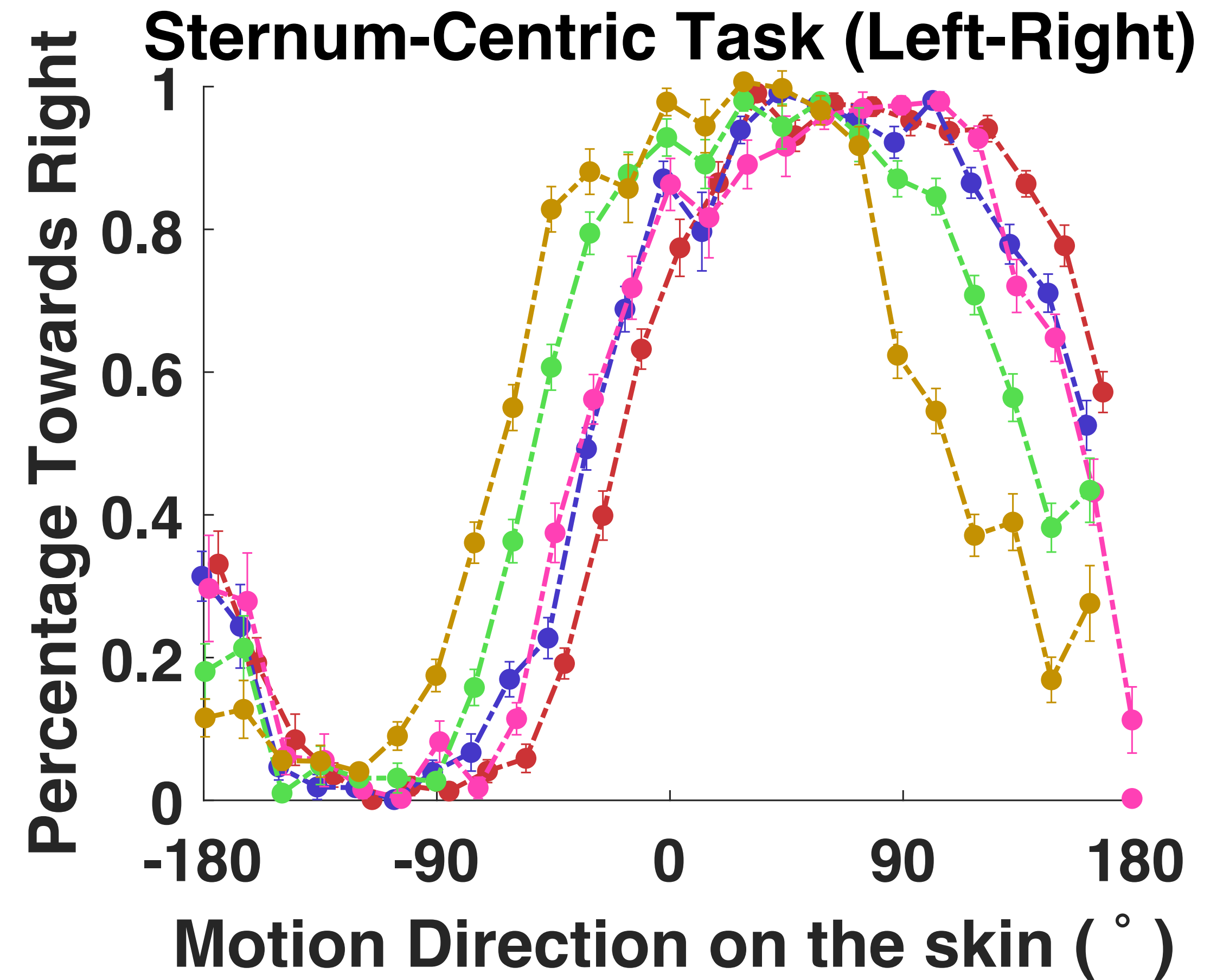
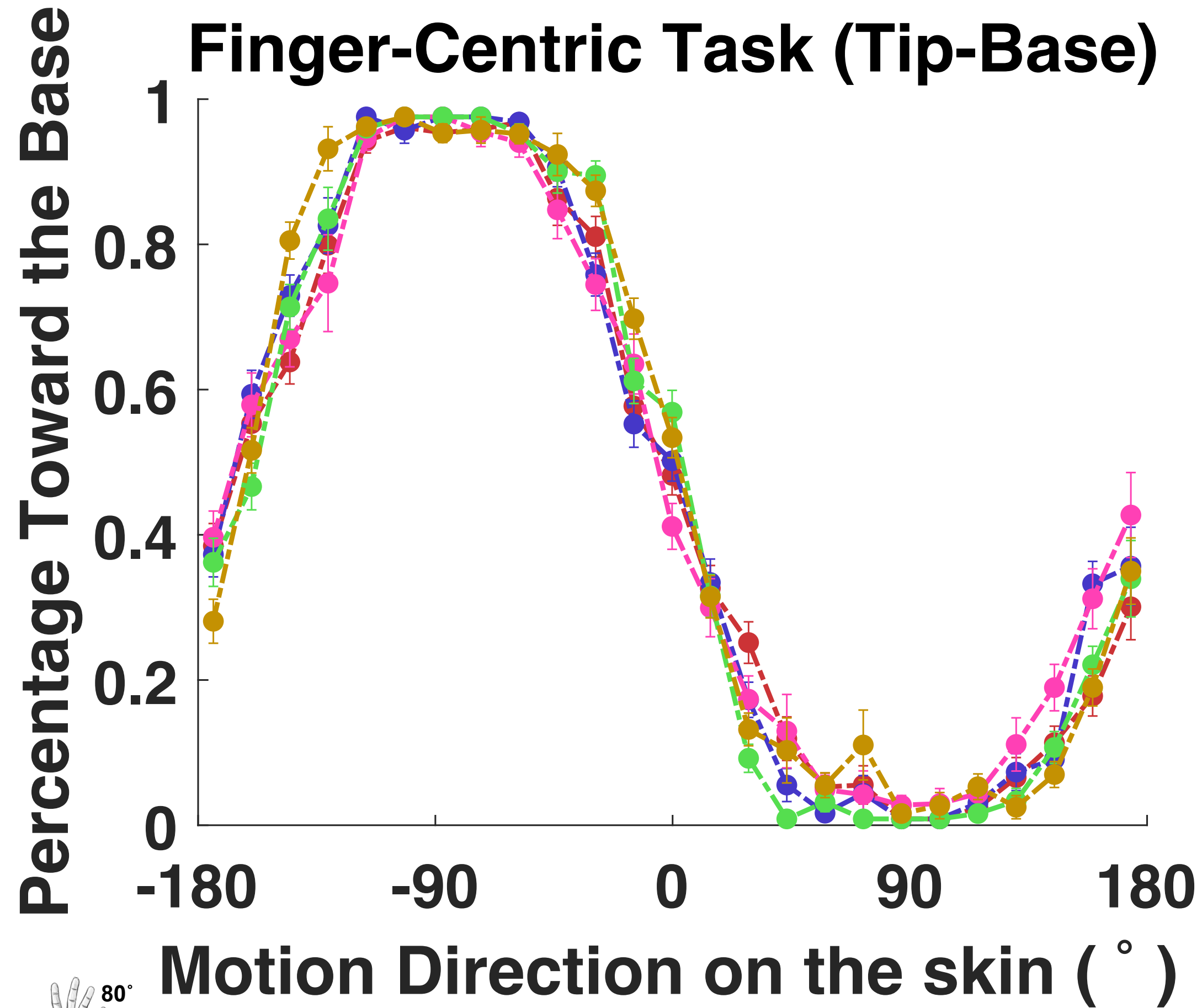


# Motivations for an enhanced experiment design

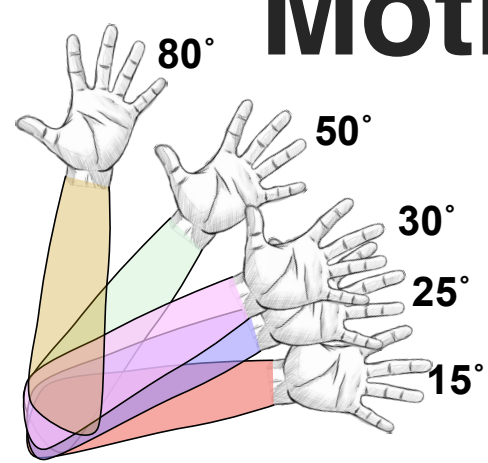
- Strategize associations between the discrimination boundaries at a blocked posture.
  - ➔ **Modulate proprioceptive state on each trial**
  - ➔ **Generalize observations to other coordinate systems.**
- Low number of individual subject trials
  - ➔ **Sensitivity of motion discrimination in different coordinate systems**
  - ➔ **Systematic biases across coordinate systems and proprioceptive states.**



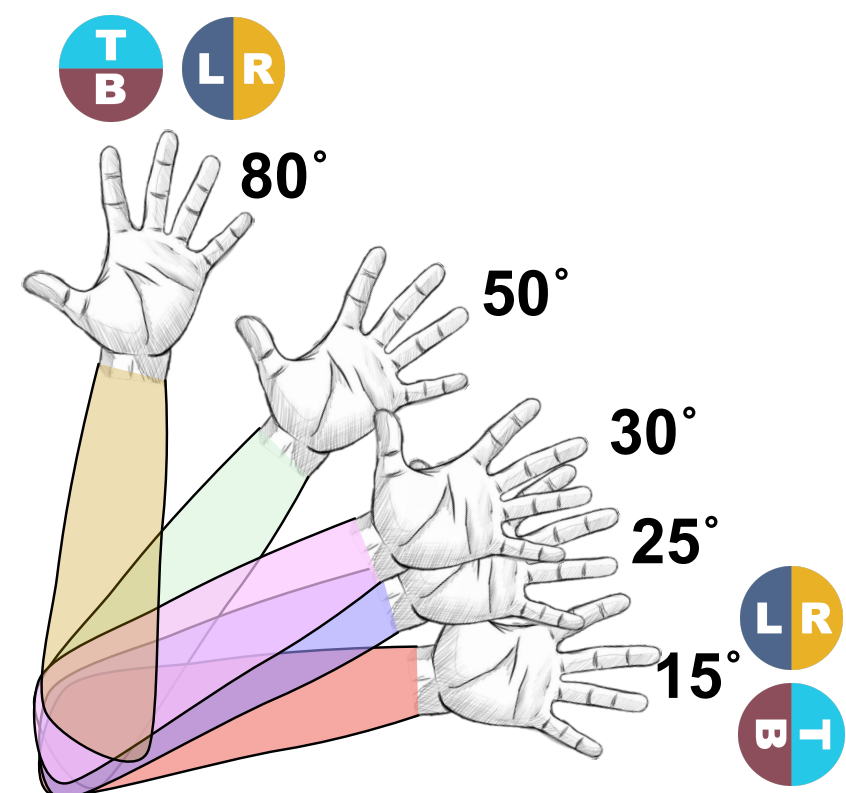
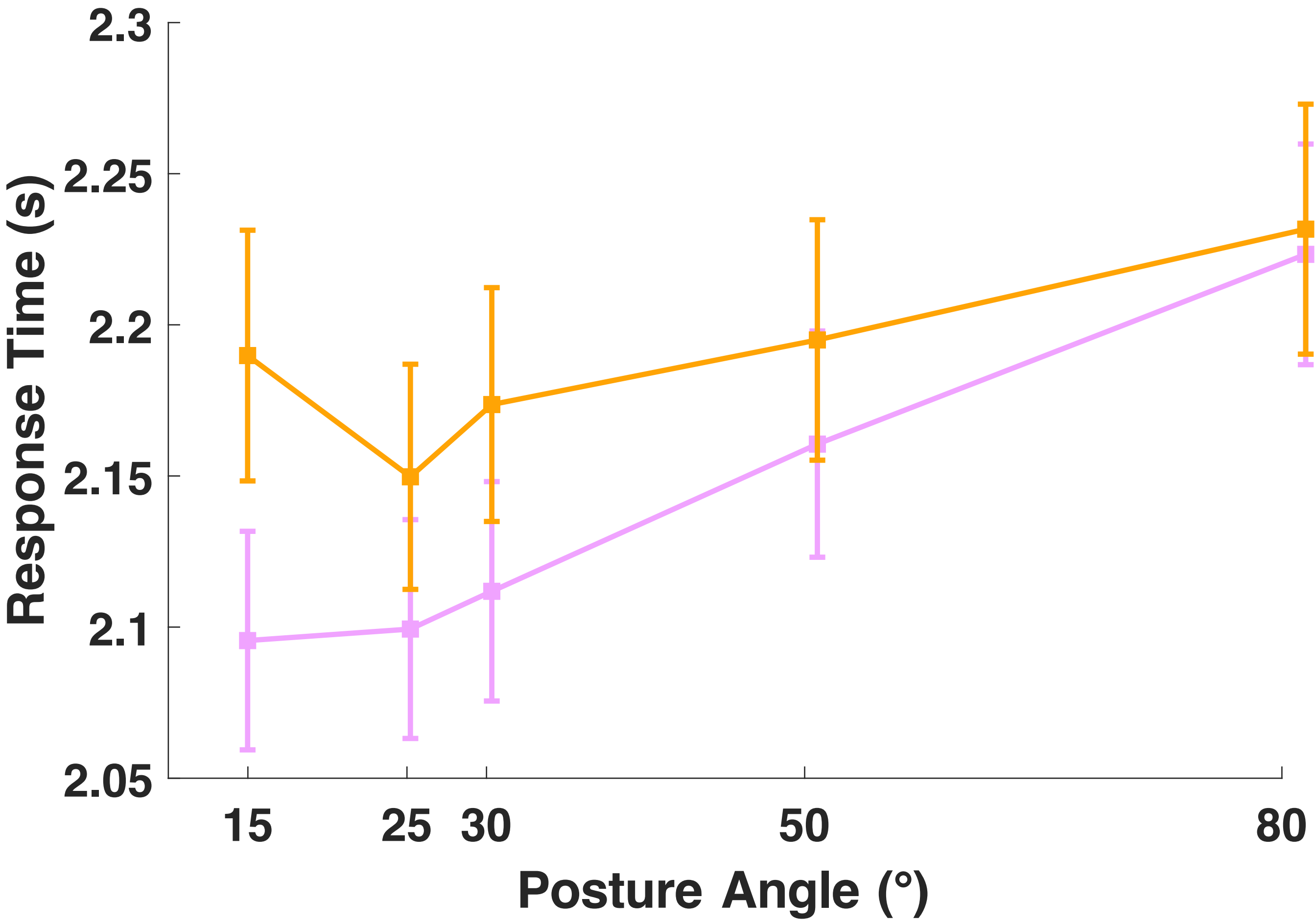
# Proprioception modulates tactile motion perception in a reference frame-dependent manner



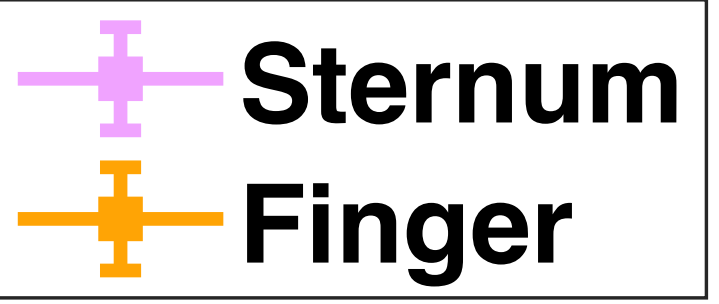
N = 14



# Faster readout in the sternum-centric condition

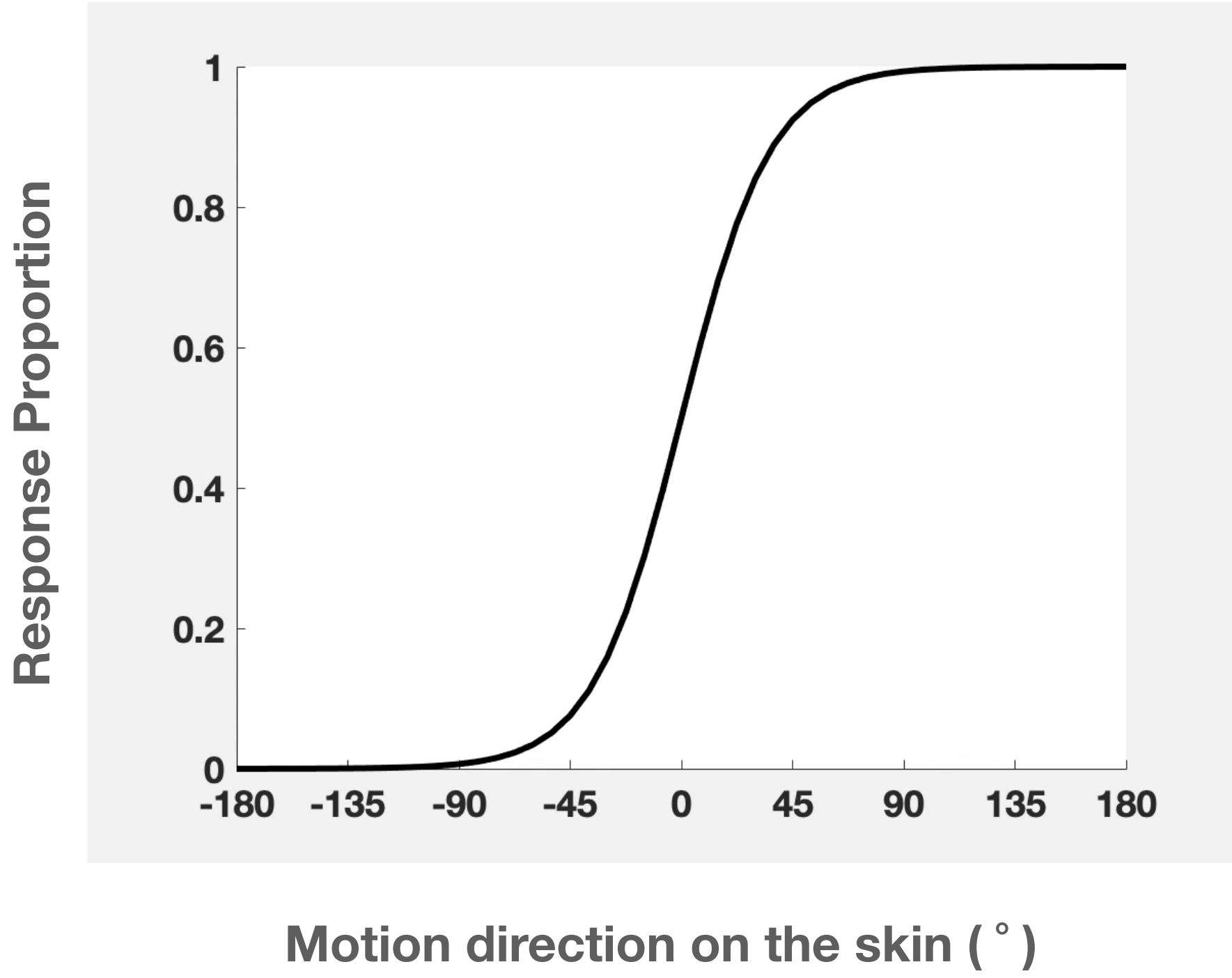


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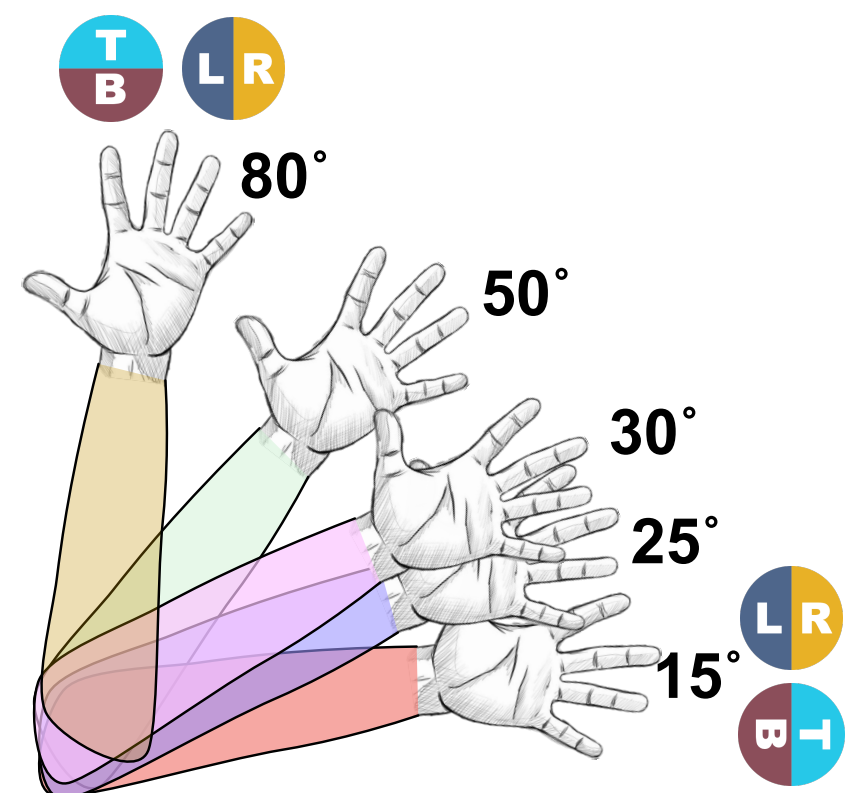
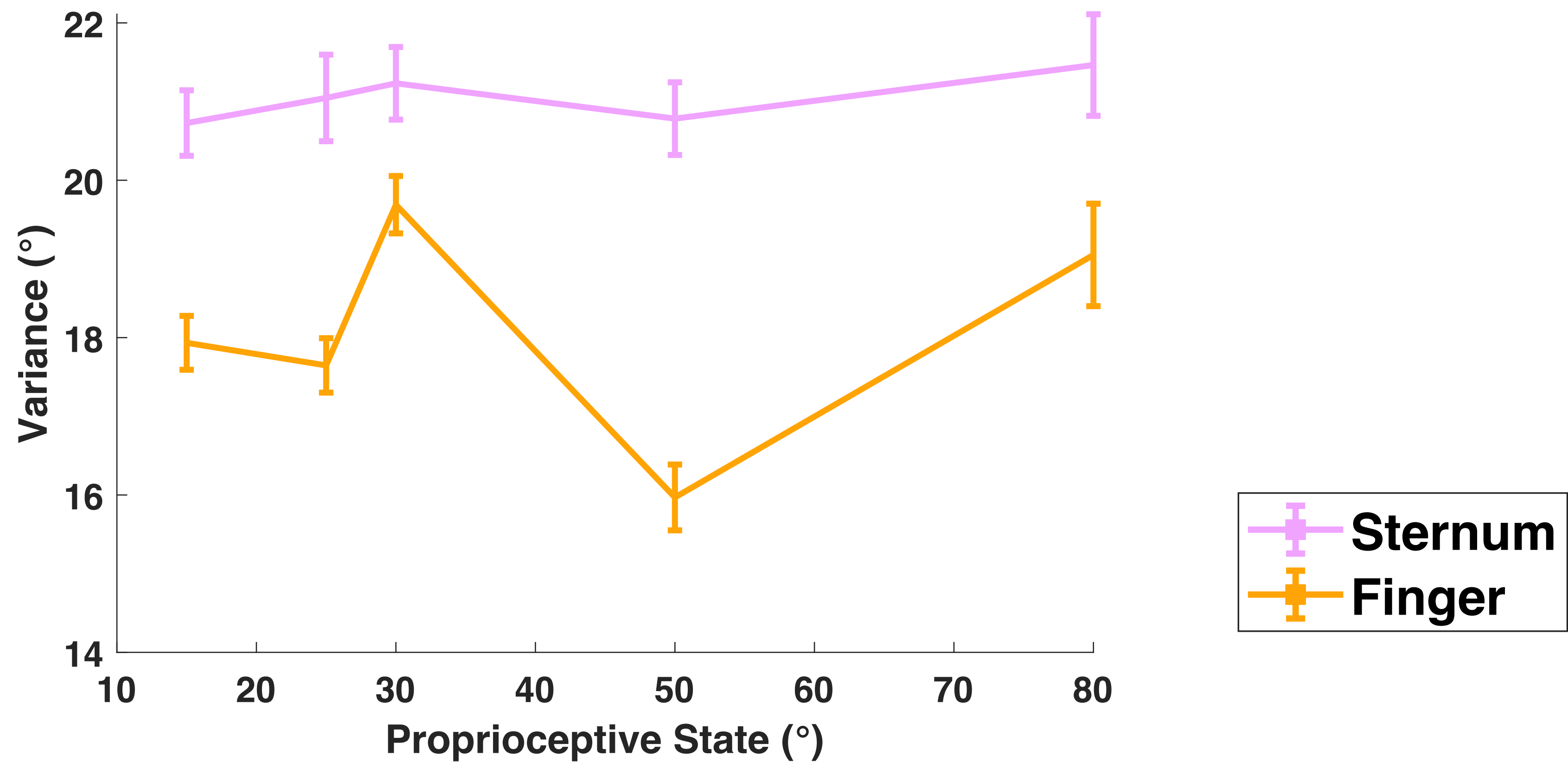
# Variance of the psychometric curve

Lower Variance = Increased Discrimination Sensitivity



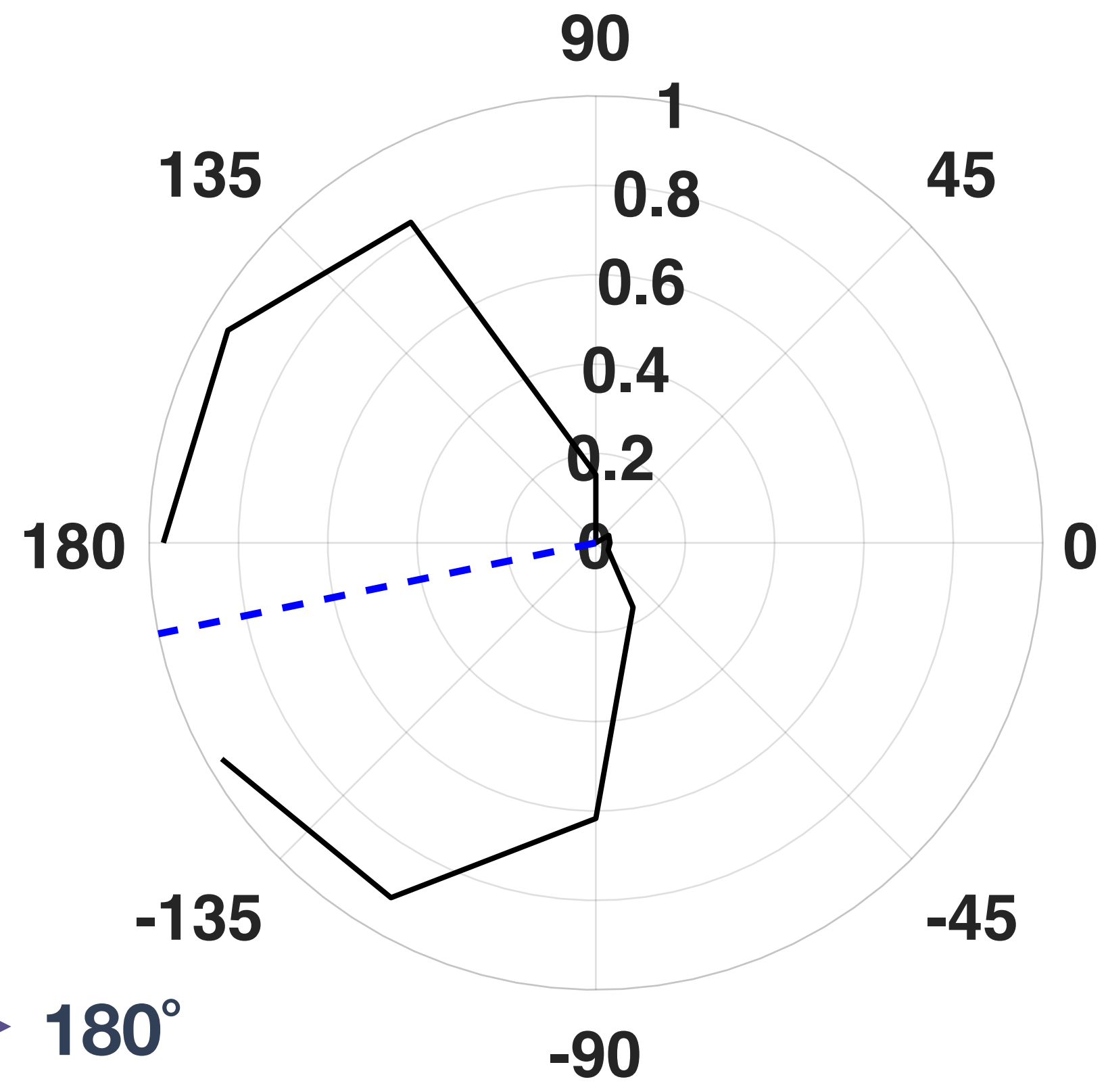
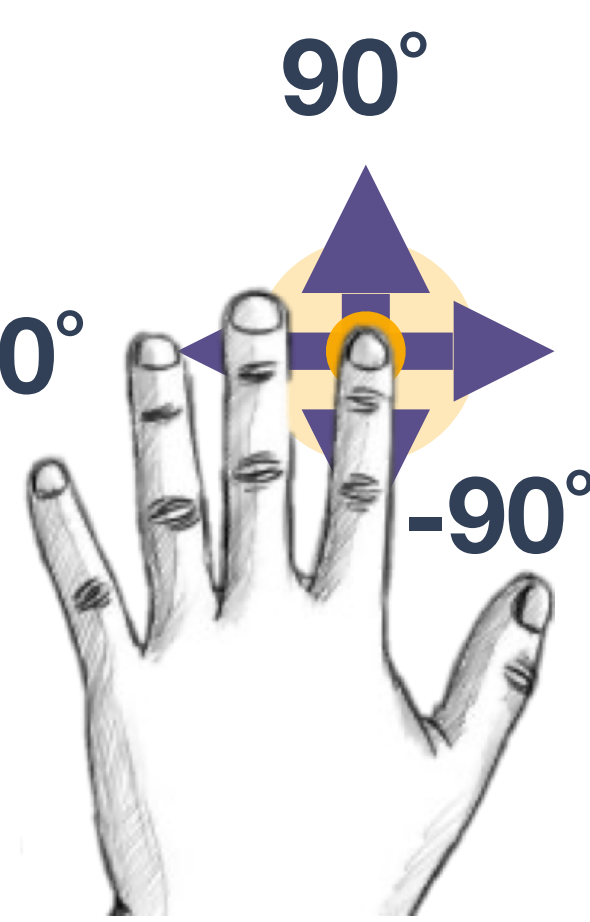
N = 14

# Sternum-centric reference frame has lower discrimination sensitivity

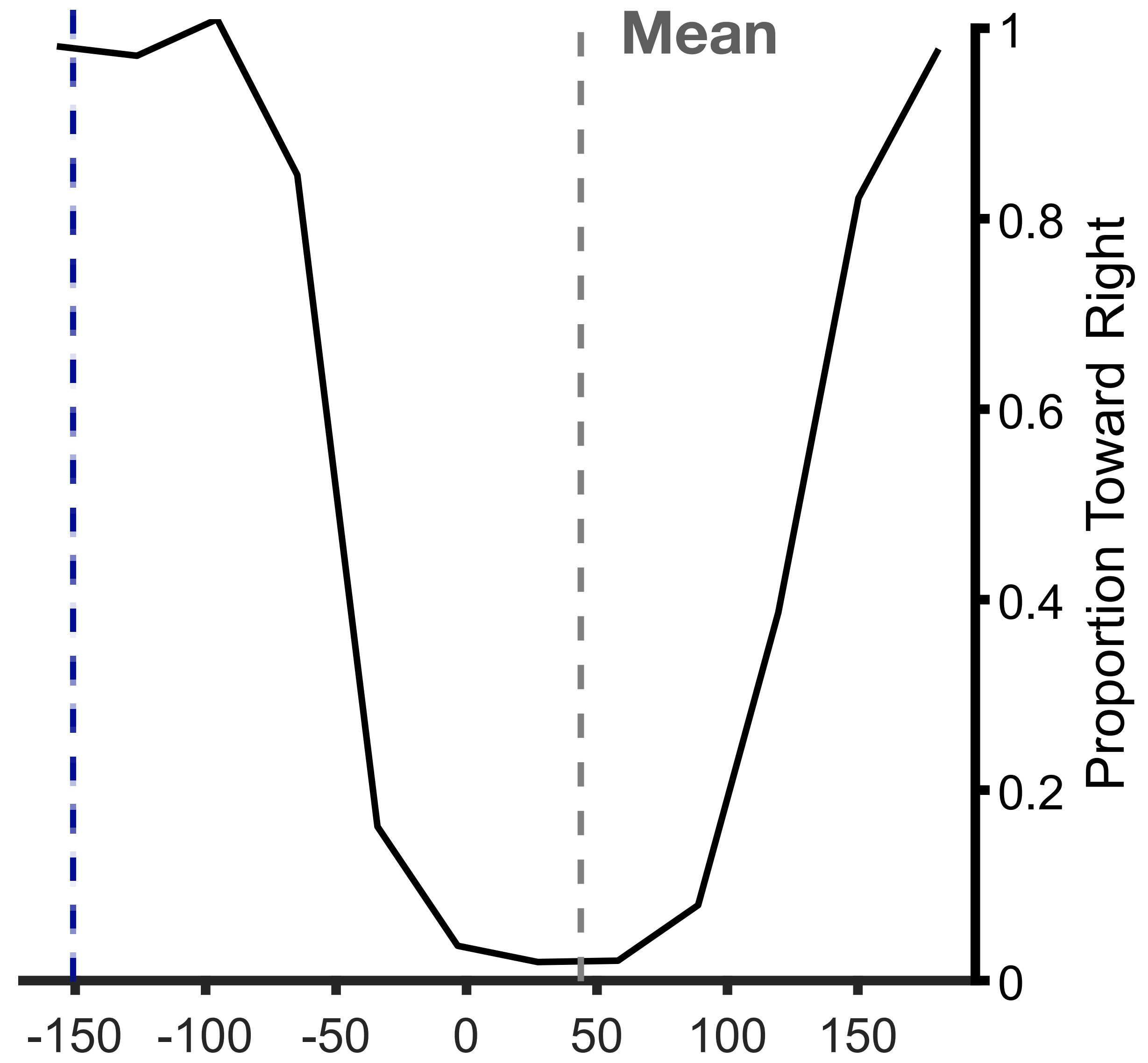


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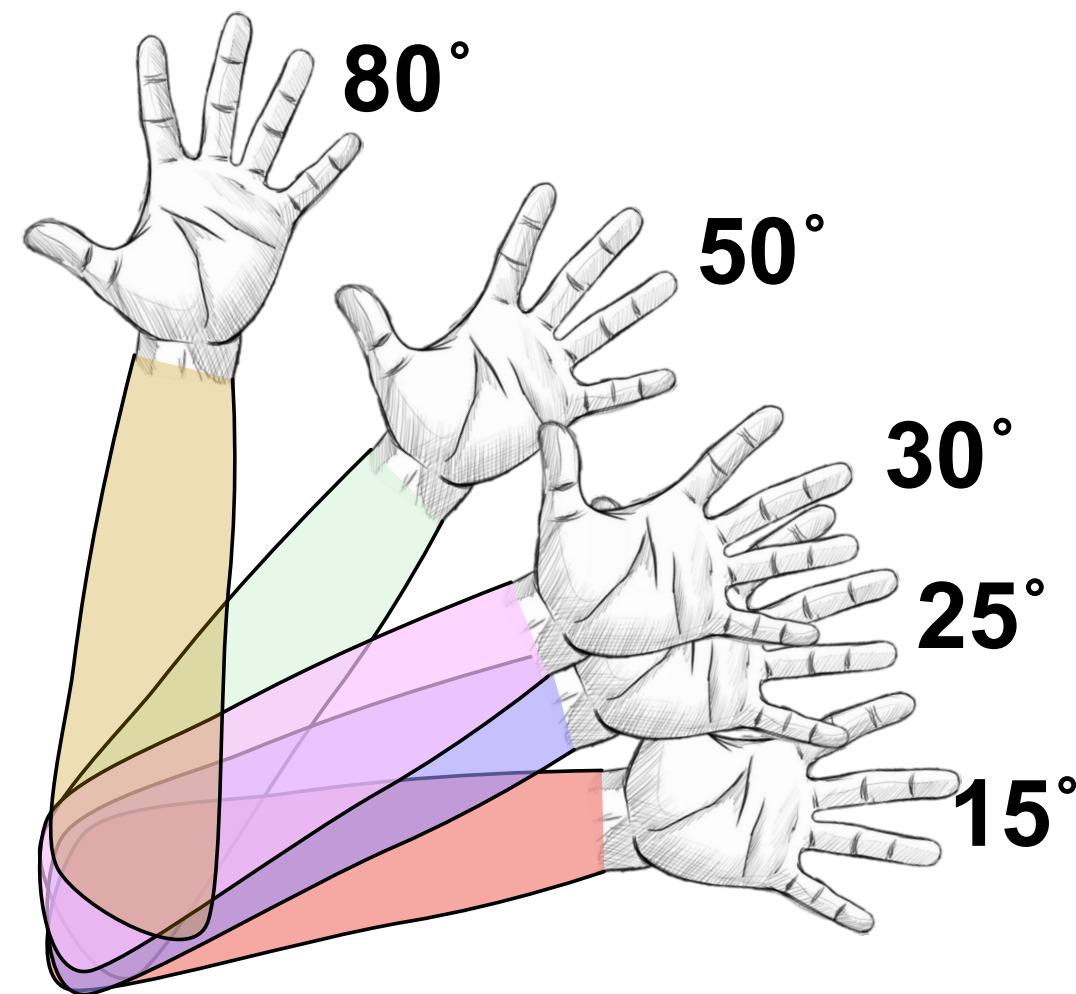
# Understanding Circular mean



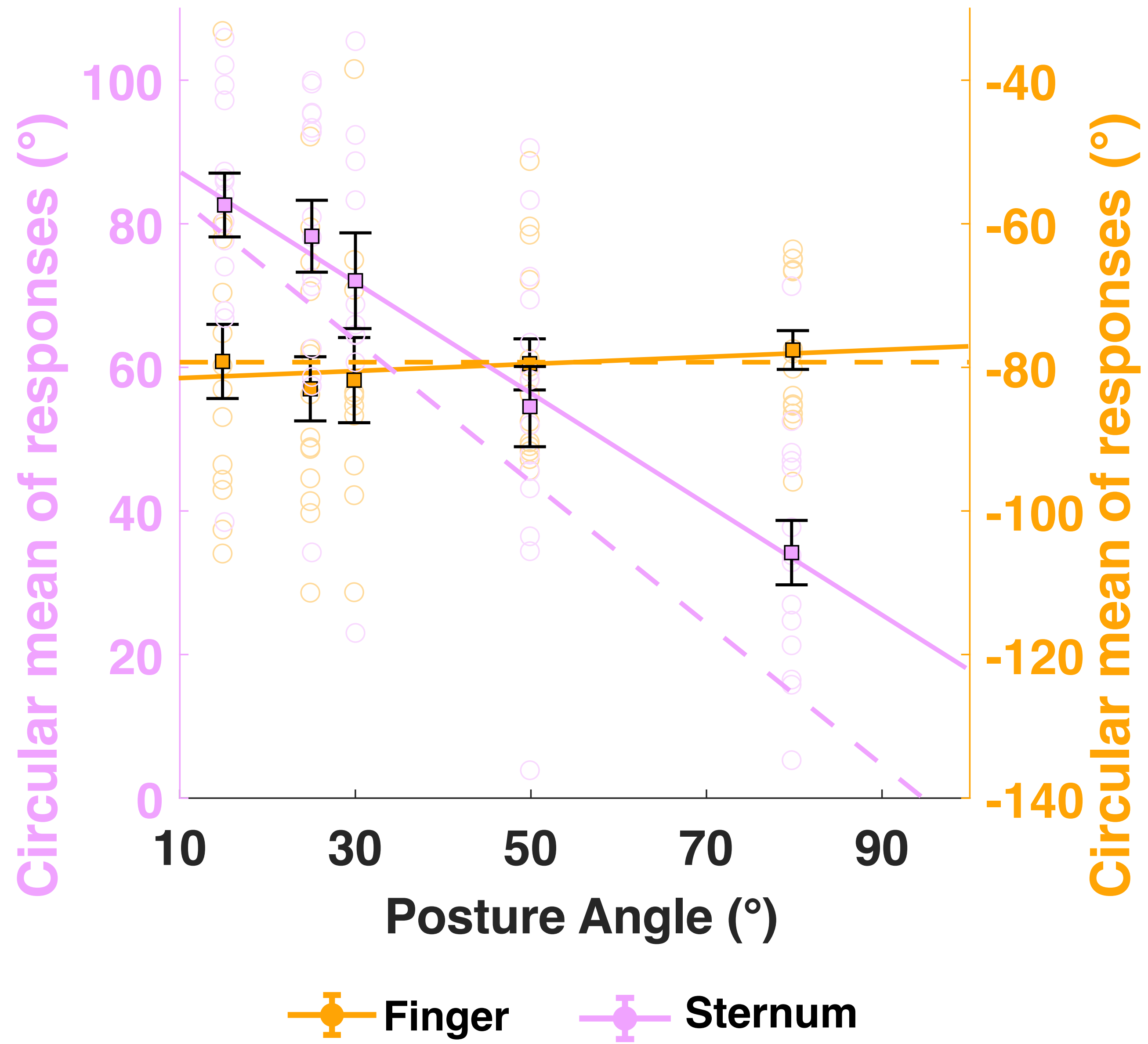
## Circular Mean



# Proprioception biases motion judgement only in the sternum-centric reference frame



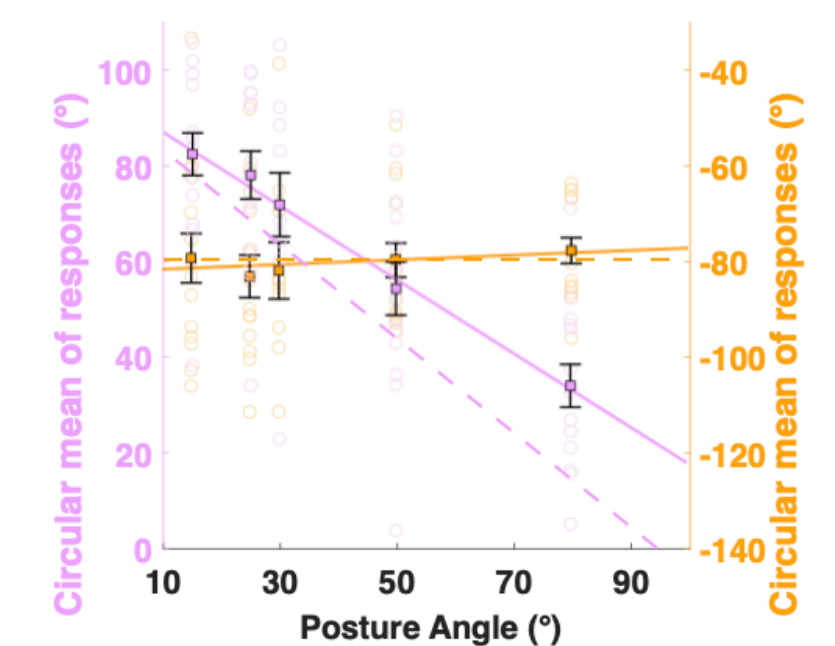
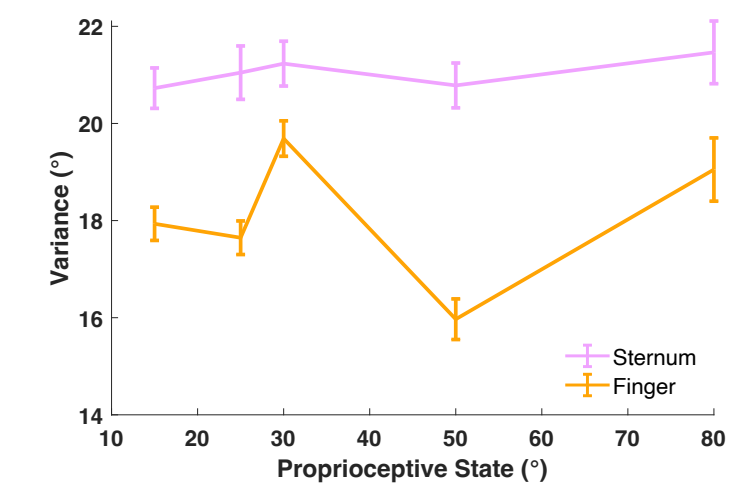
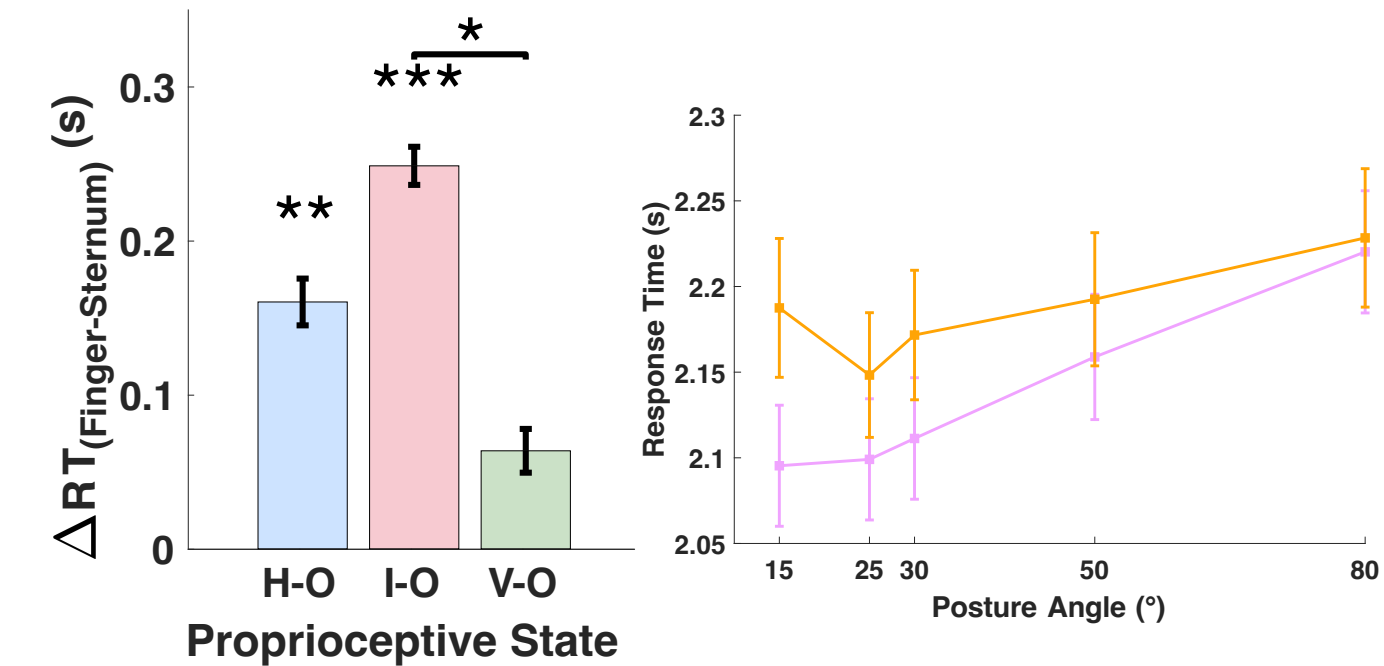
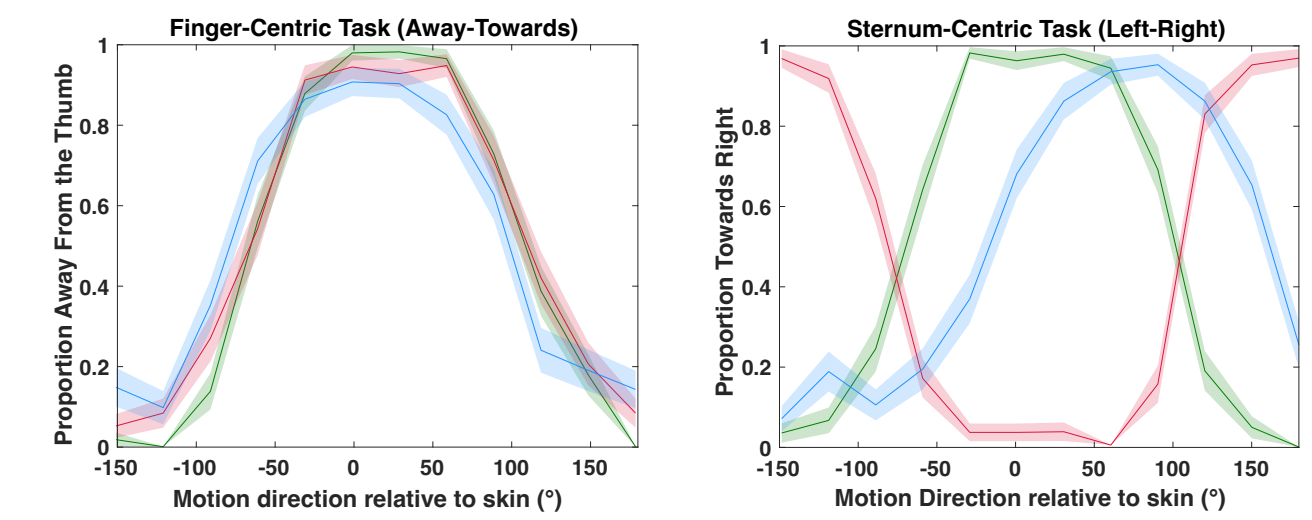
N = 14



# Goal 1: Determine if humans can flexibly perceive tactile motion in different proprioceptive states and reference frames?



- Proprioception modulates tactile motion perception in a reference-frame dependent manner.
- Sternum-centric responses are readout faster.
- Reduced motion discrimination sensitivity in the sternum-centric task indicating proprioceptive noise.
- Proprioception biases motion judgement in a reference-frame dependent manner.

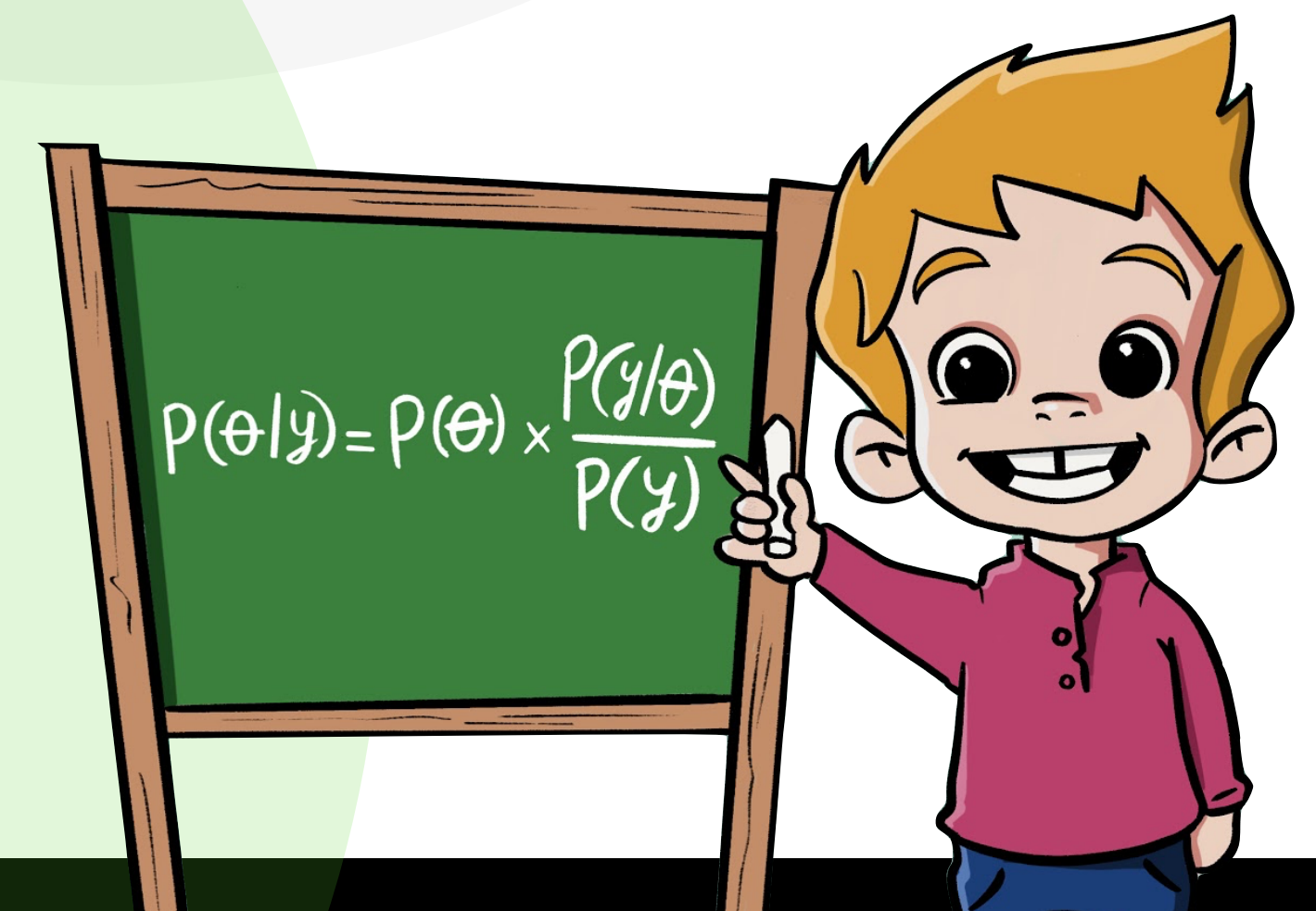
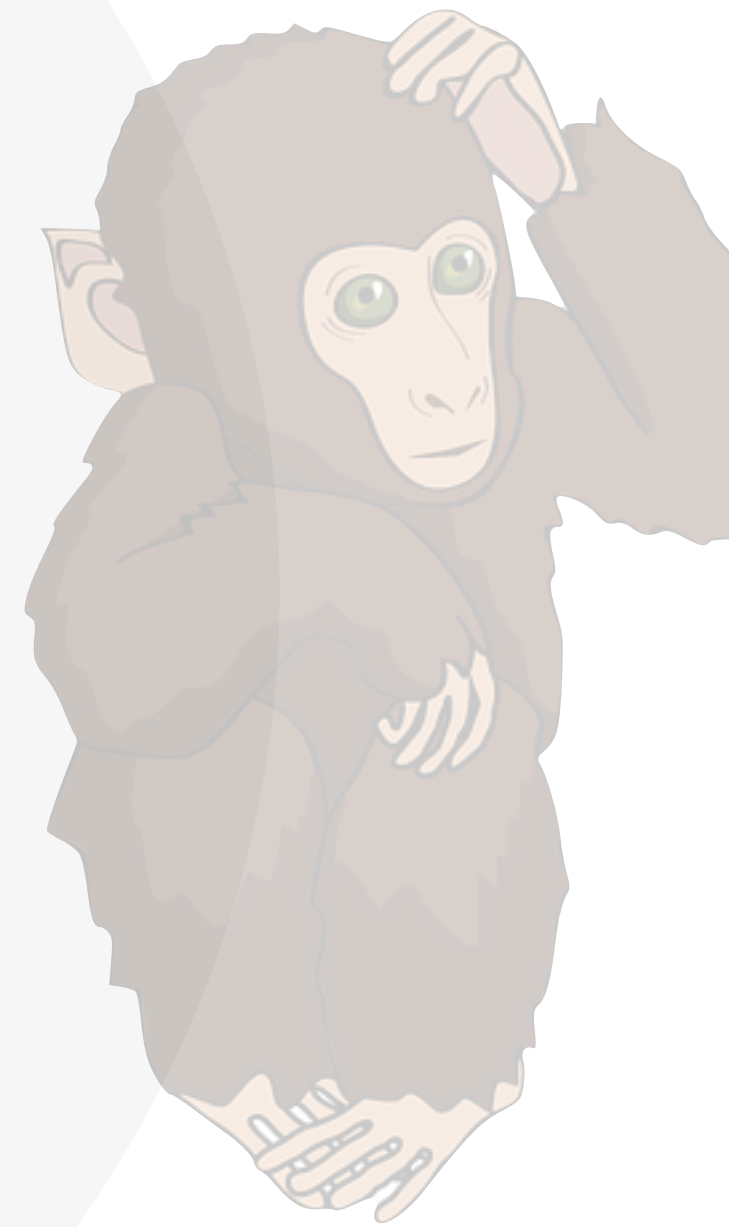


# Research questions of interest

**Goal 1:** Determine if humans can flexibly perceive tactile motion in different proprioceptive states and reference frames?

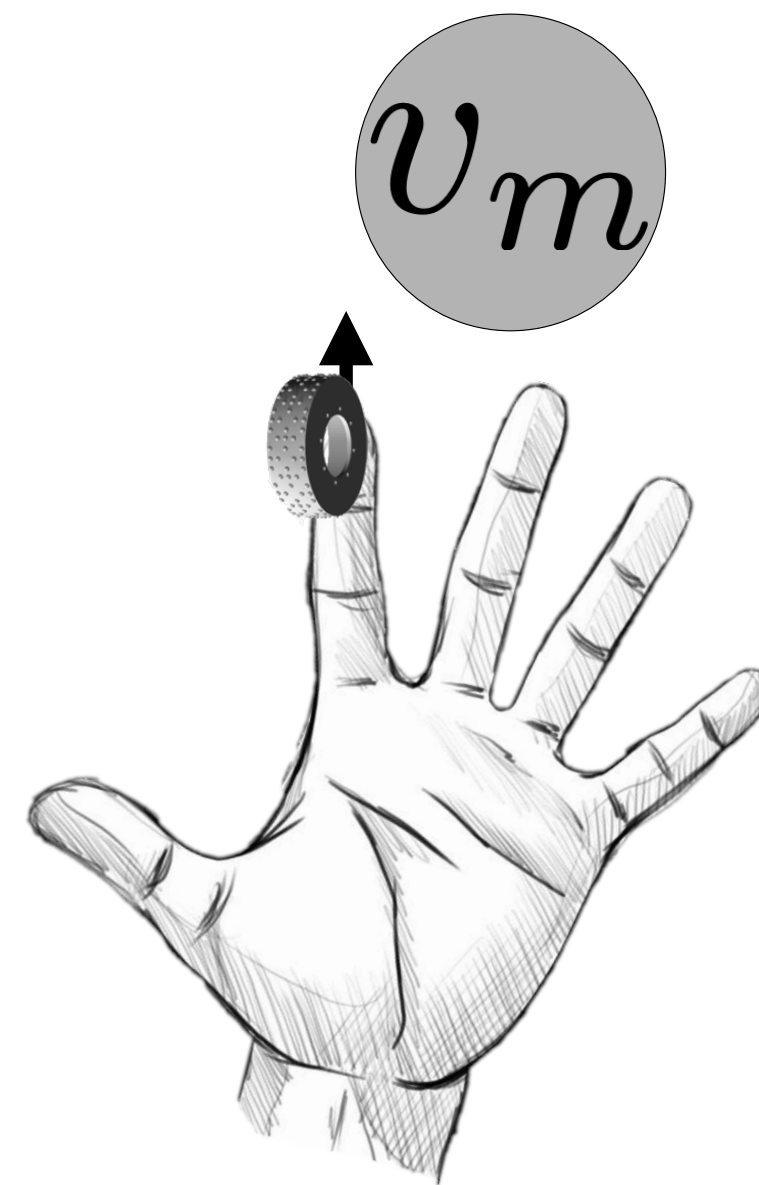
**Goal 3:** Determine how tactile motion information is modulated by proprioception in the brain?

**Goal 2:** Develop a generalizable computational model that explains human behavioral report.



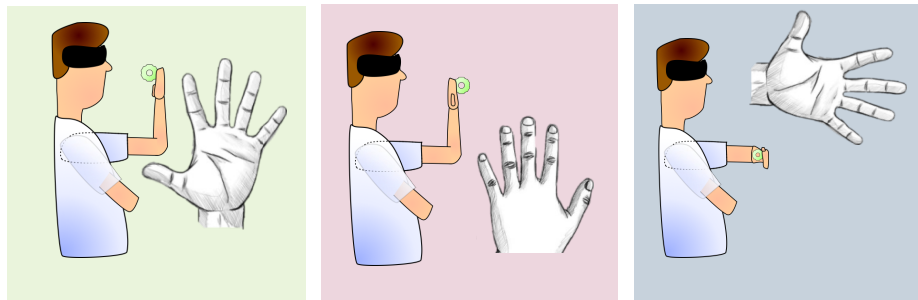
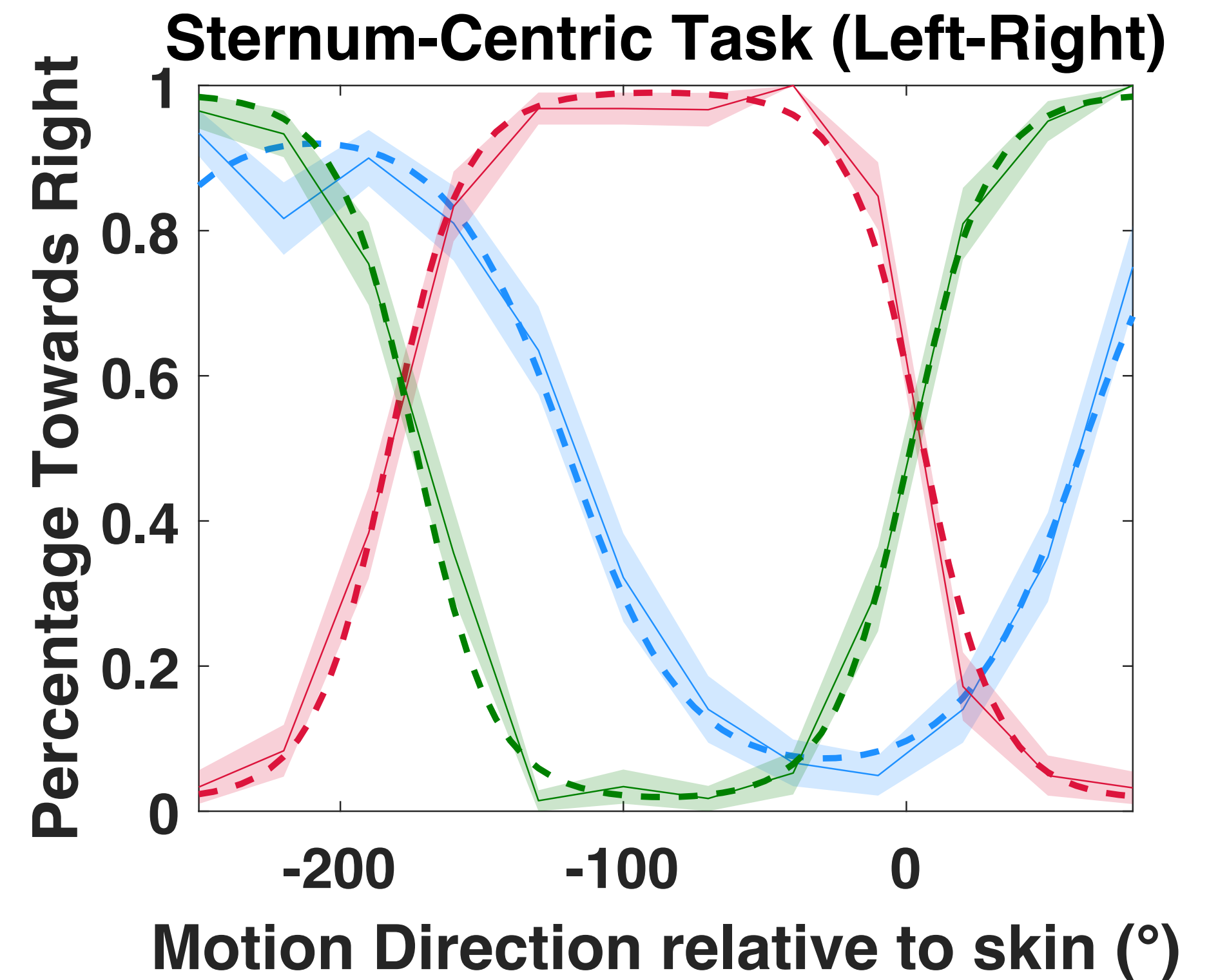
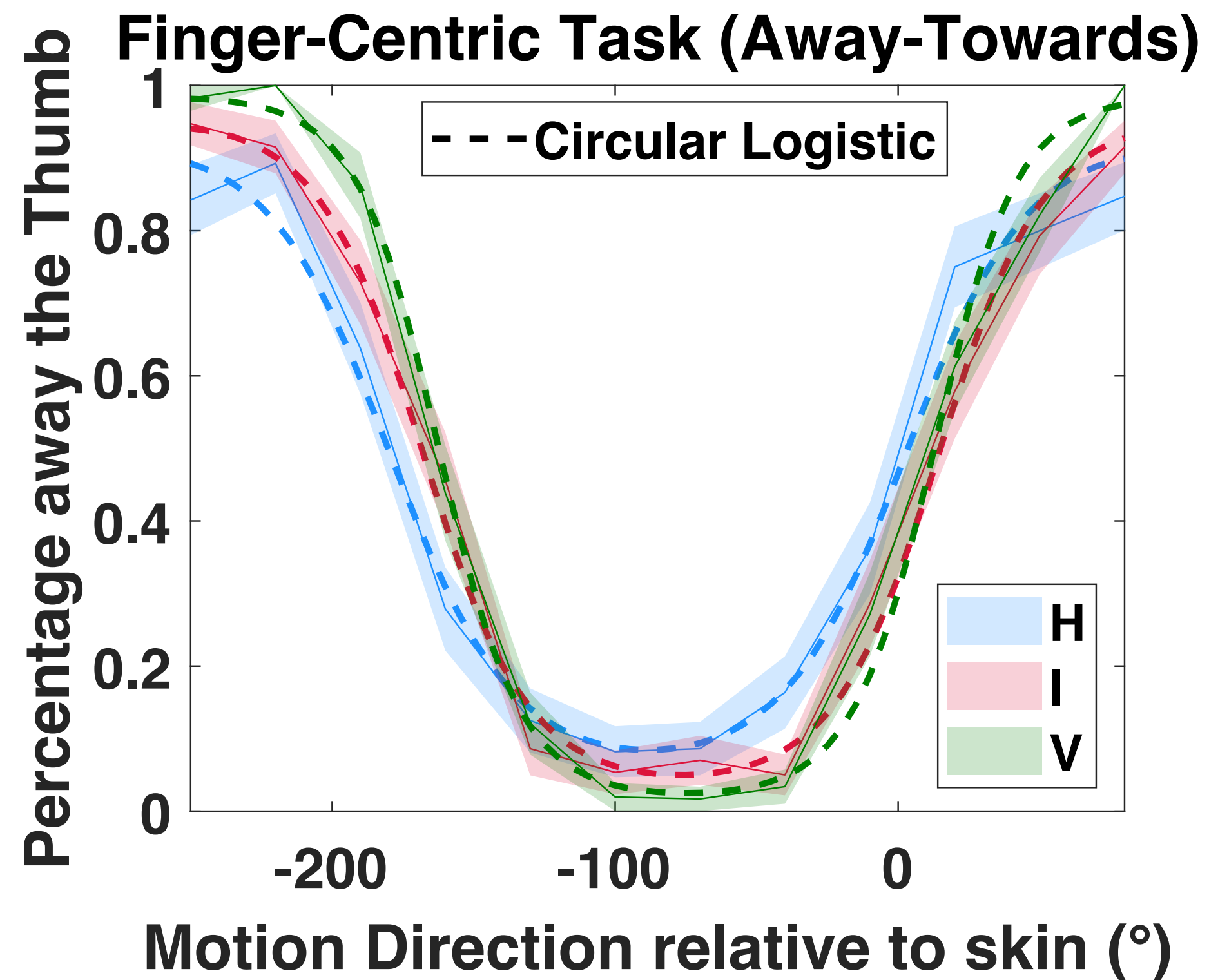
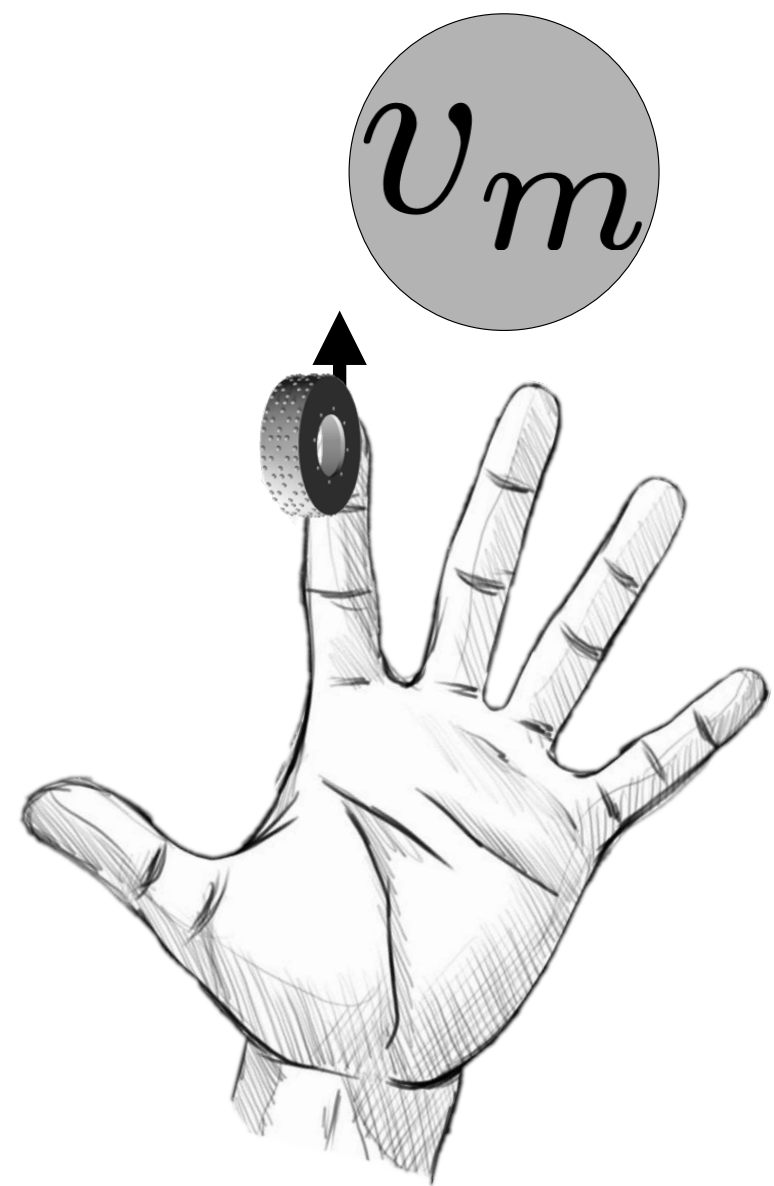
# Circular Logistic Function

$$\log\left(\frac{p^{(i)}}{1-p^{(i)}}\right) = \beta_0 + \beta_1 \cos(v_m^{(i)}) + \beta_2 \sin(v_m^{(i)})$$



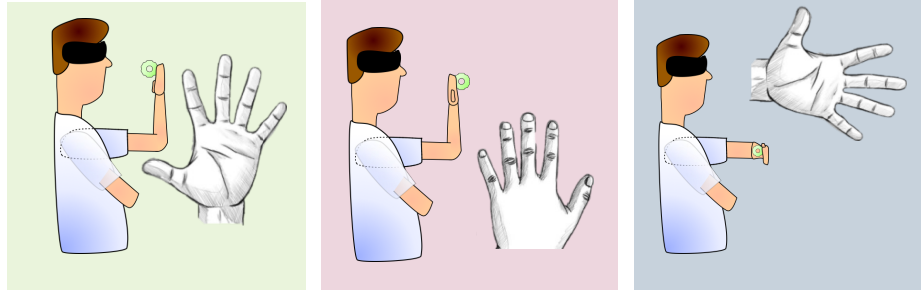
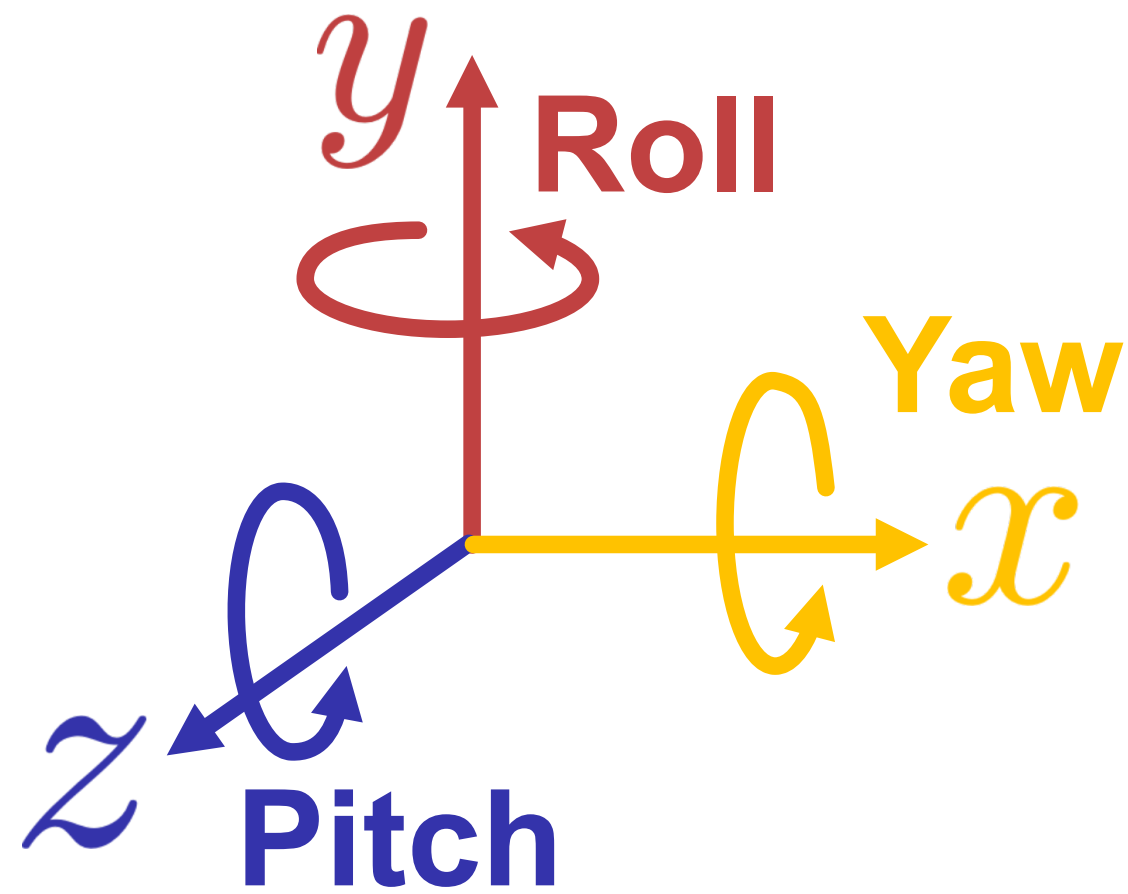
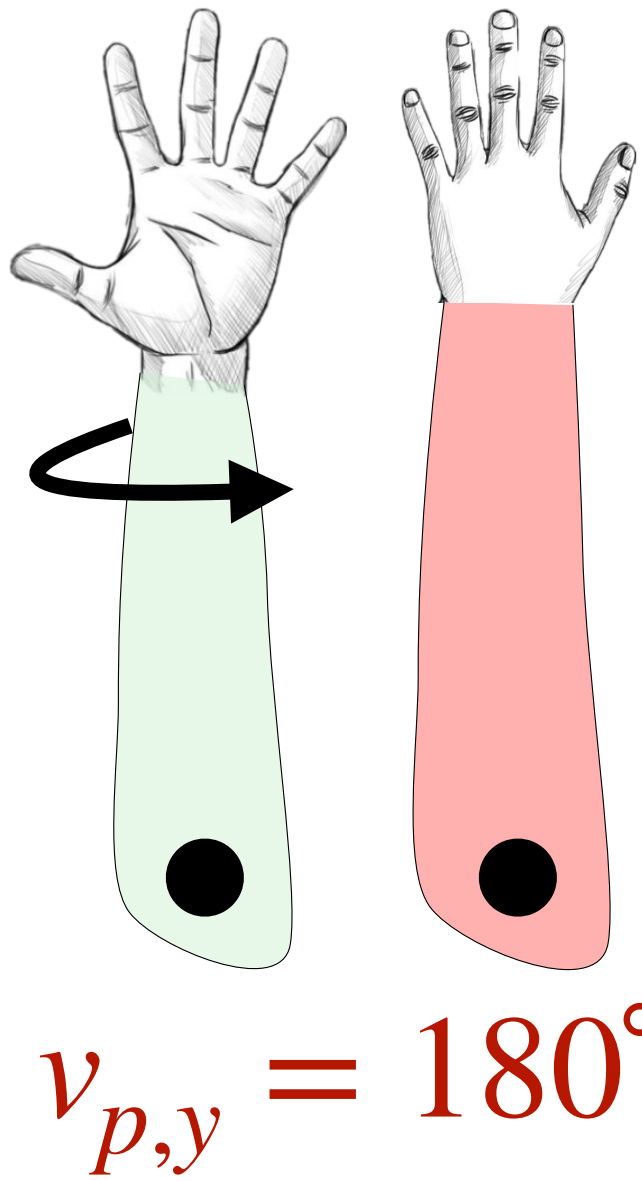
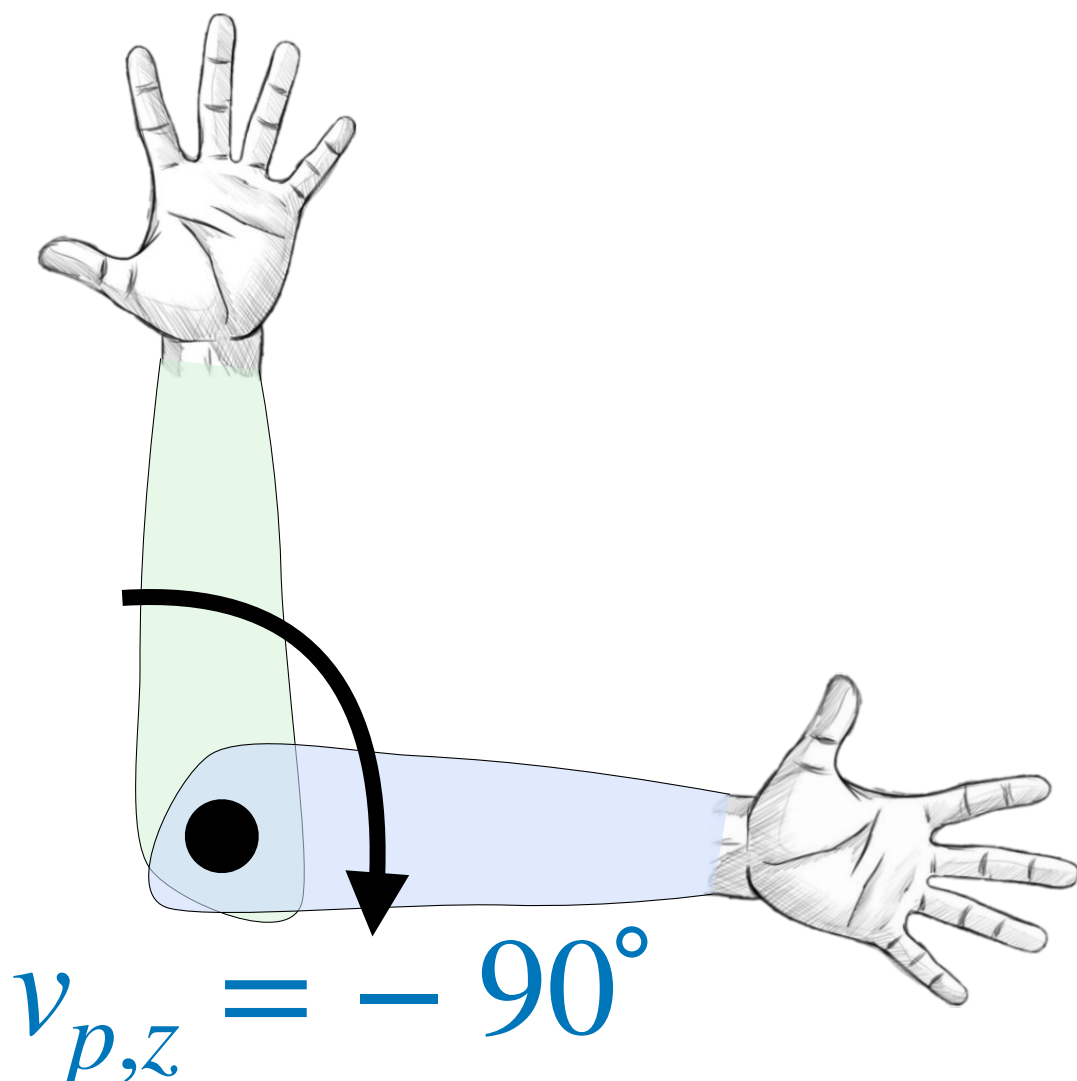
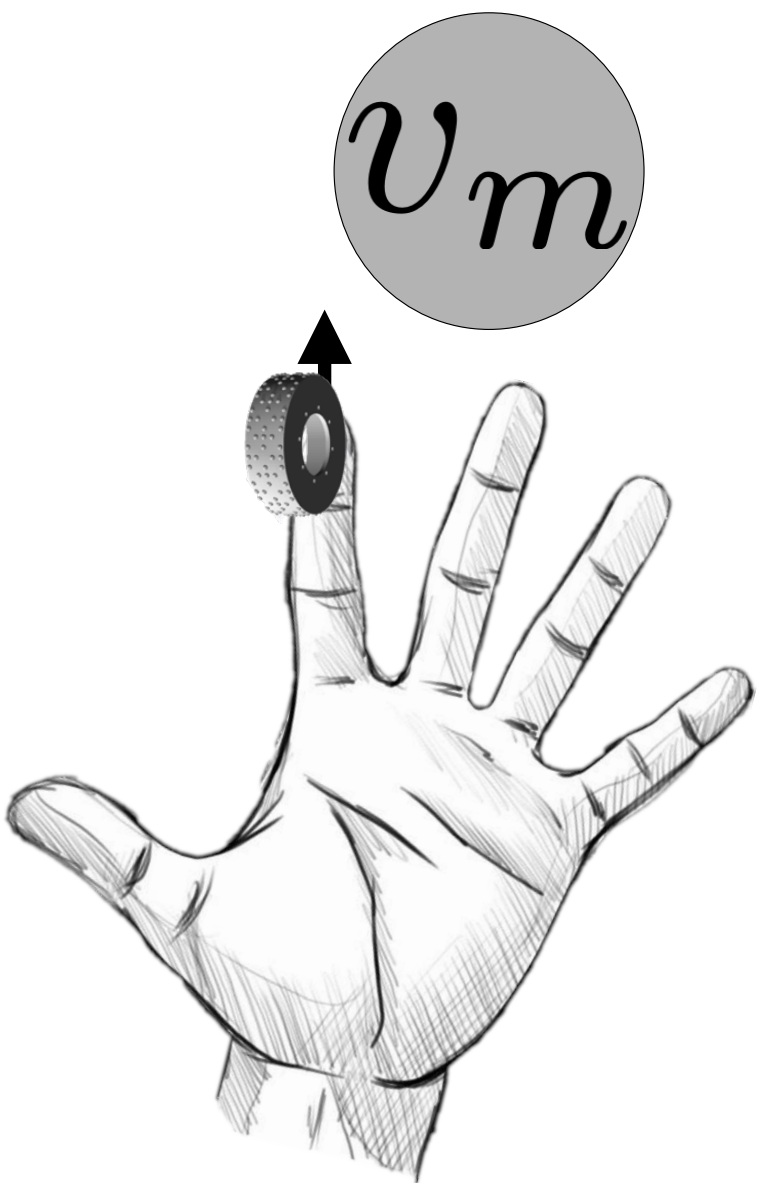
# Circular Logistic fits the data but is not generalizable

$$\log\left(\frac{p^{(i)}}{1-p^{(i)}}\right) = \beta_0 + \beta_1 \cos(v_m^{(i)}) + \beta_2 \sin(v_m^{(i)})$$

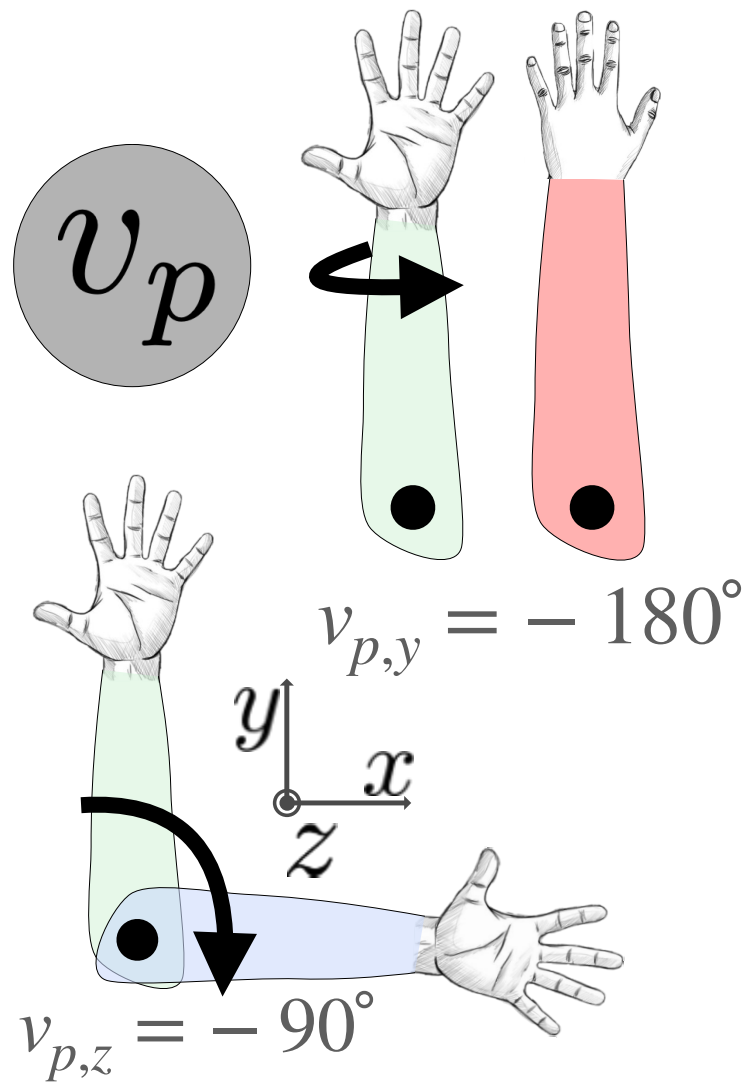


# Circular Logistic function for each rotation axis

$$\log\left(\frac{p^{(i)}}{1 - p^{(i)}}\right) = \beta_0 + \beta_1 \cos(v_m^{(i)}) + \beta_2 \sin(v_m^{(i)})$$



# Circular Logistic function for each rotation axis



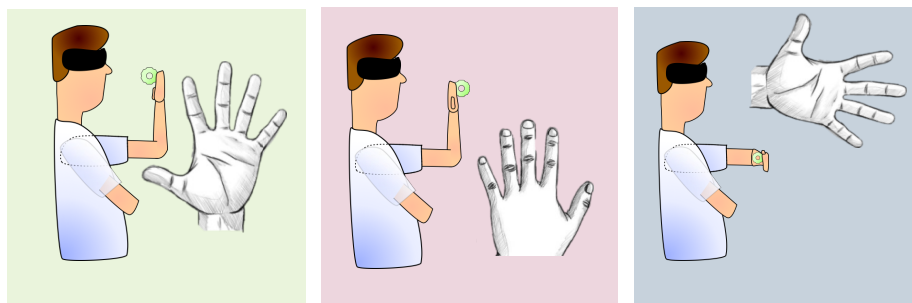
$$\log \left( \frac{p^{(i)}}{1 - p^{(i)}} \right) = \beta_0 + \beta_1 \cos(v_m^{(i)} + v_{p,z}^{(i)}(\mathbf{RF}) + \beta_2 \sin(v_m^{(i)} + v_{p,z}^{(i)}(\mathbf{RF}))$$

$$\log \left( \frac{p^{(i)}}{1 - p^{(i)}} \right) = \beta_0 + \beta_1 \cos(v_m^{(i)} + v_{p,y}^{(i)}(\mathbf{RF}) + \beta_2 \sin(v_m^{(i)} + v_{p,y}^{(i)}(\mathbf{RF}))$$

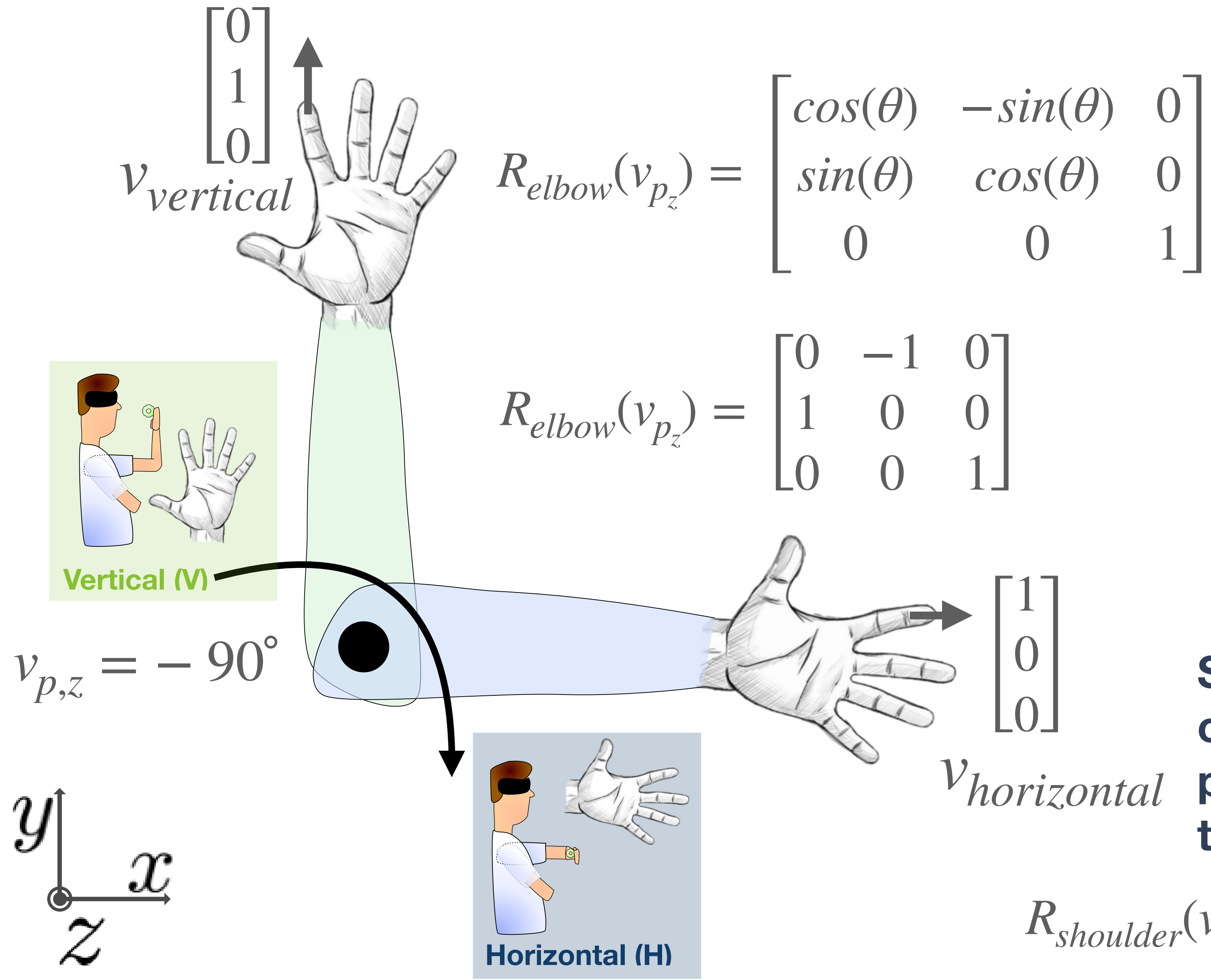


$$\log \left( \frac{p^{(i)}}{1 - p^{(i)}} \right) = \beta_0 + \beta_1 \cos(v_m^{(i)} + v_{p,x}^{(i)}(\mathbf{RF}) + \beta_2 \sin(v_m^{(i)} + v_{p,x}^{(i)}(\mathbf{RF}))$$

**Circular Logistic is not generalizable to multiple transformations and reference frames!**



# Euler Matrix Transformations



$$R_{elbow}(v_{p,z}) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_{elbow}(v_{p,z}) = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

**Only 4 Parameters!**

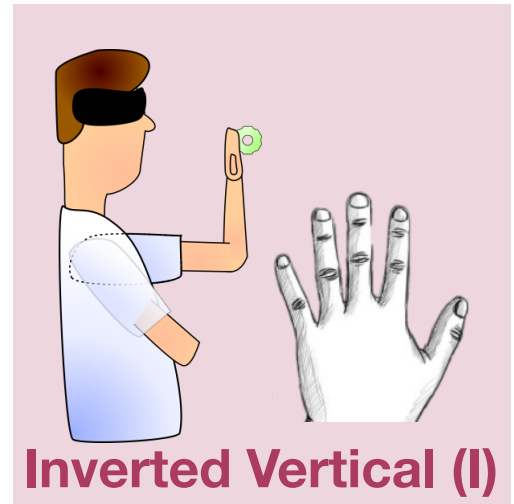
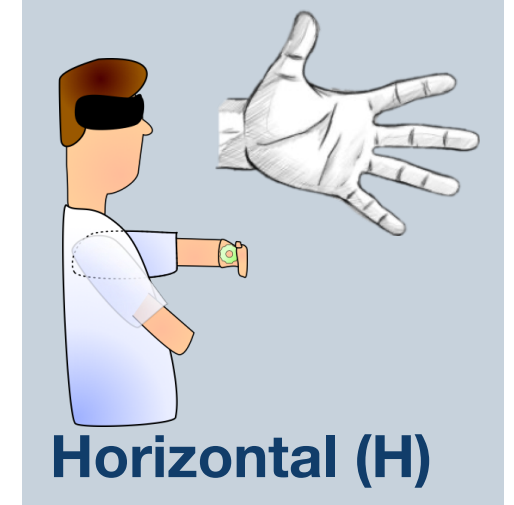
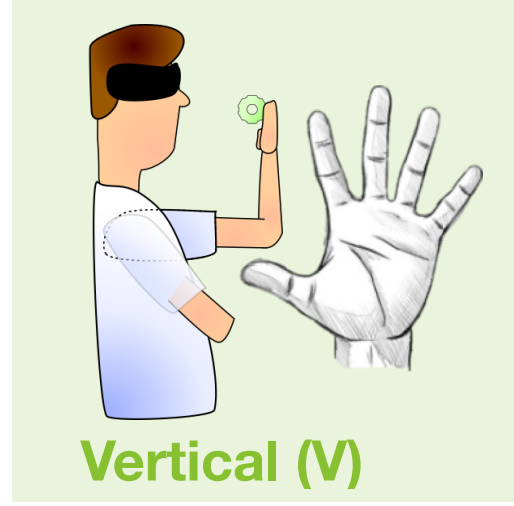
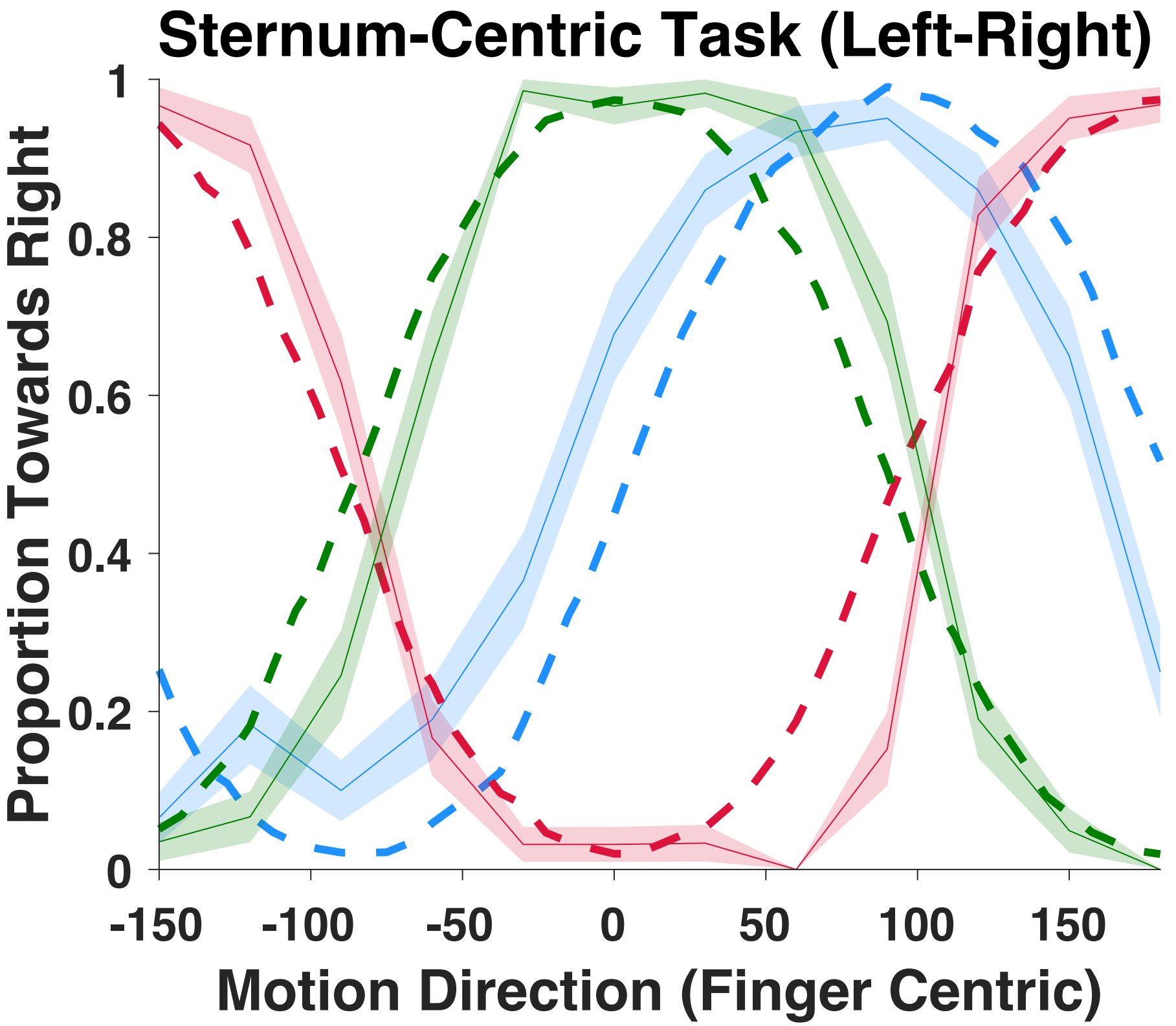
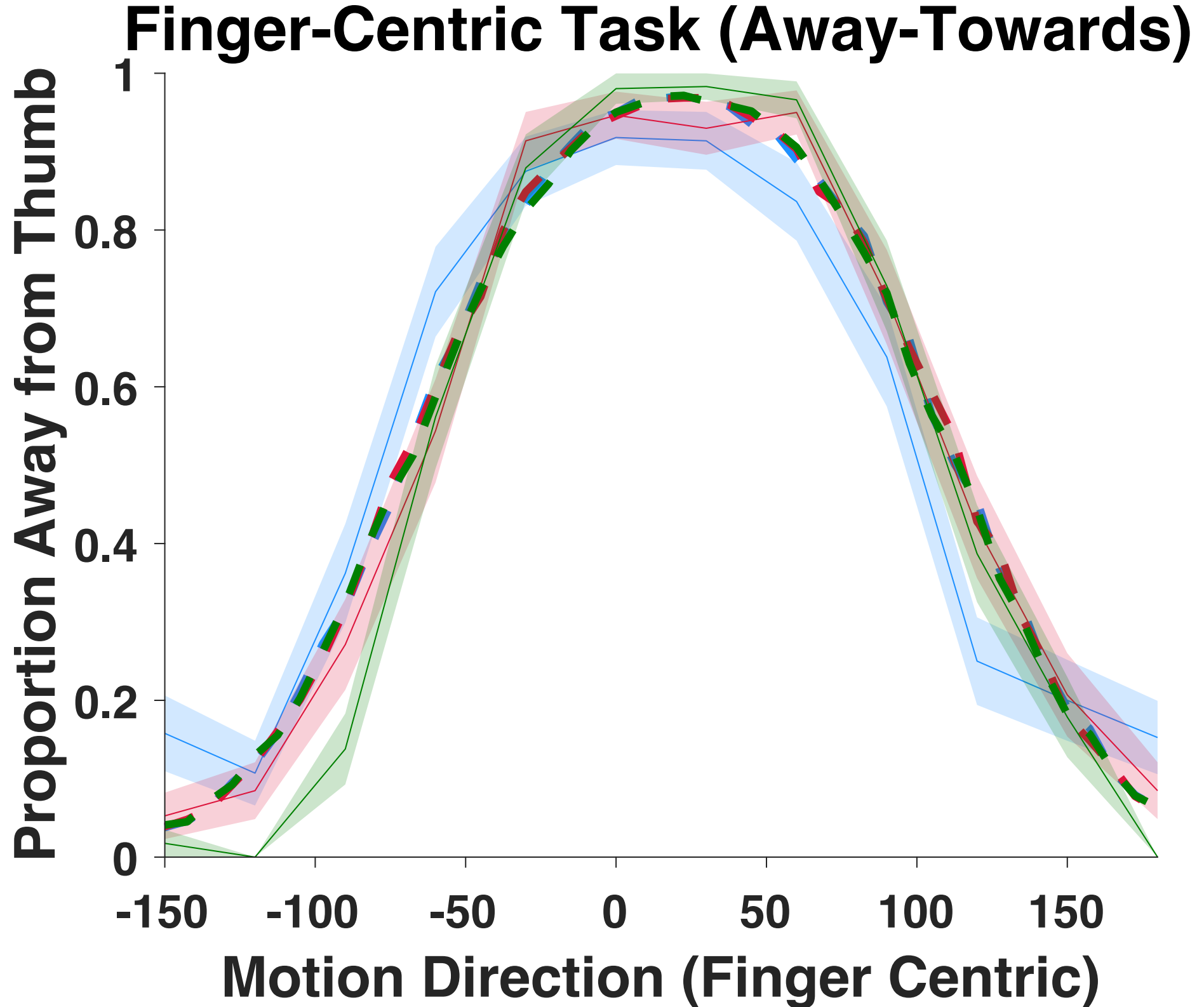
$$R_{elbow}(v_{p,z}) \cdot v_{vertical} = v_{horizontal}$$

$$\begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

**Similar matrix transformation can be performed at each proprioceptor joints between two reference frames**

$$R_{shoulder}(v_{p,x}) \cdot \dots \cdot R_{elbow}(v_{p,z}) \cdot R_{wrist}(v_{p,y}) \cdot v = v'$$

# Euler-Matrix Transformations explain behavioral results

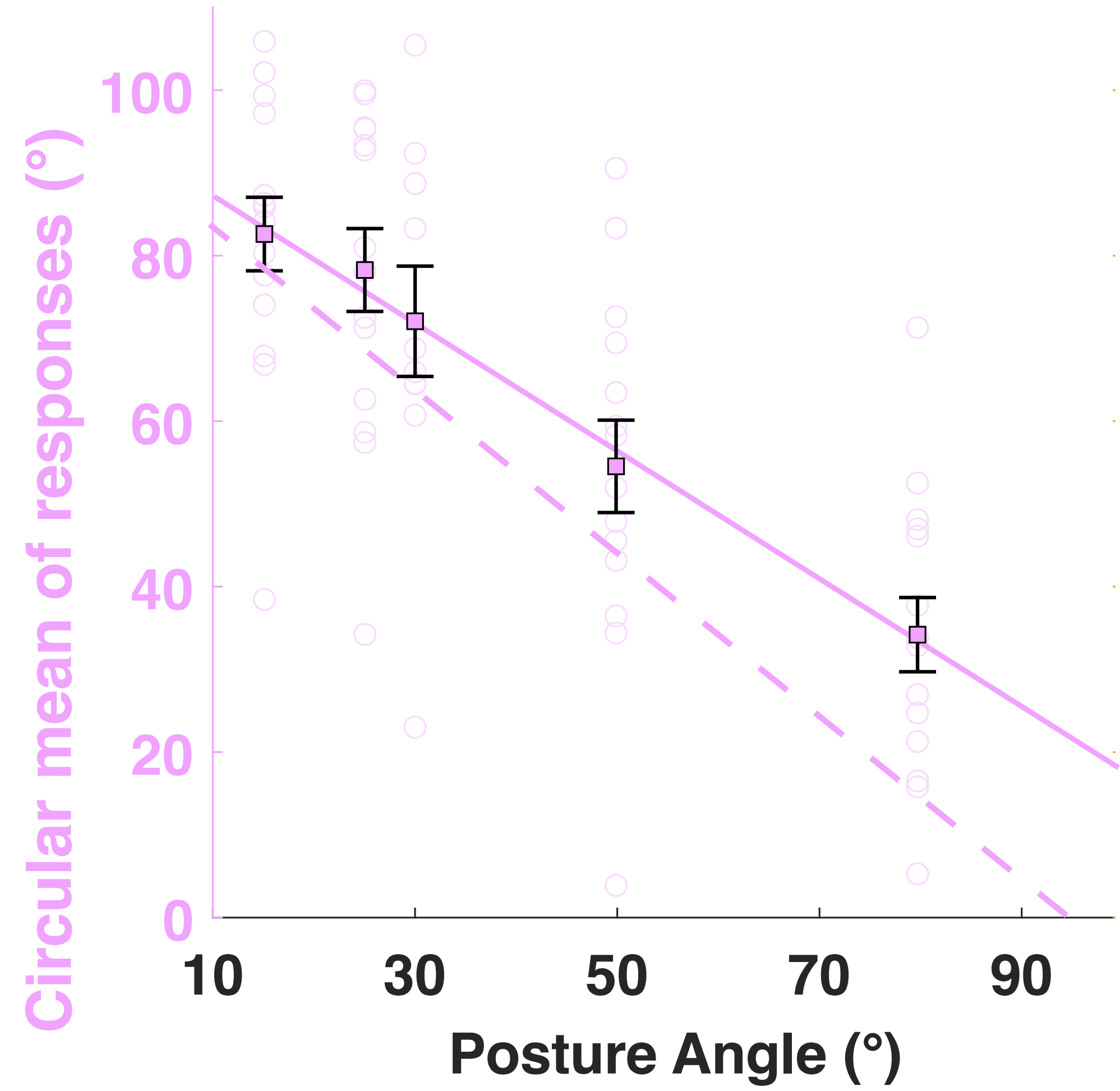
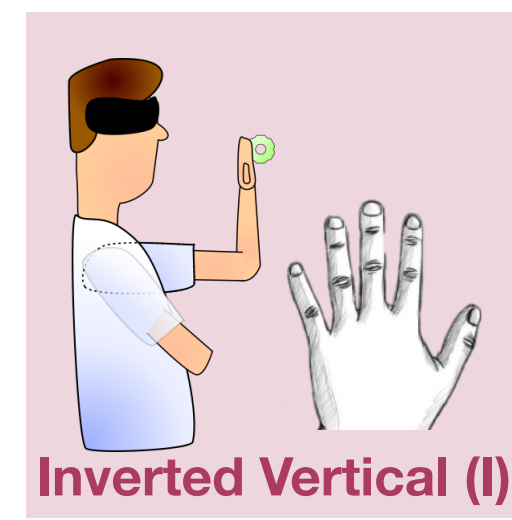
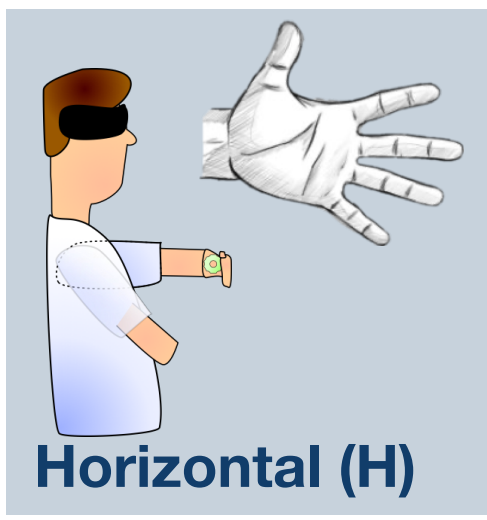
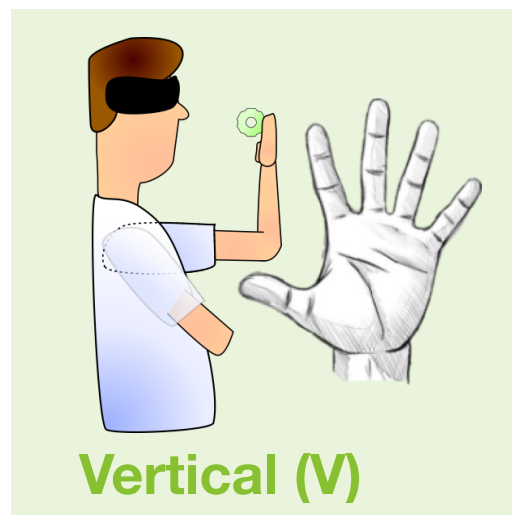
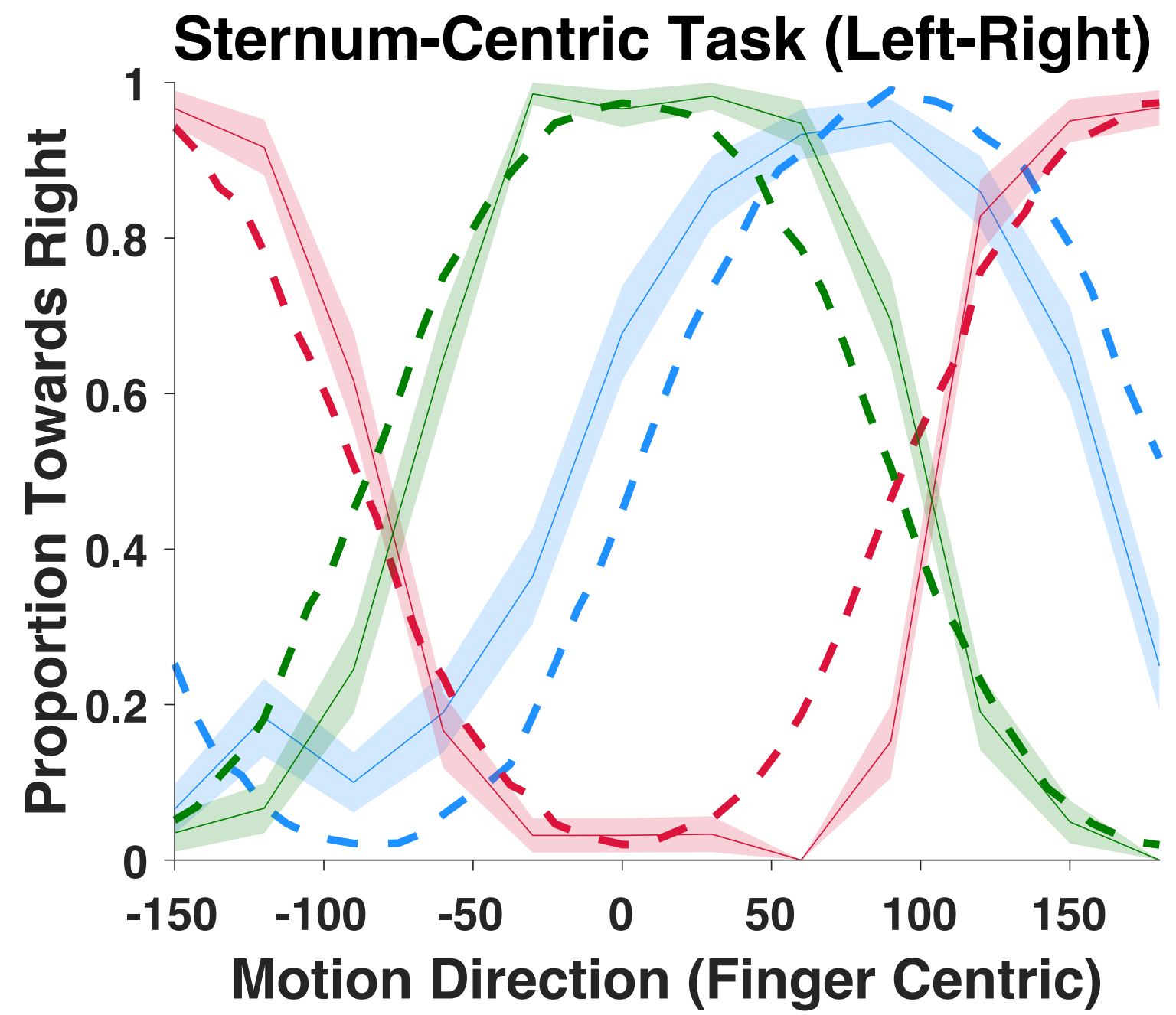


--- Model Fit    — Observed

# Comparing Circular Logistics and Euler Model

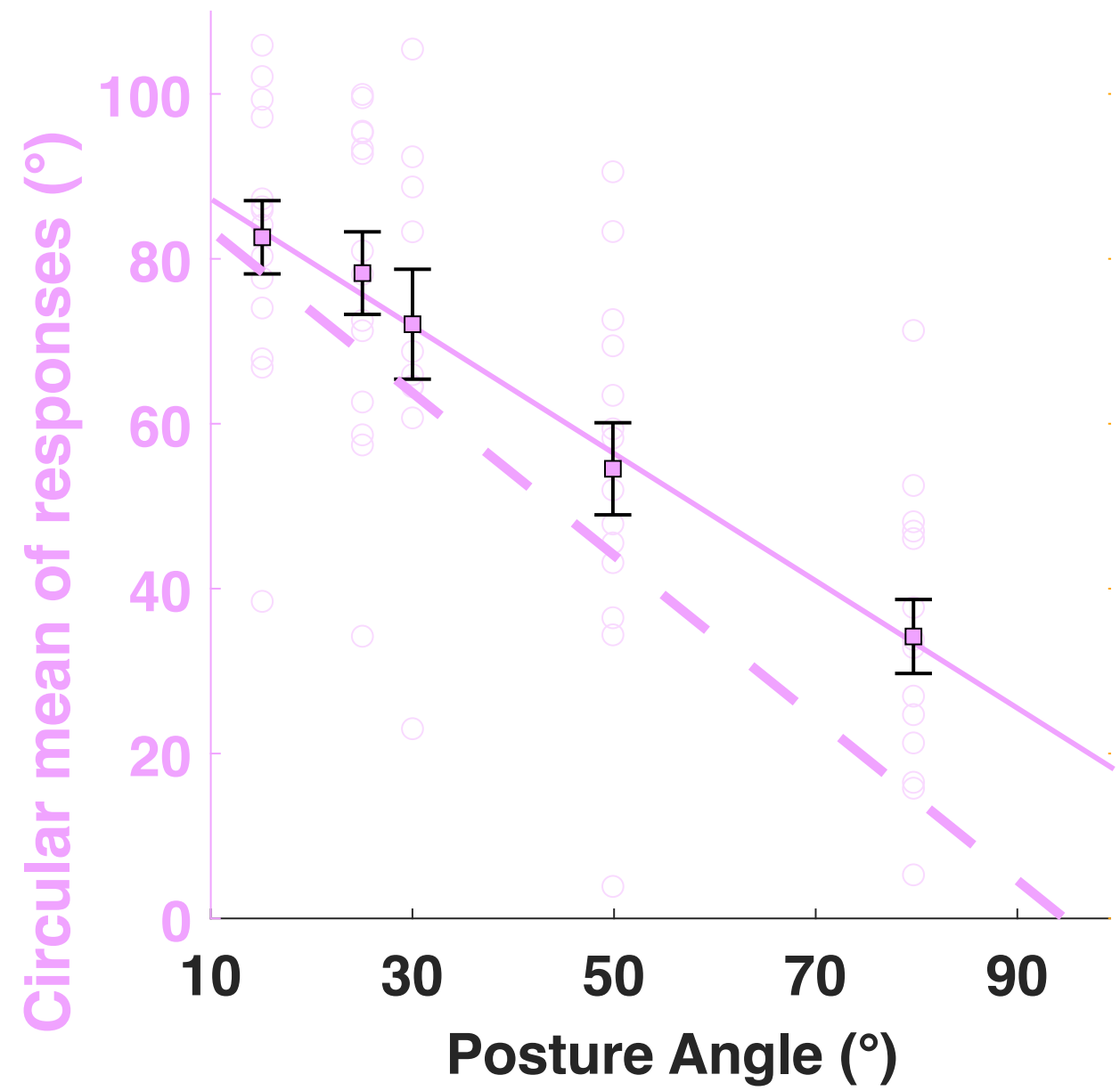
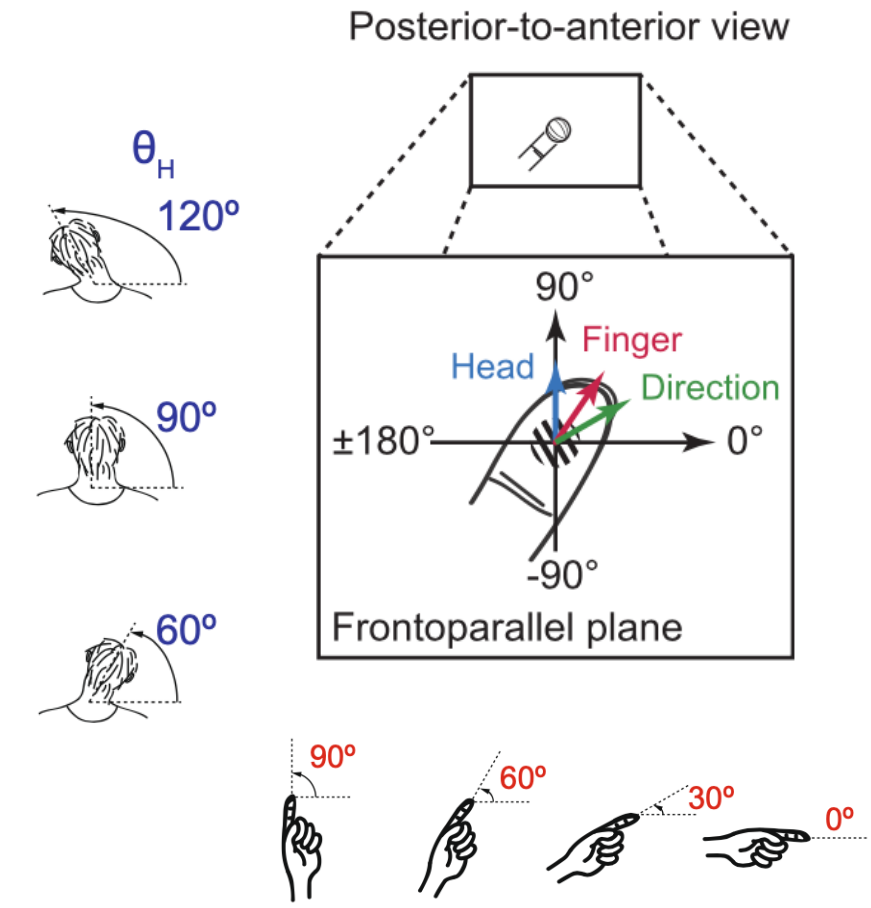
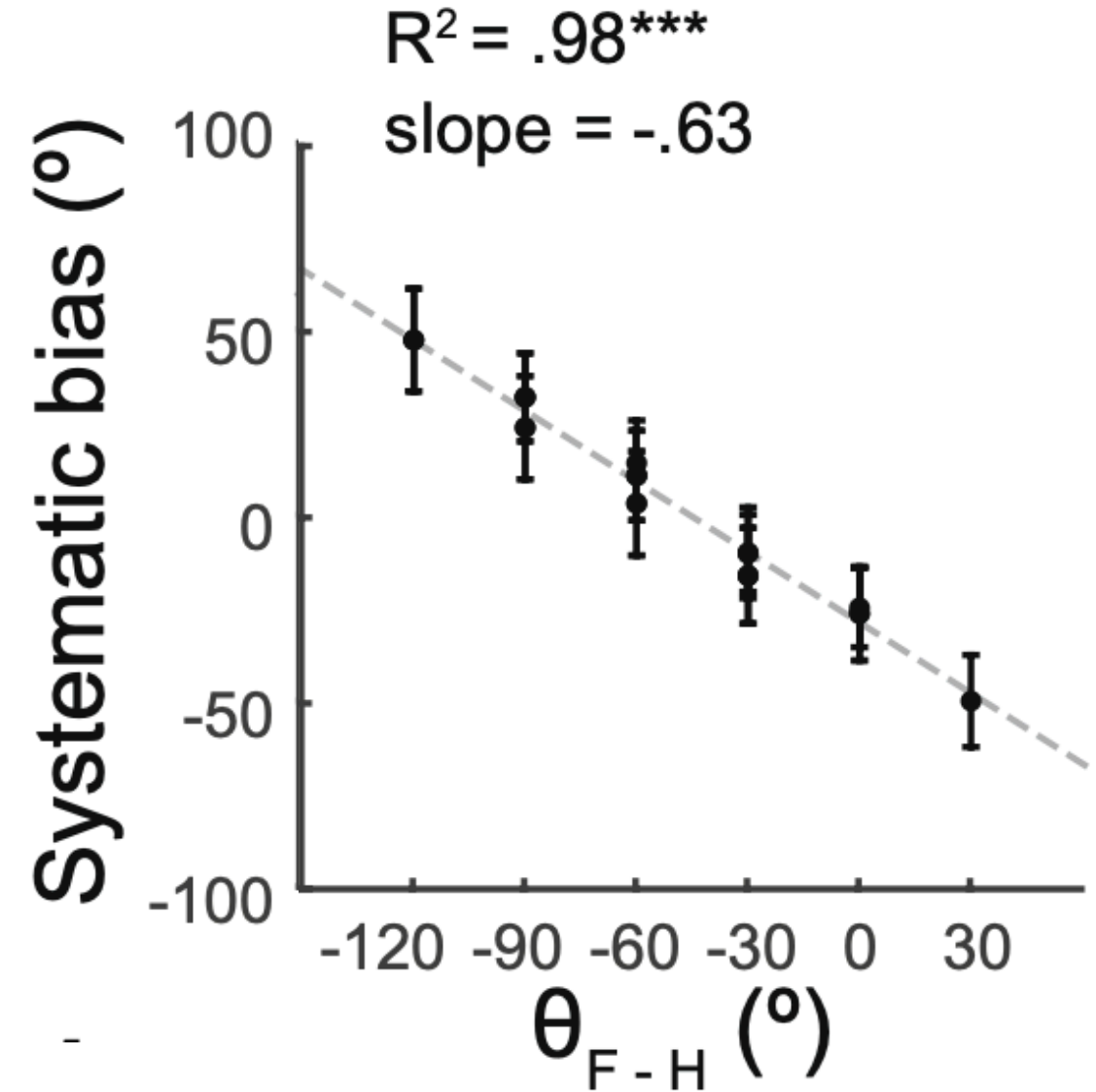
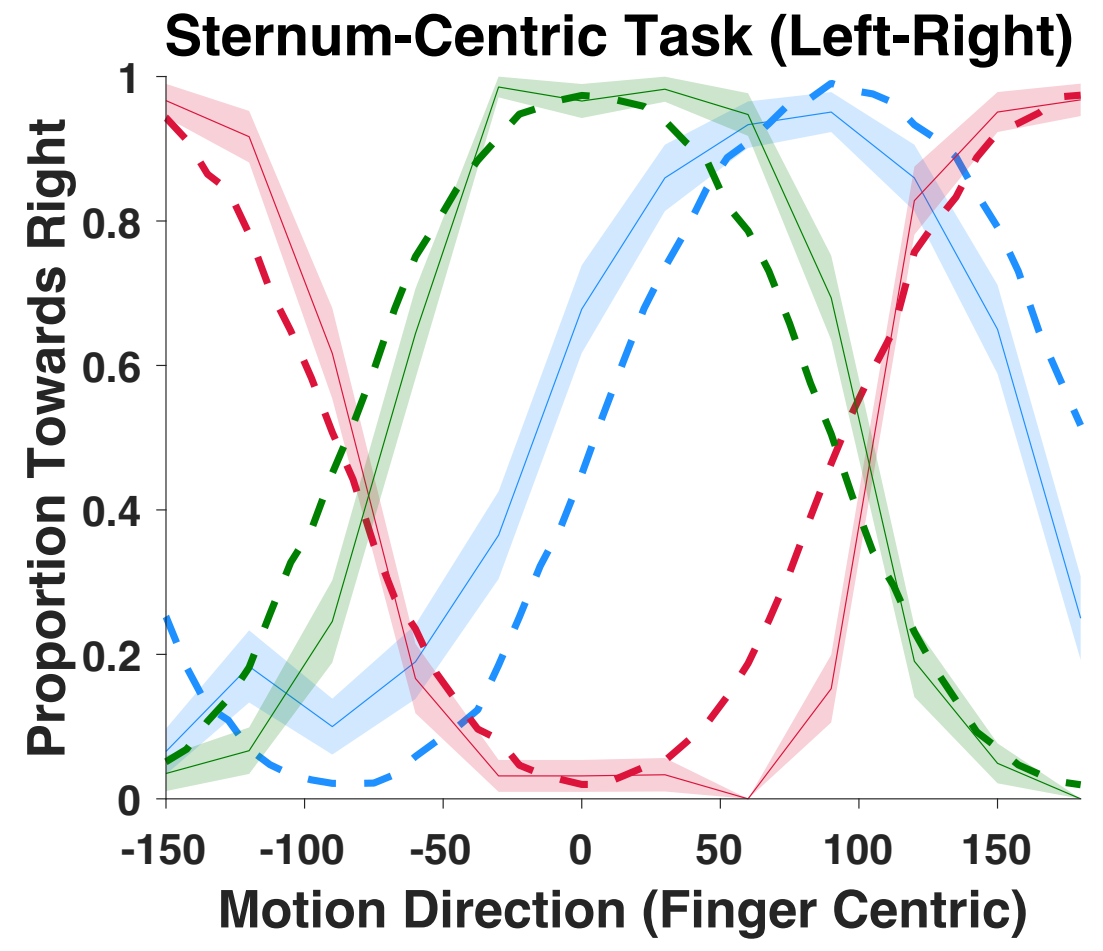
Model Name	Number of Parameters	McFadden's R <sup>2</sup> Finger-centric task	McFadden's R <sup>2</sup> Sternum-centric task	AIC
Circular Logistic	18	0.42	<b>0.51</b>	7625.8
Euler Model	4	0.41	0.45	<b>3375</b>

# Sternum-centric behavior deviates from Ideal Observer



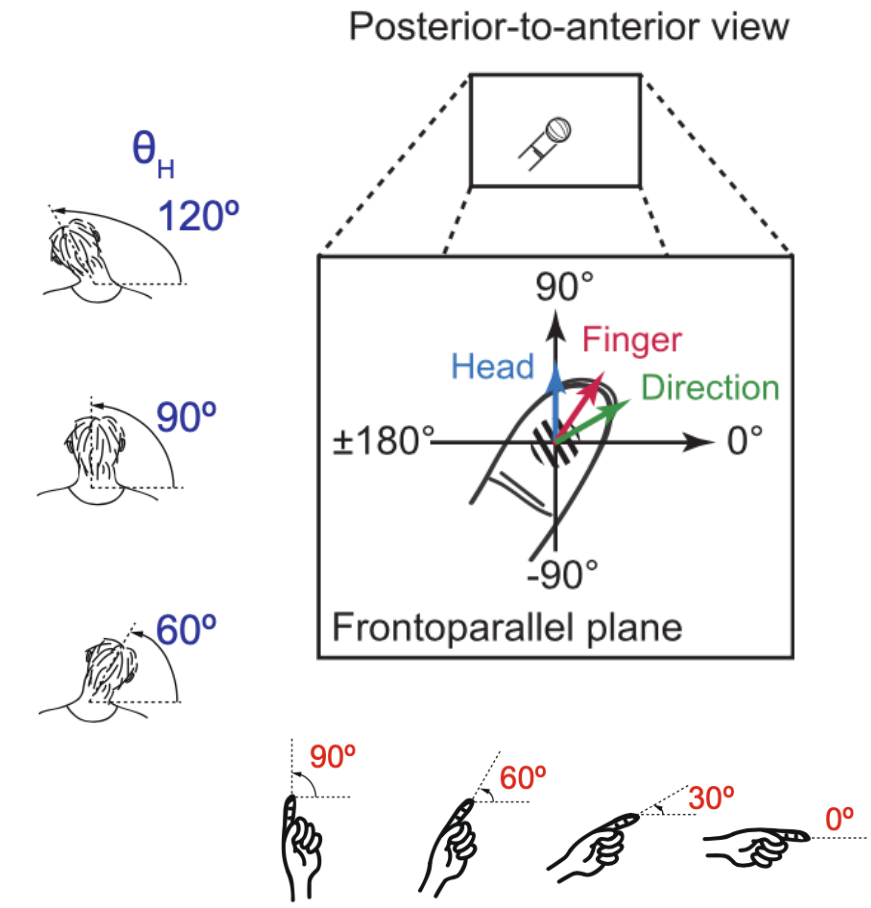
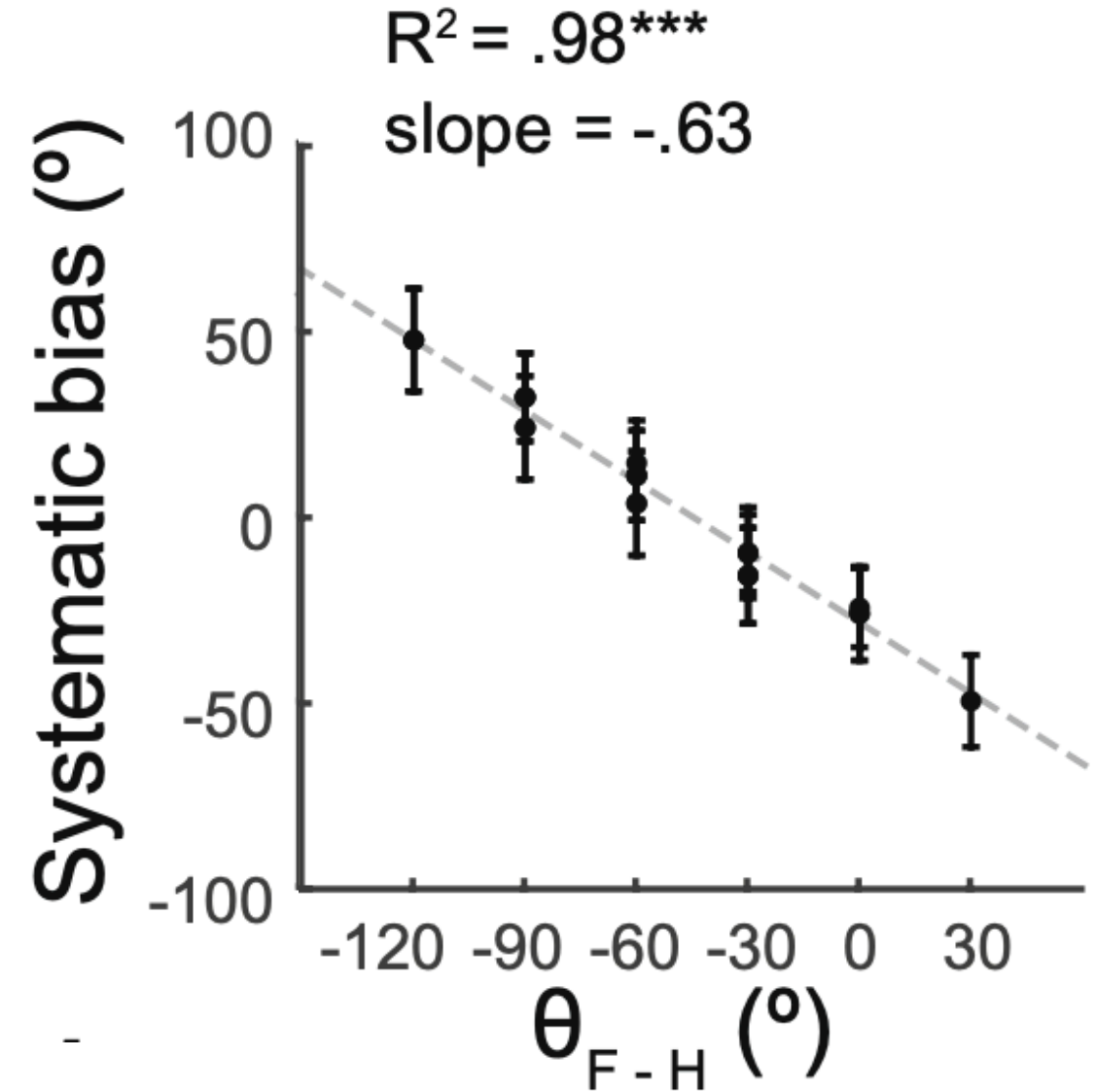
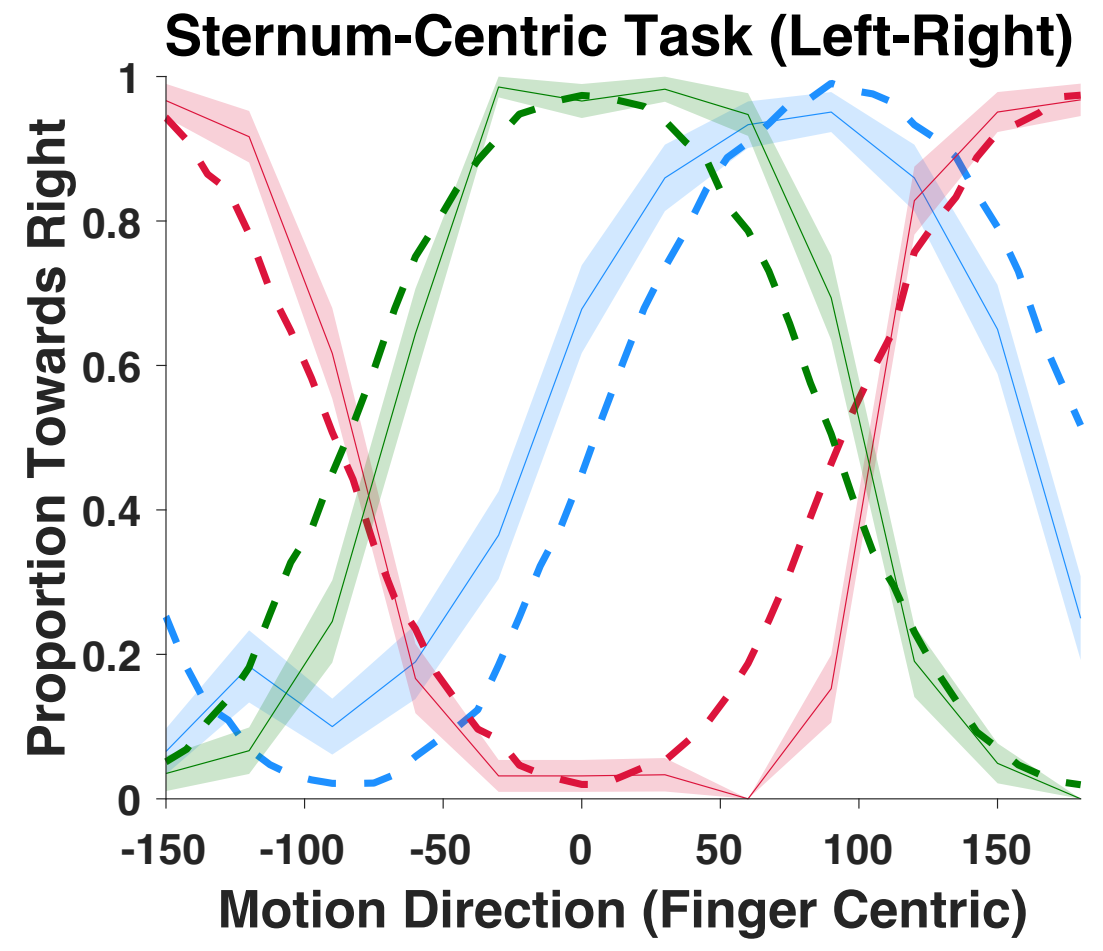
--- Model Fit      — Observed

# Sternum-centric behavior deviates from Ideal Observer

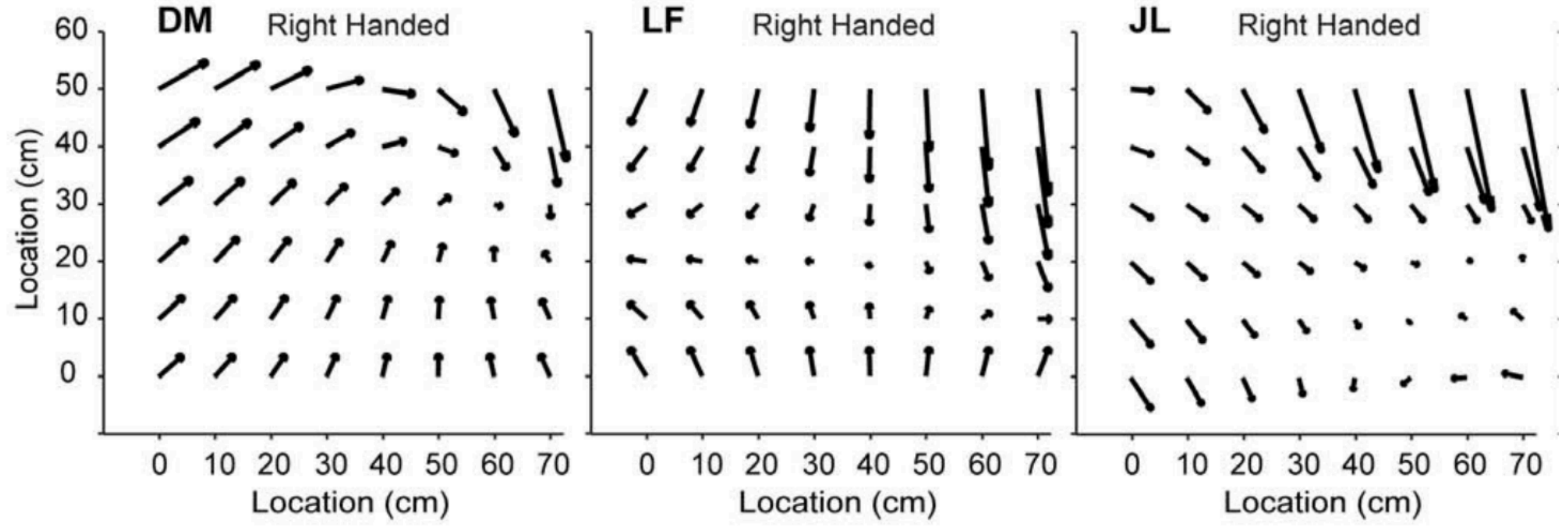
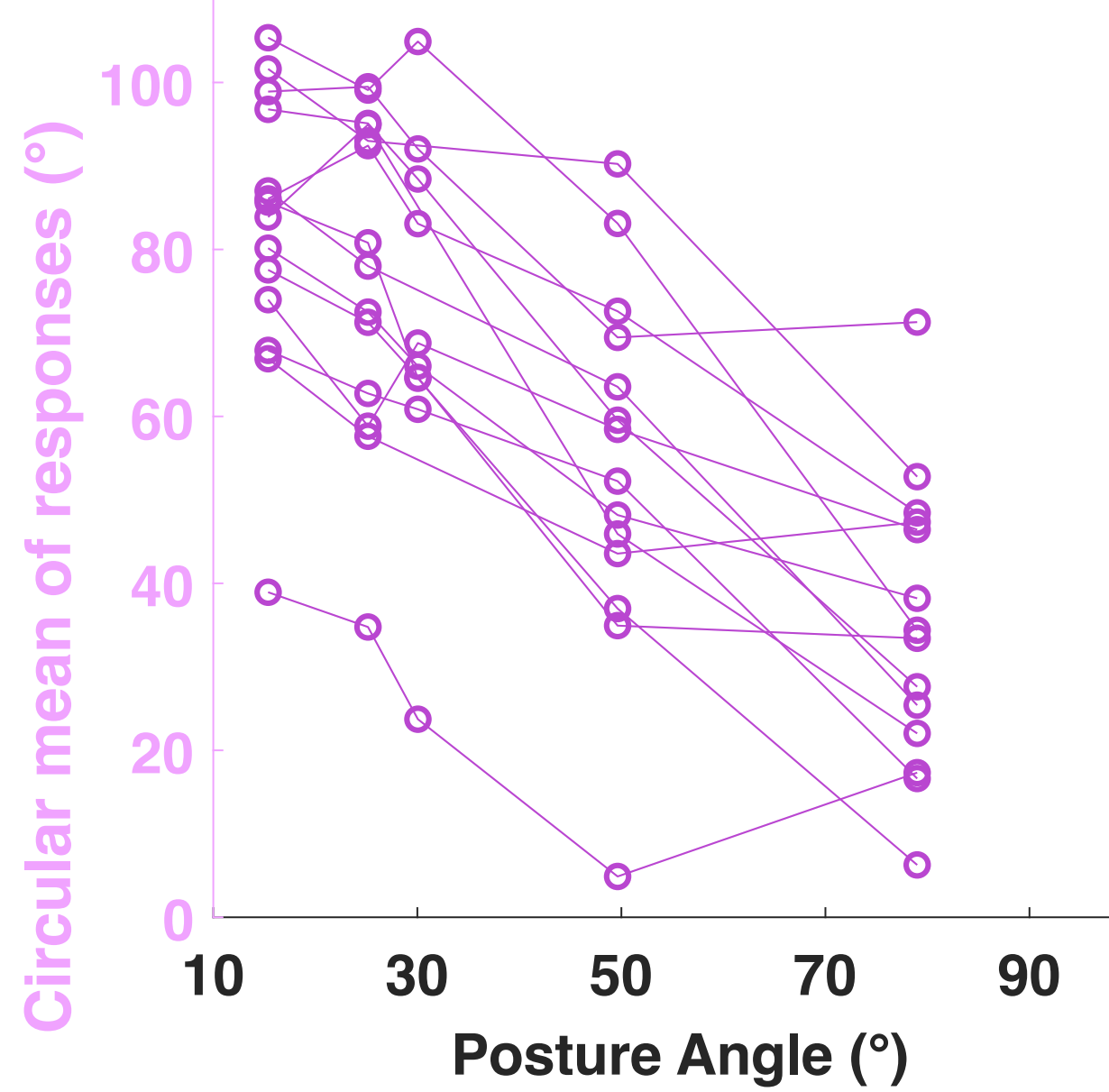


YP Chen et. al 2020 Scientific Reports

# Idiosyncratic estimation or proprioceptive state

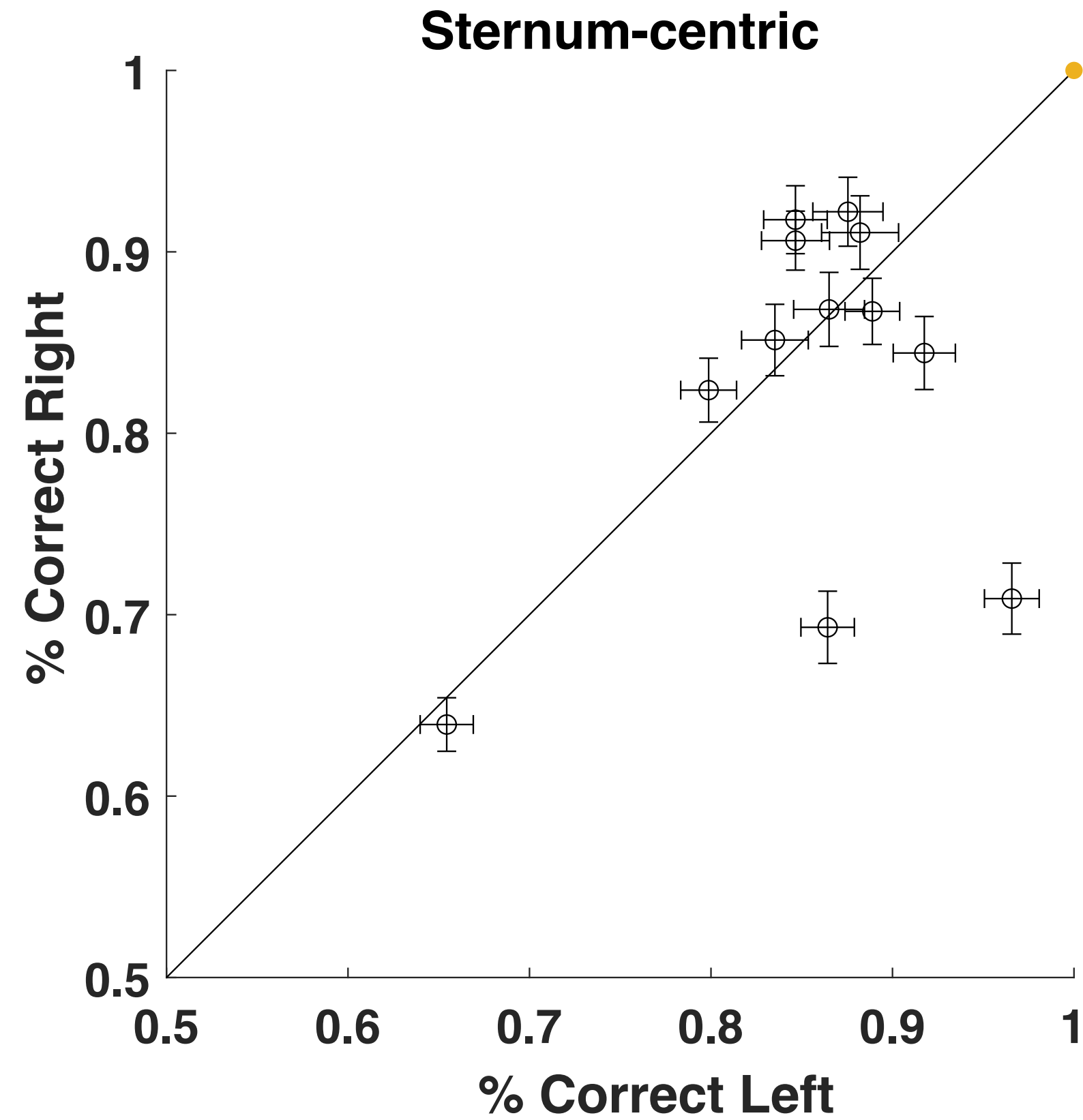
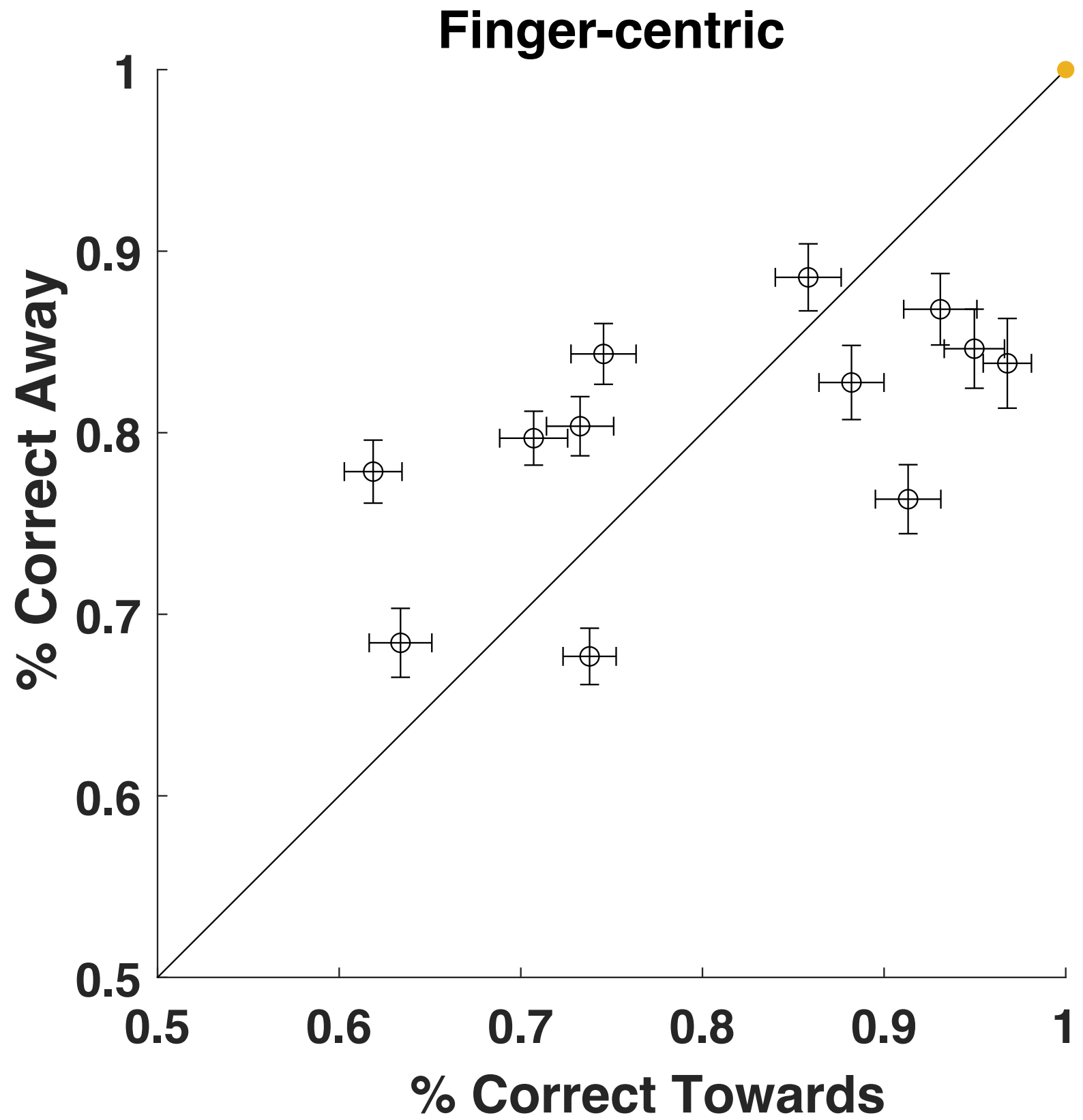


YP Chen et. al 2020 Scientific Reports

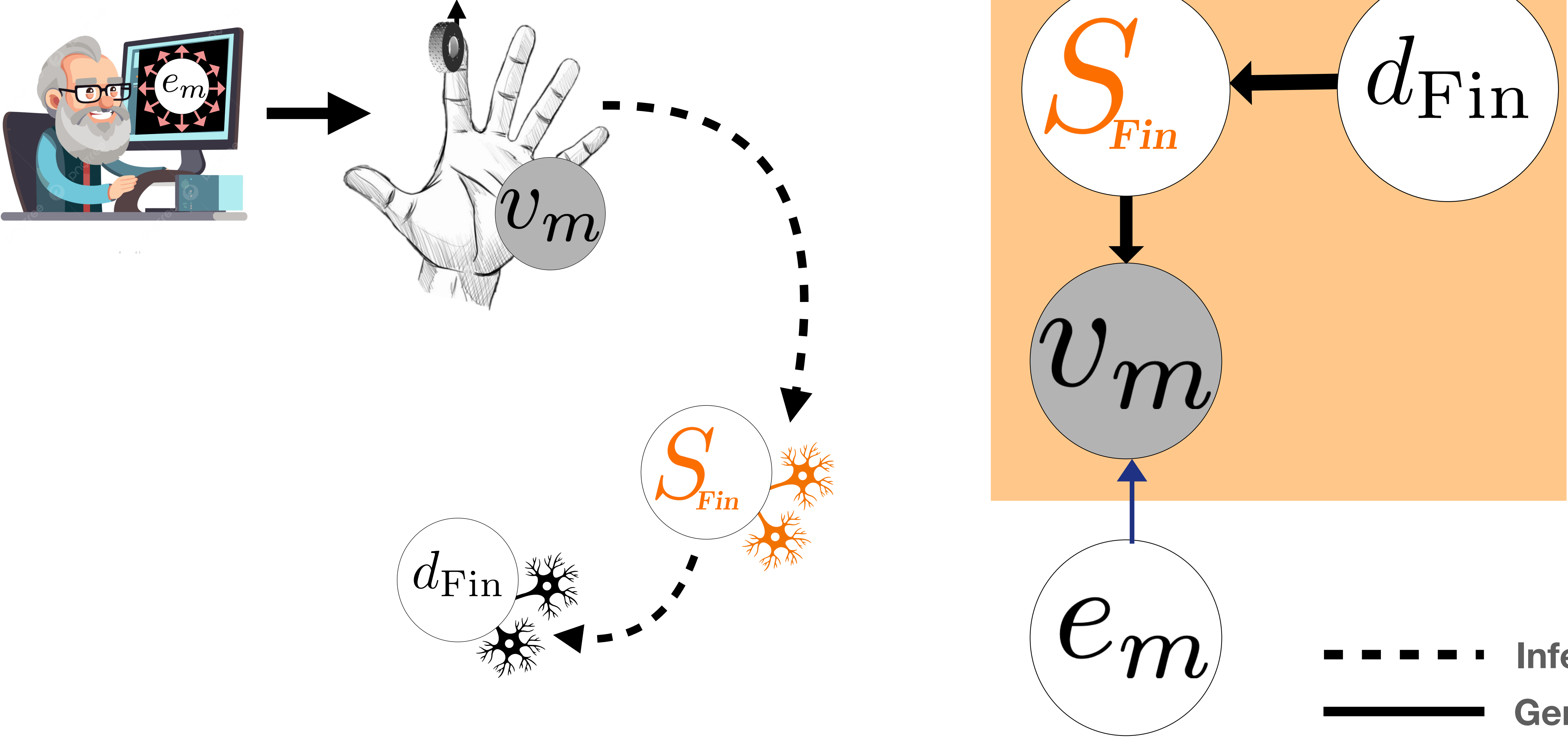


Rincon-Gonzalez et. al 2011

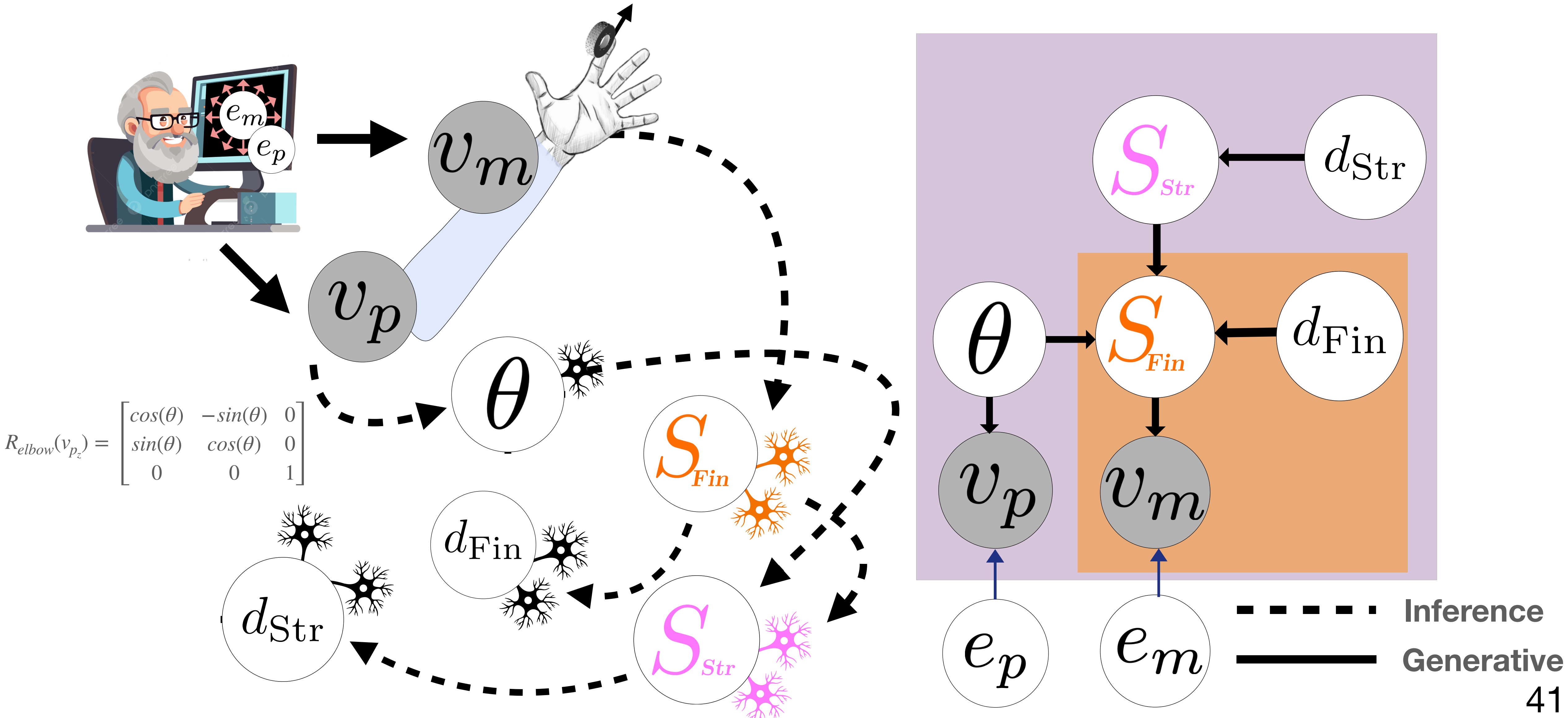
# Subjects are choice biased (Experiment 1)



# Finger-centric Generative Model

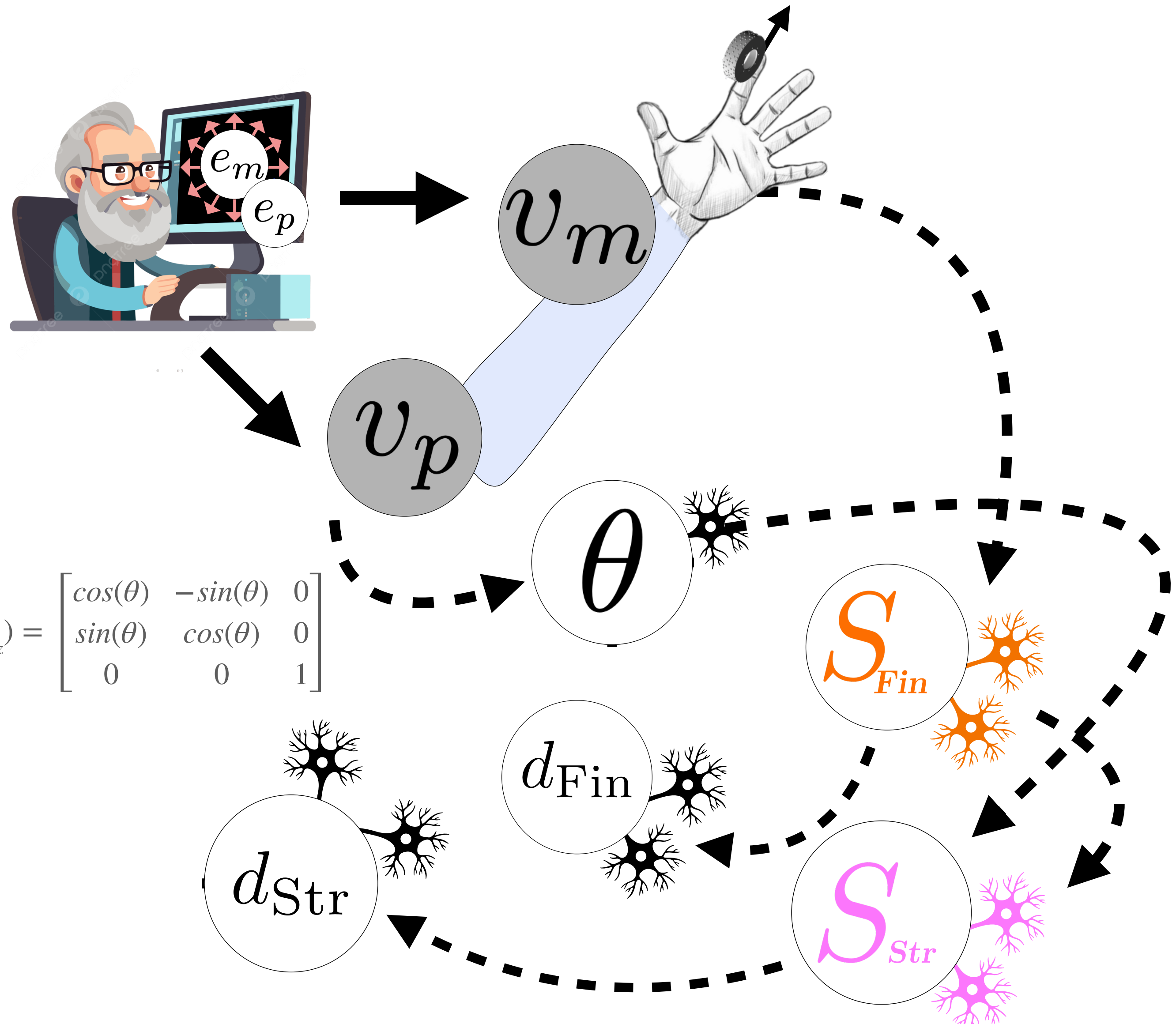


# Sternum-centric generative model

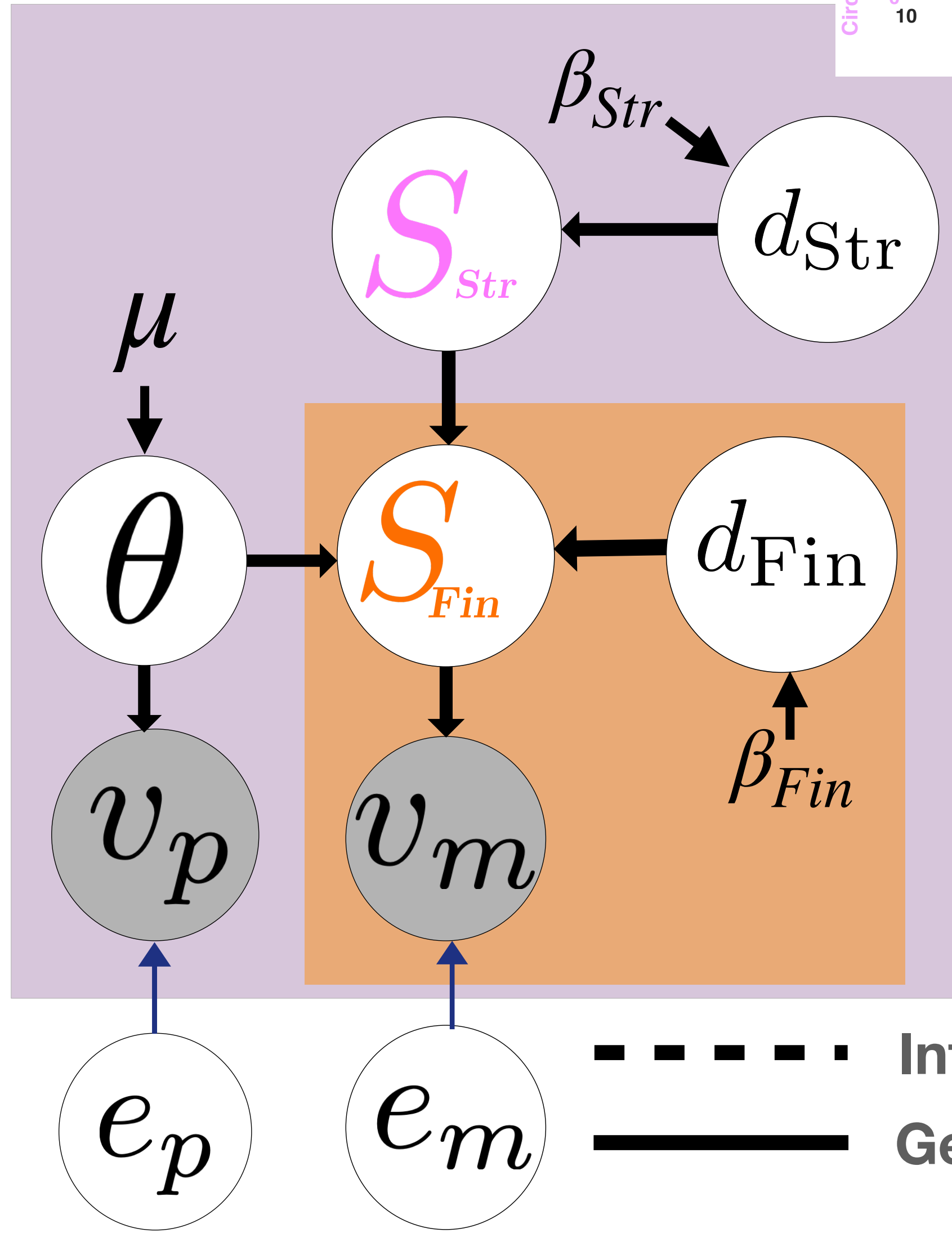
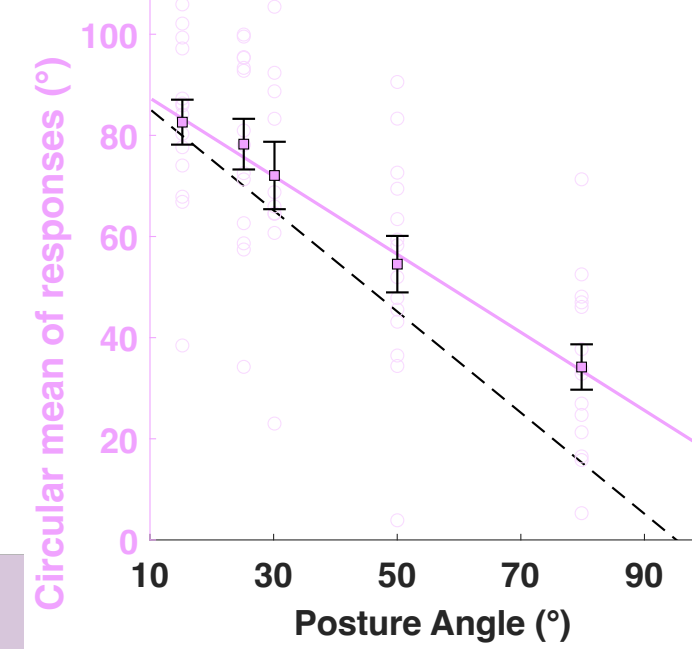


# Bayesian generative model with

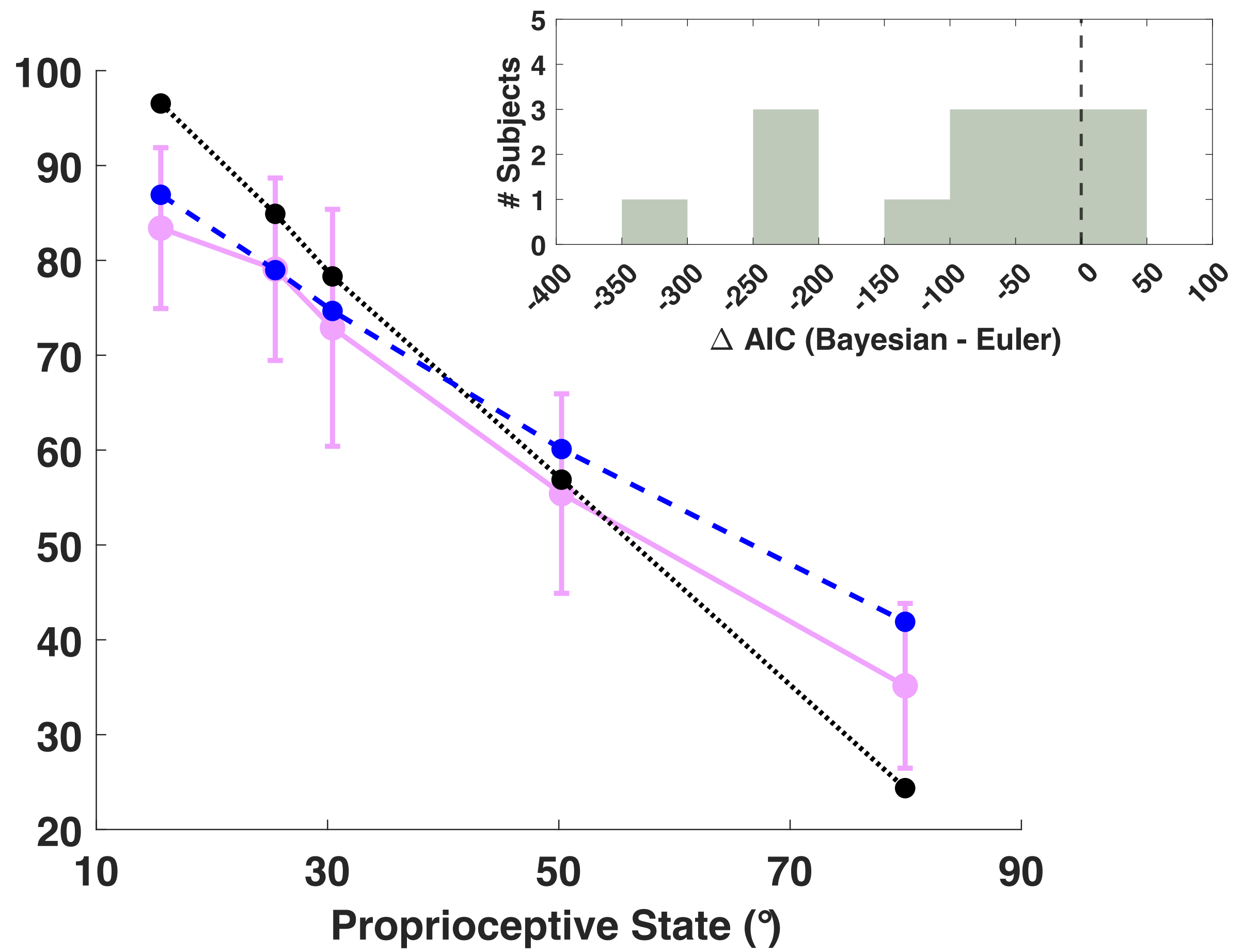
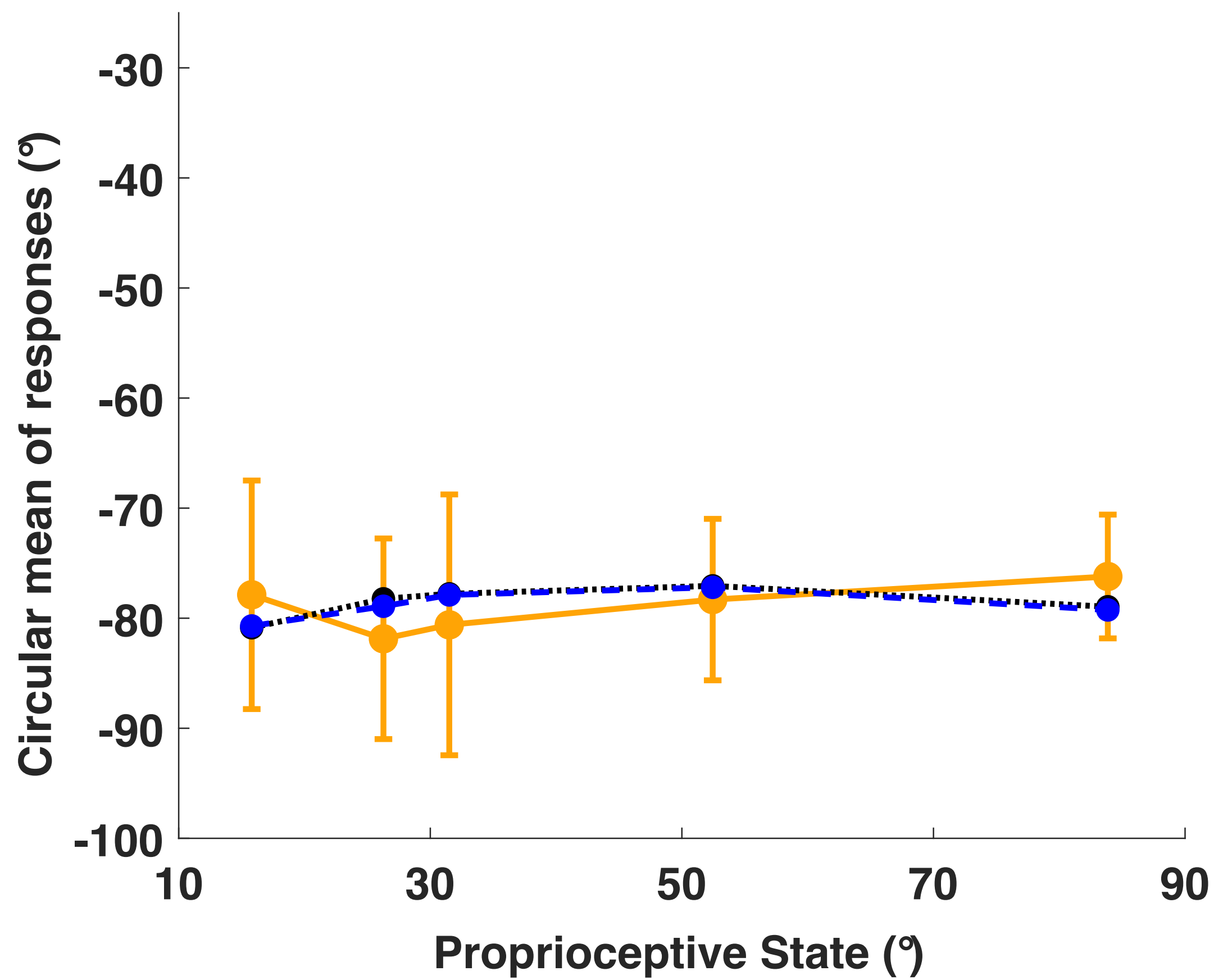
# Choice Bias & Proprioceptive Prior



$$R_{elbow}(v_{p_z}) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



# Bayesian generative model with prior and choice bias explains data and is generalizable

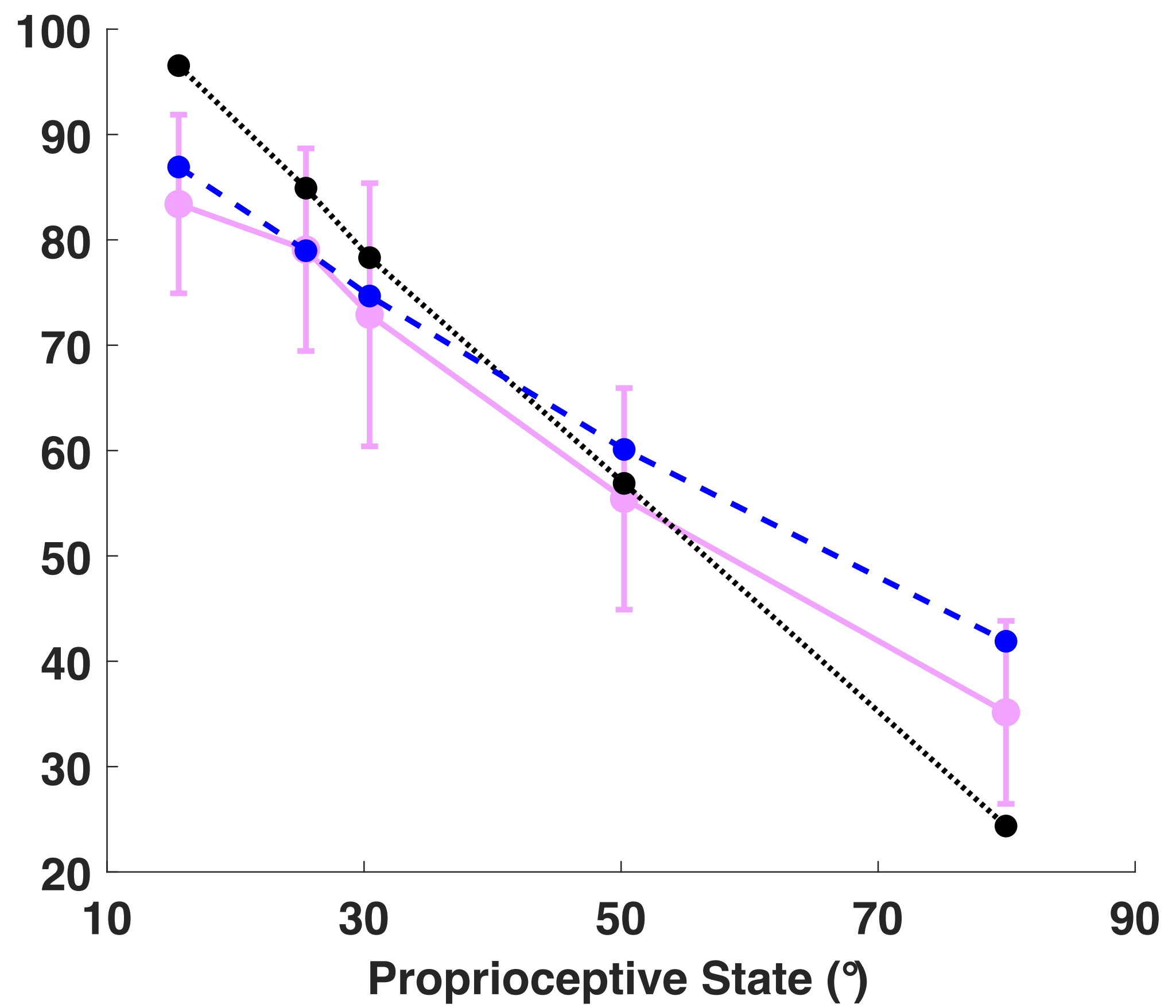
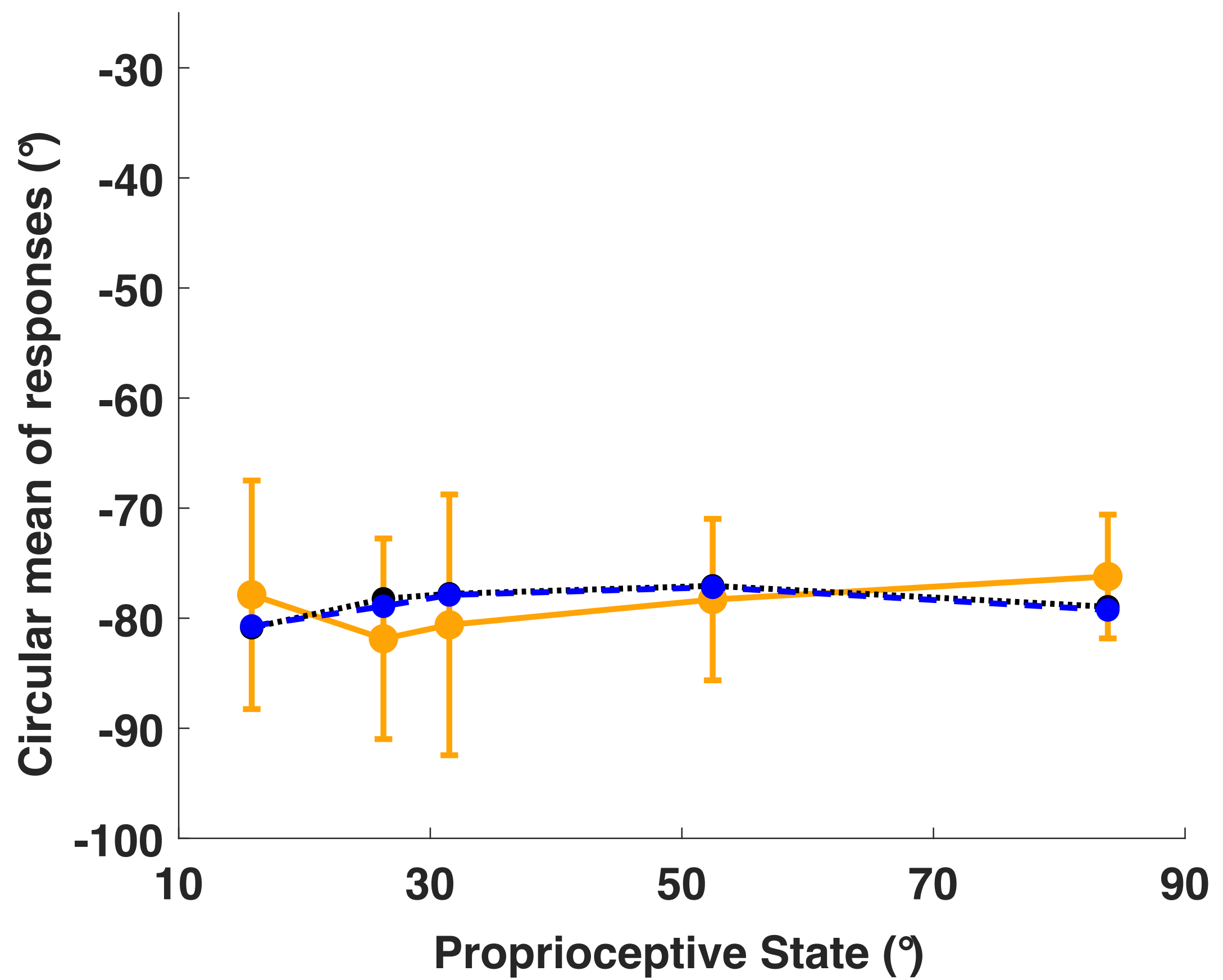


N = 14

Finger    Sternum    Euler    Bayesian

Error bars: S.E.M. 43

# explains data and is generalizable

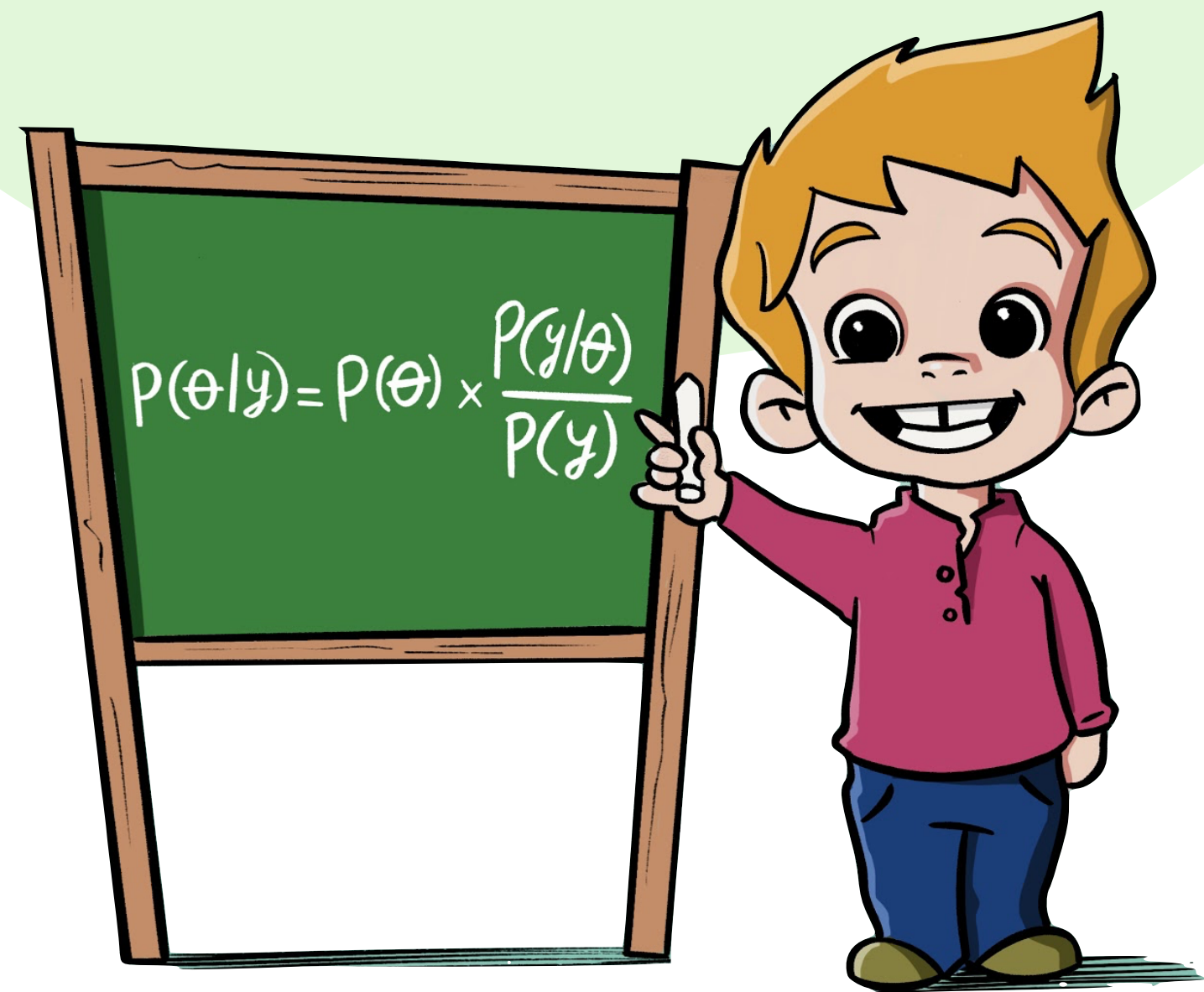


N = 14

Finger    Sternum    Euler    Bayesian

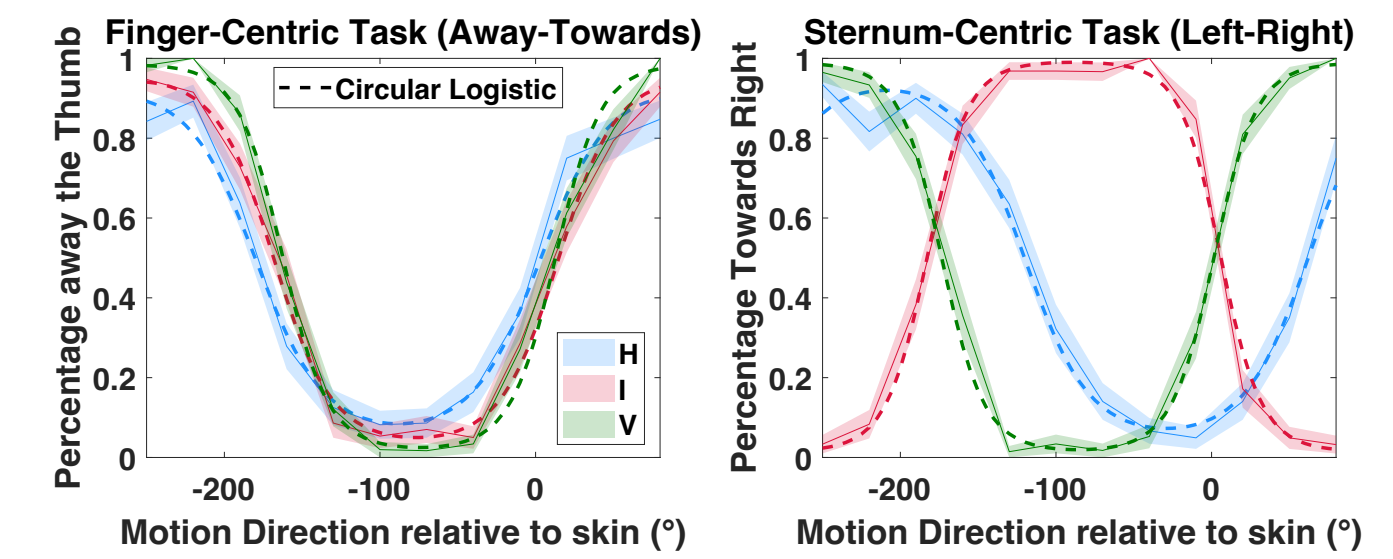
Error bars: S.E.M. 44

**Goal 2:** Develop a generalizable computational model that explains human behavioral report.



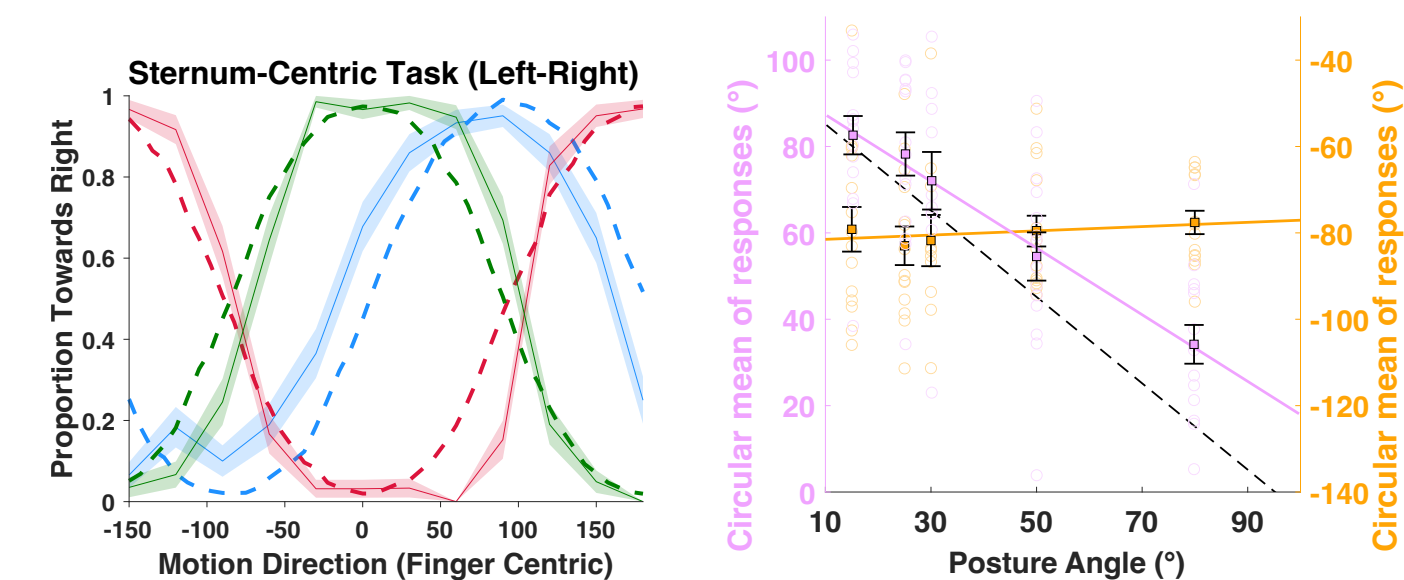
- Circular logistic does not generalize to new reference frames and postures.

$$\log\left(\frac{p^{(i)}}{1-p^{(i)}}\right) = \beta_0 + \beta_1 \cos(v_m^{(i)} + v_{p,\blacksquare}^{(i)}(\mathbf{RF})) + \beta_2 \sin(v_m^{(i)} + v_{p,\blacksquare}^{(i)}(\mathbf{RF}))$$

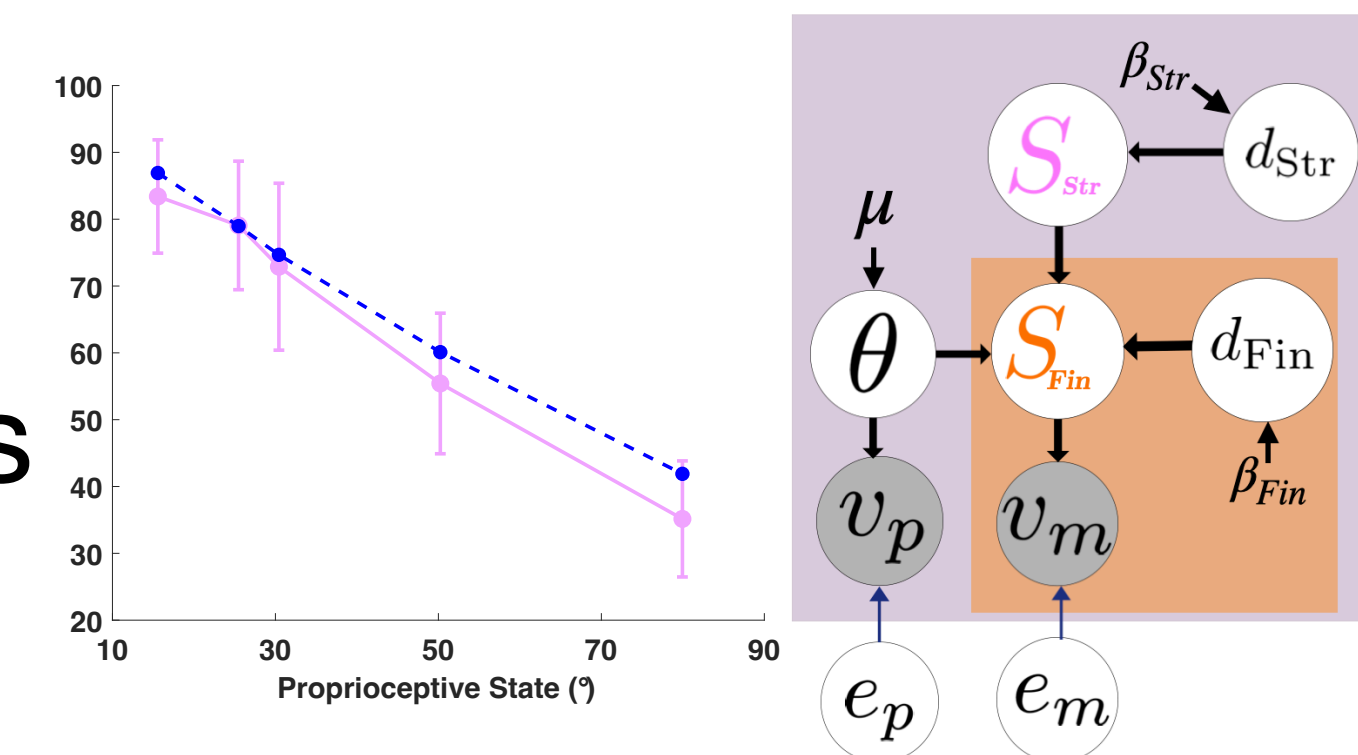


- Sternum-centric data deviates from standard Euler model

$$R_{elbow}(v_{p_z}) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



- Bayesian Generative model accommodates individual choice biases and proprioceptive prior.

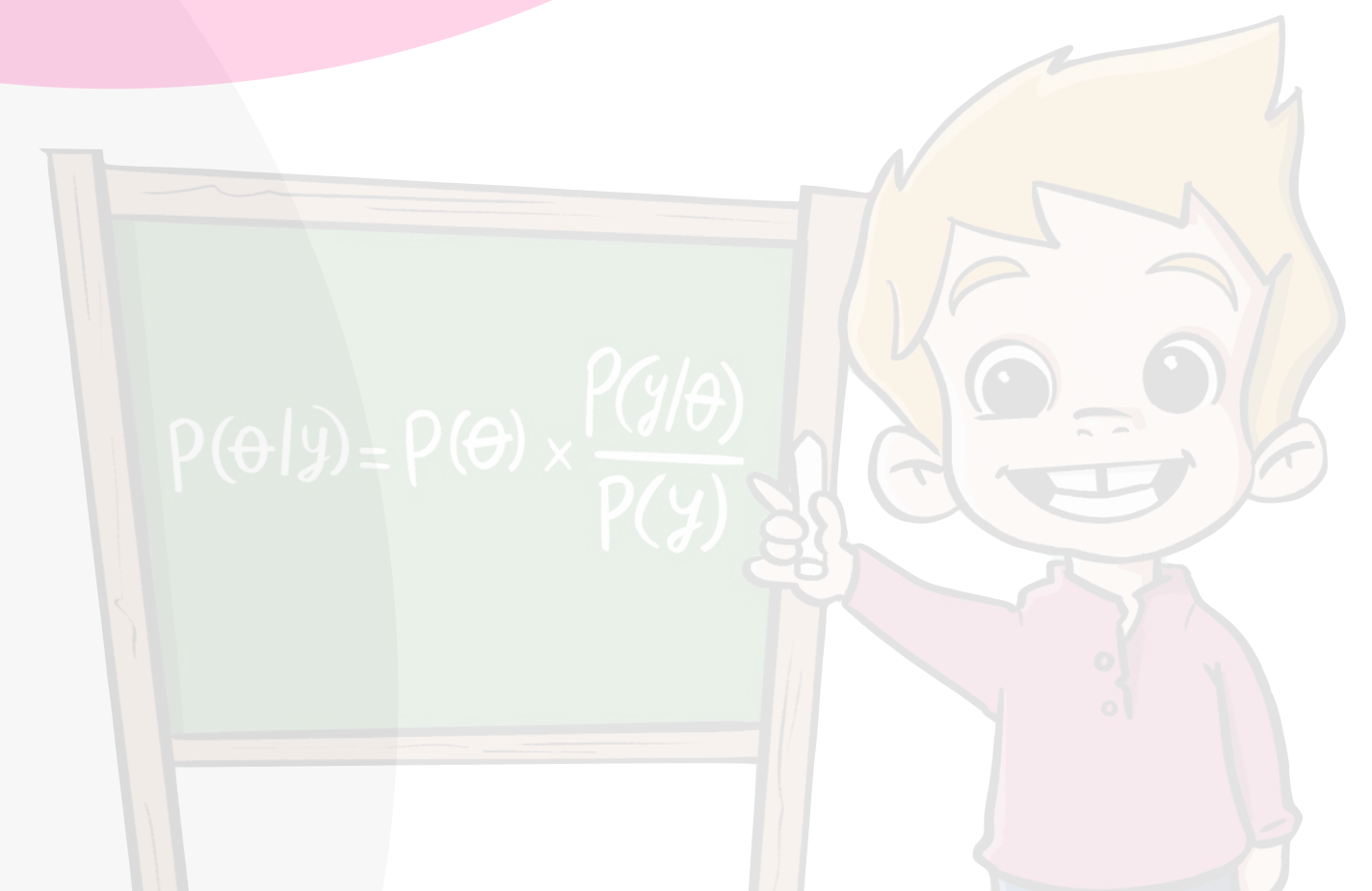


# Research questions of interest

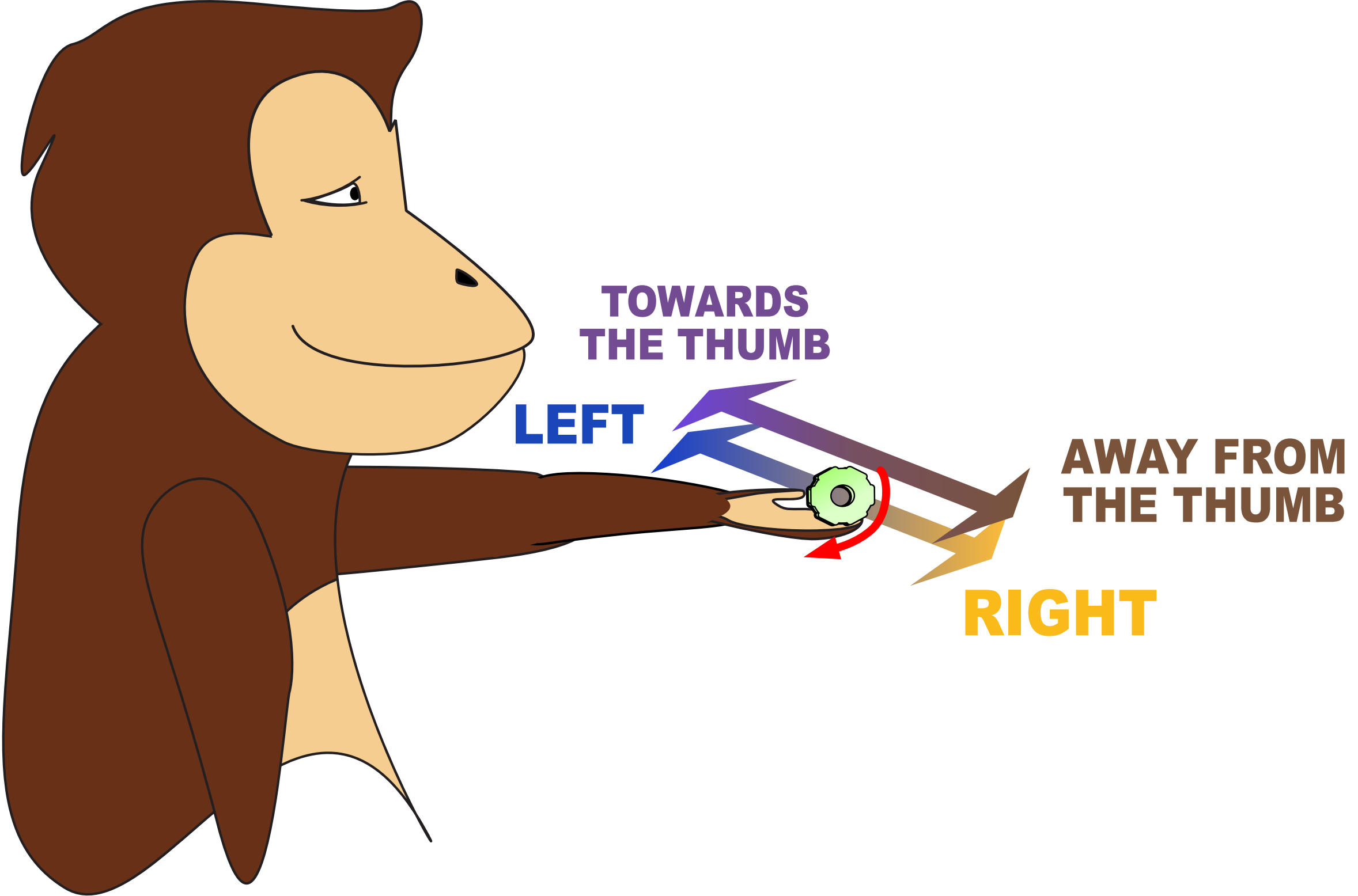
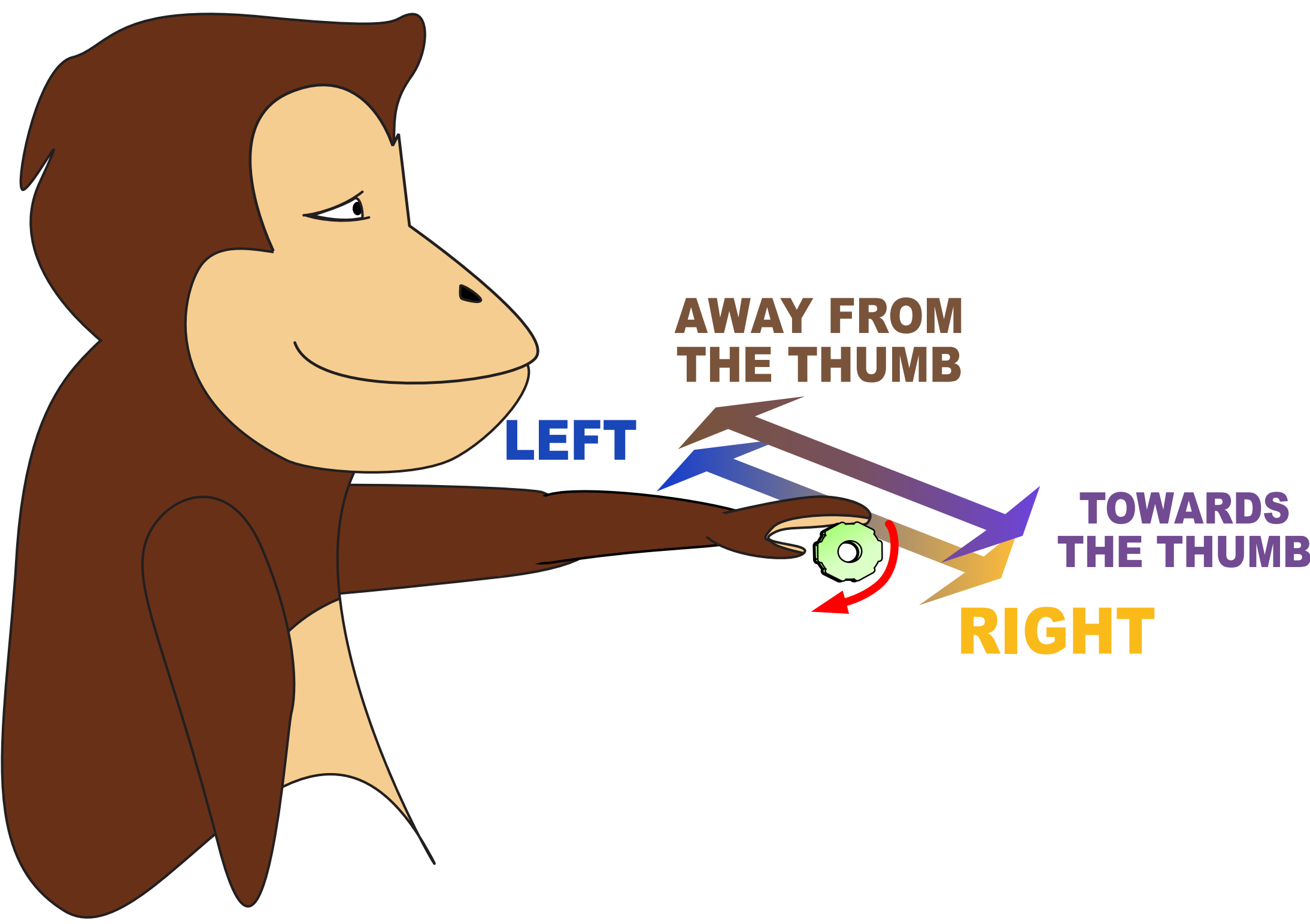
**Goal 1:** Determine if humans can flexibly perceive tactile motion in different proprioceptive states and reference frames?

**Goal 3:** Determine how tactile motion information is modulated by proprioception in the brain?

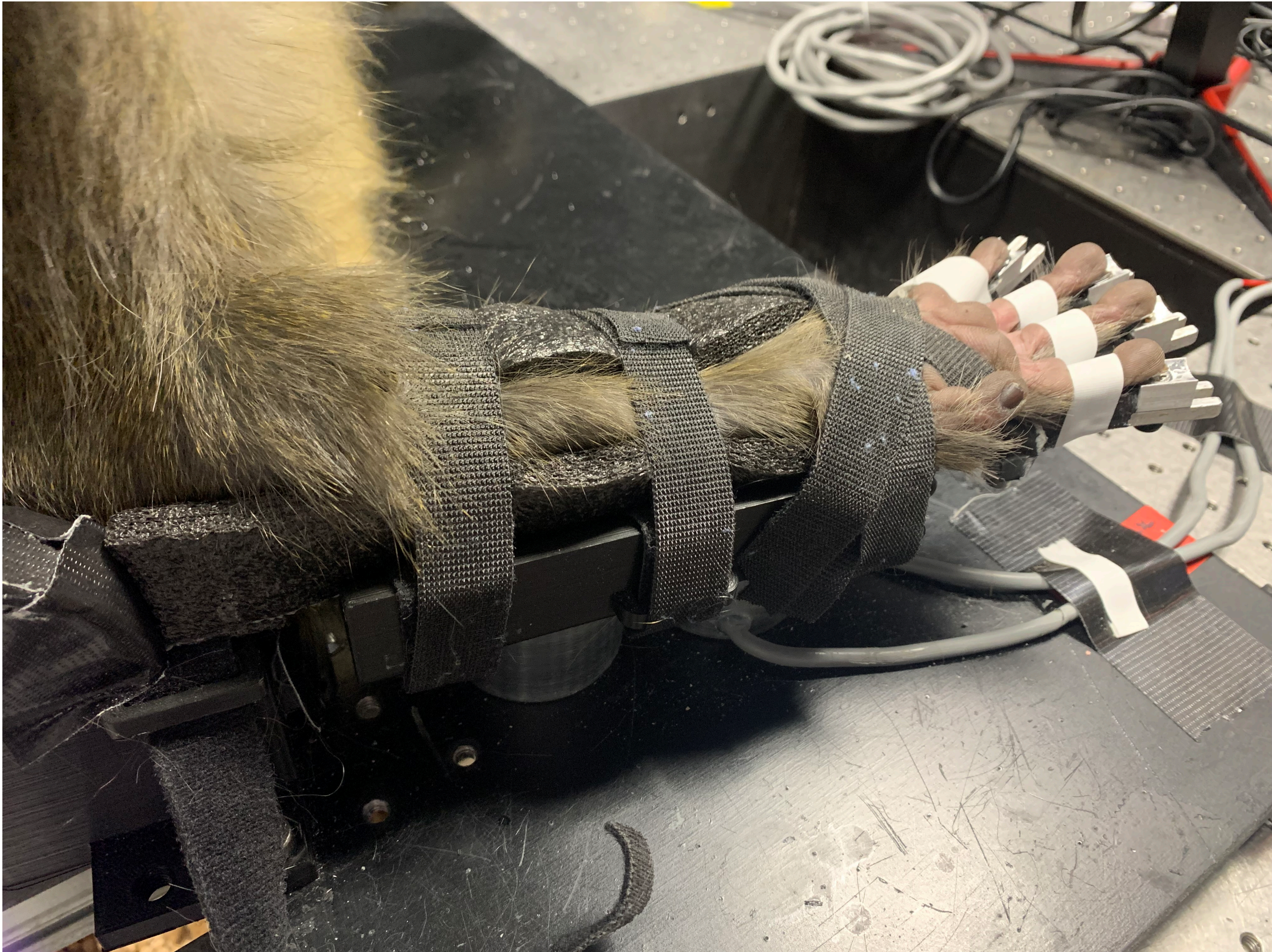
**Goal 2:** Develop a generalizable computational model that explains human behavioral report.



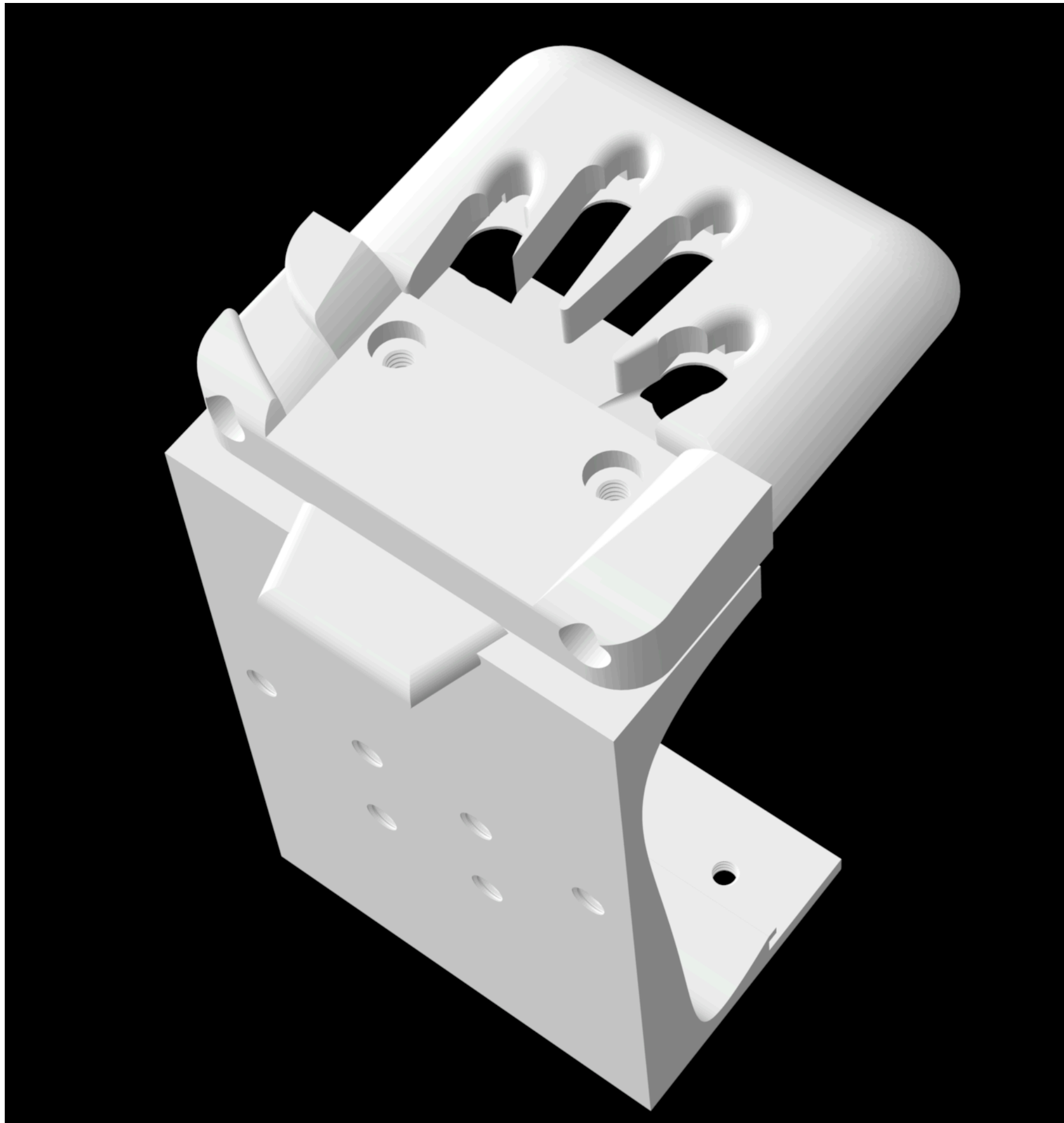
# Training a monkey to do reference-frame motion discrimination task



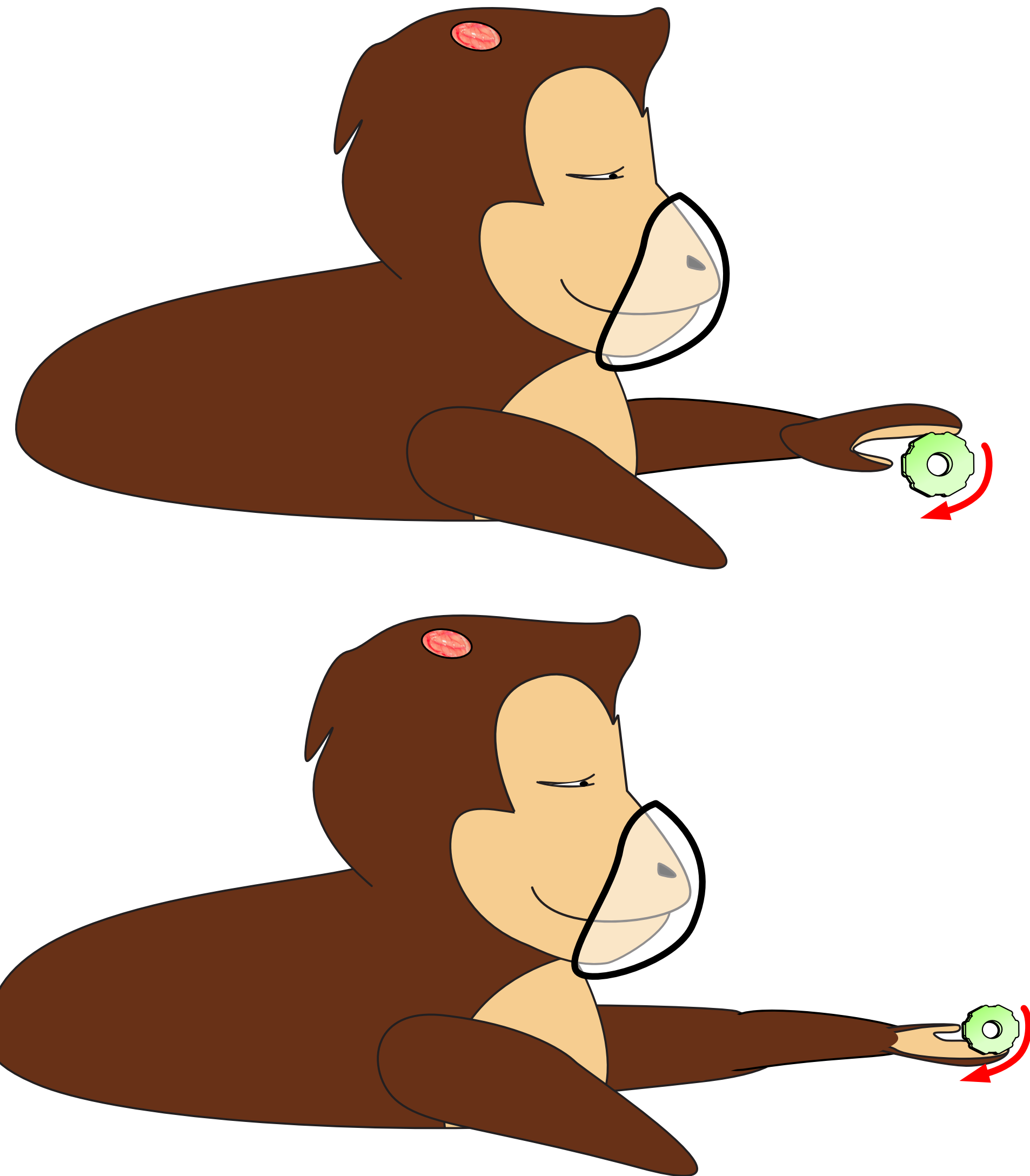
# Animal trained to do this task more naturally.



# Animal trained to do this task more naturally.



# Anesthetized recording from monkey S1



**Direction:** 0-360°, steps of 22.5°

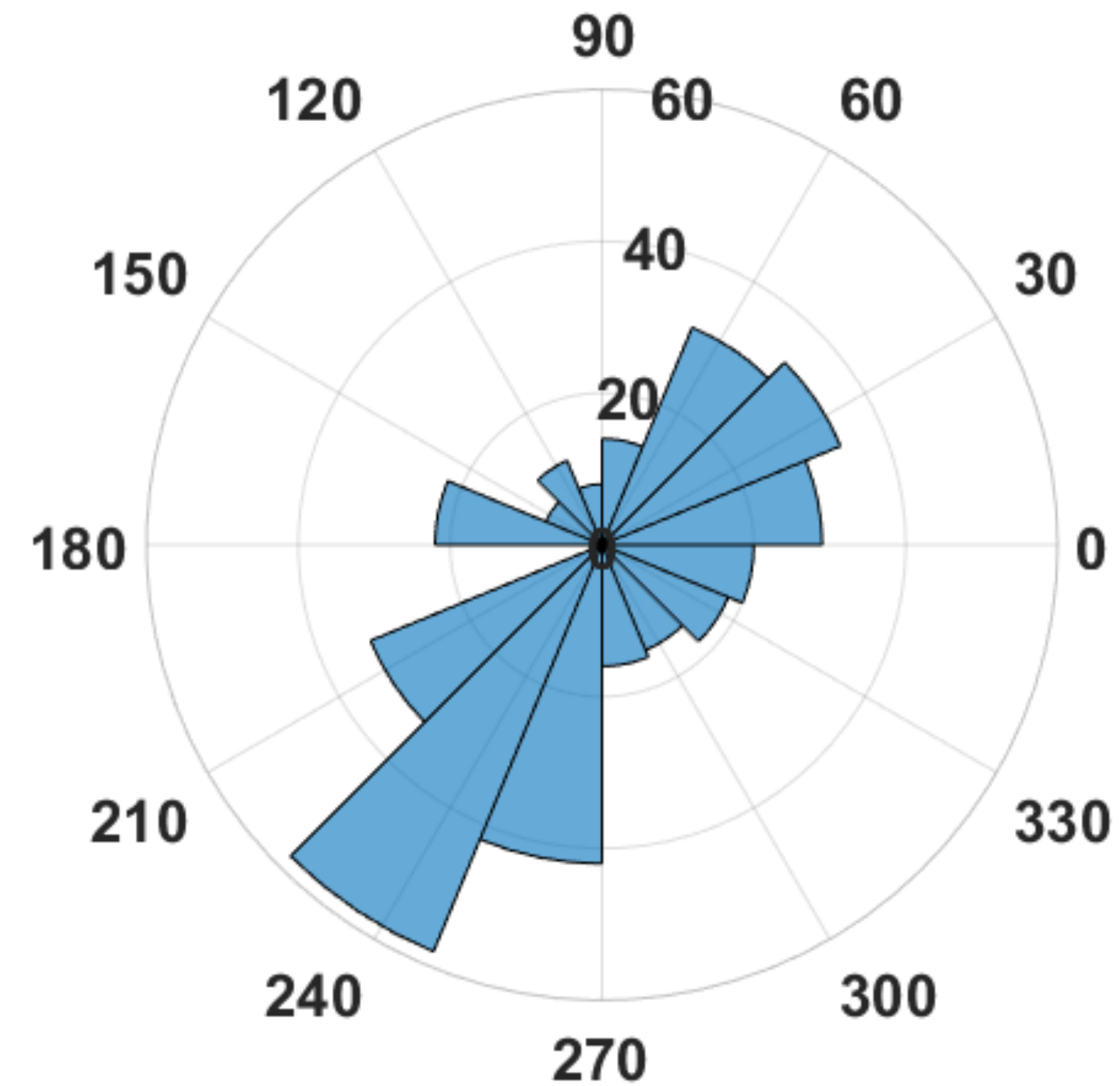
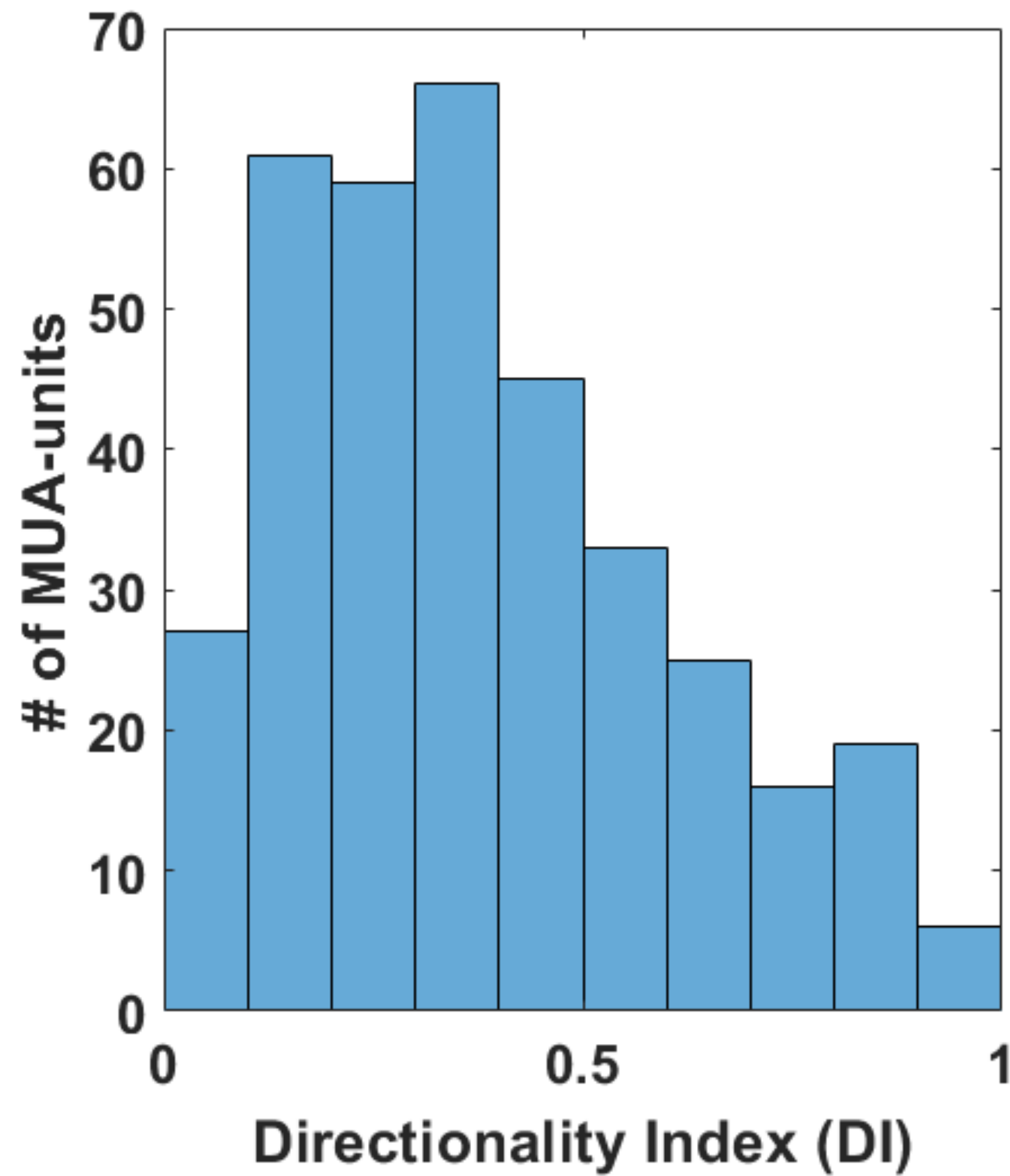
**Point of Stimulation:** Dependent on the receptive field within the somatosensory cortex

**NO** Reference frame instruction

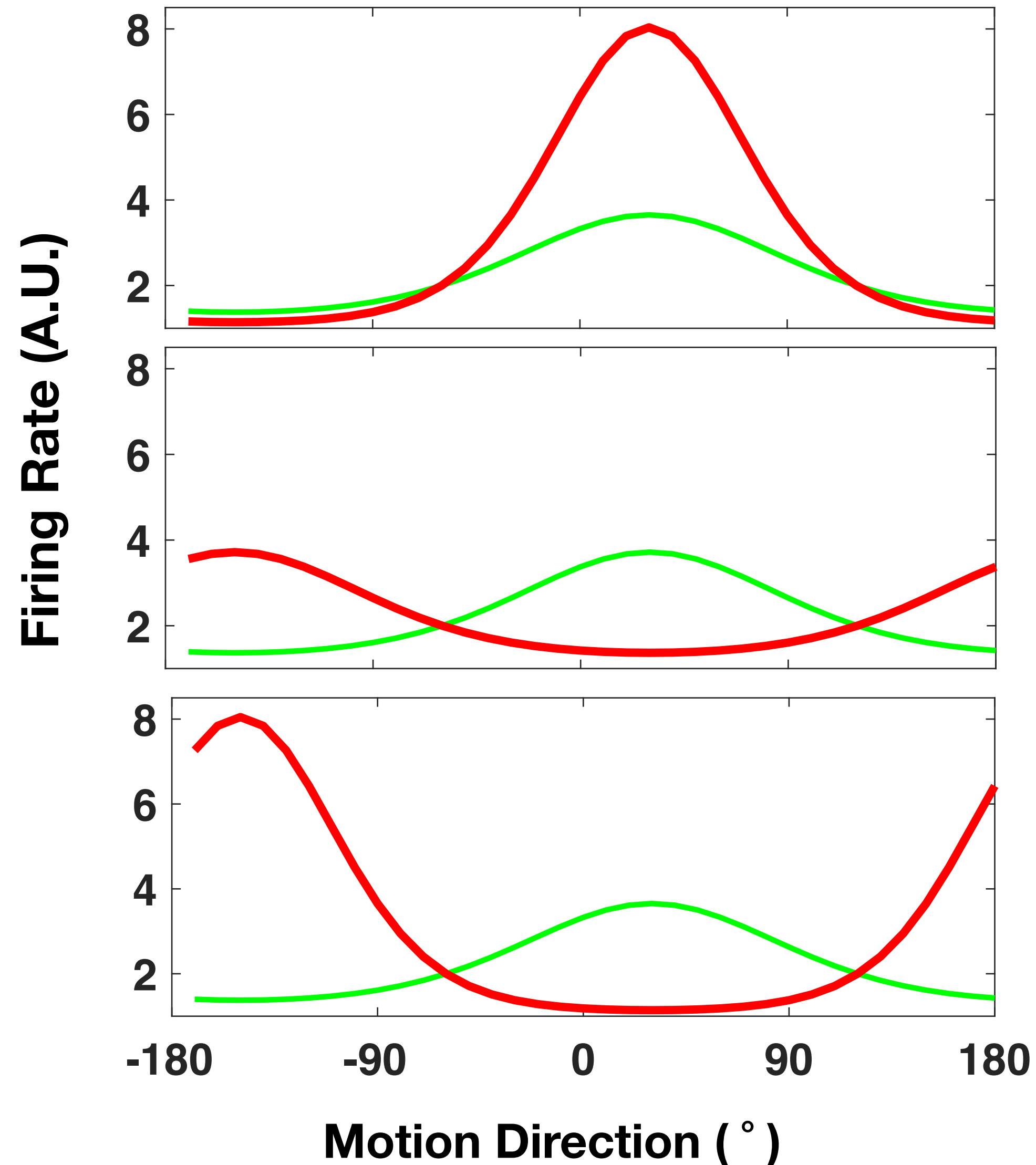
**Neuropixel-NHP** were used for the anesthetized recordings.



# Direction - sensitive neurons in somatosensory cortex



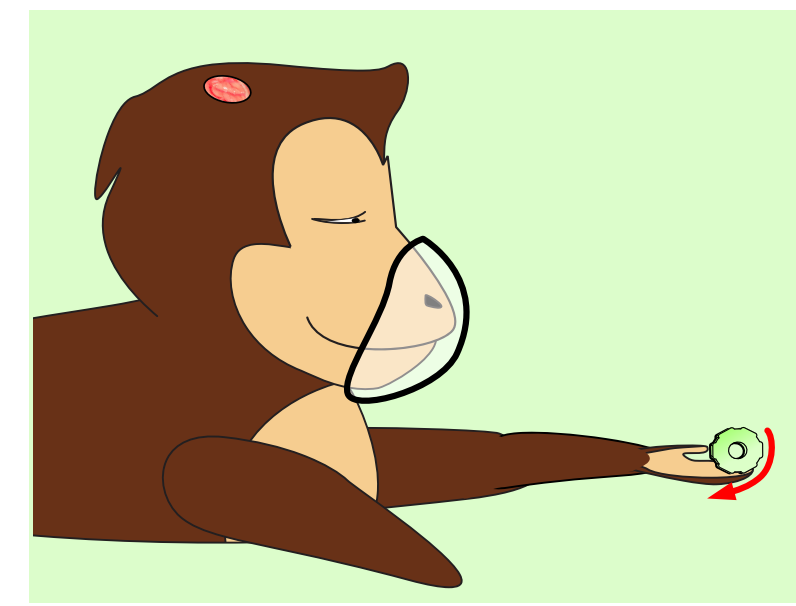
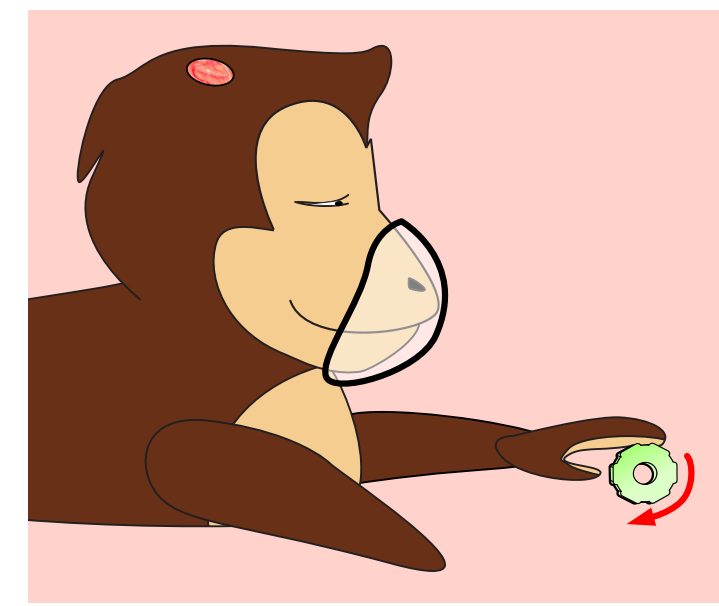
# Expected Neural Activity



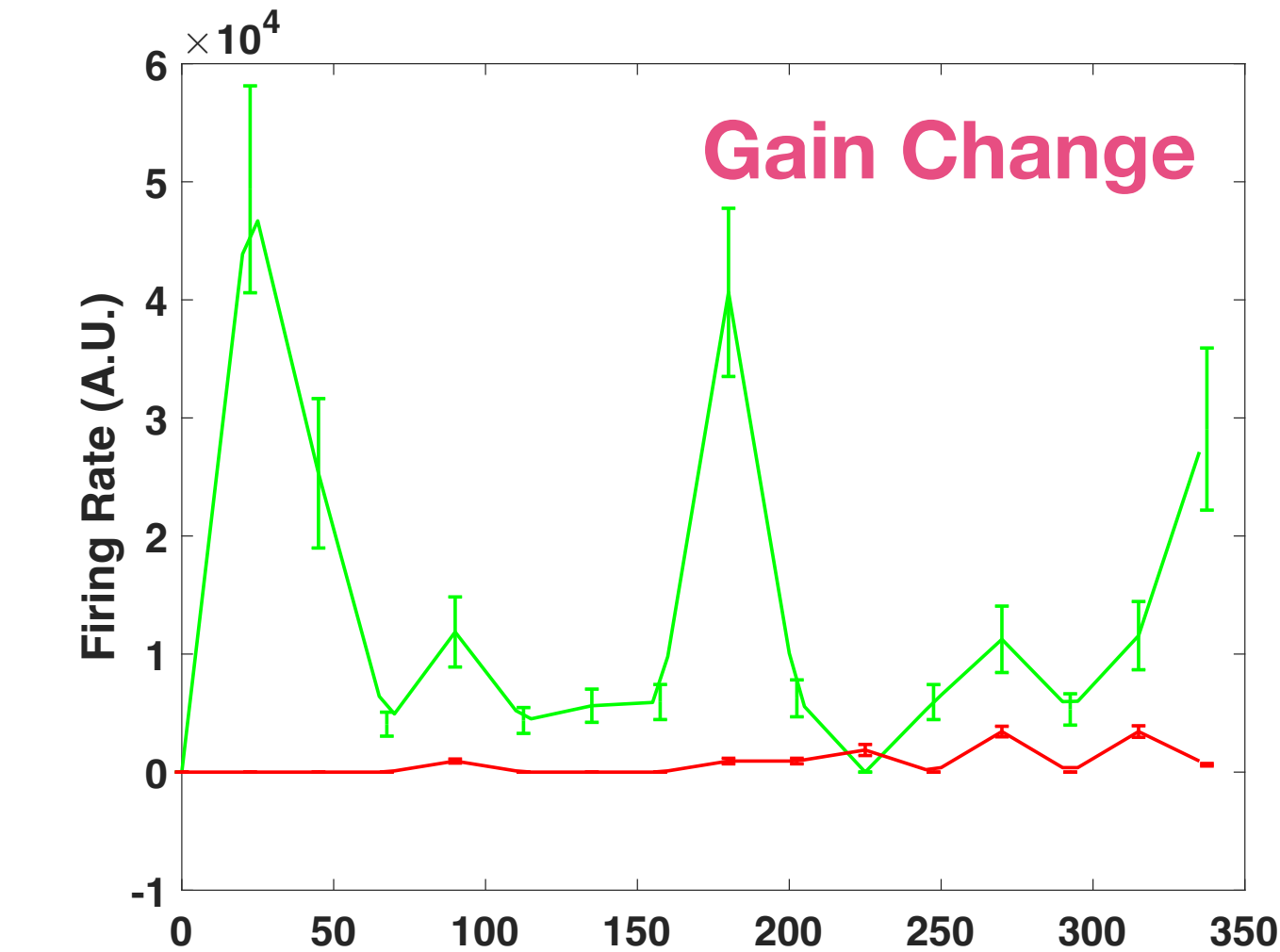
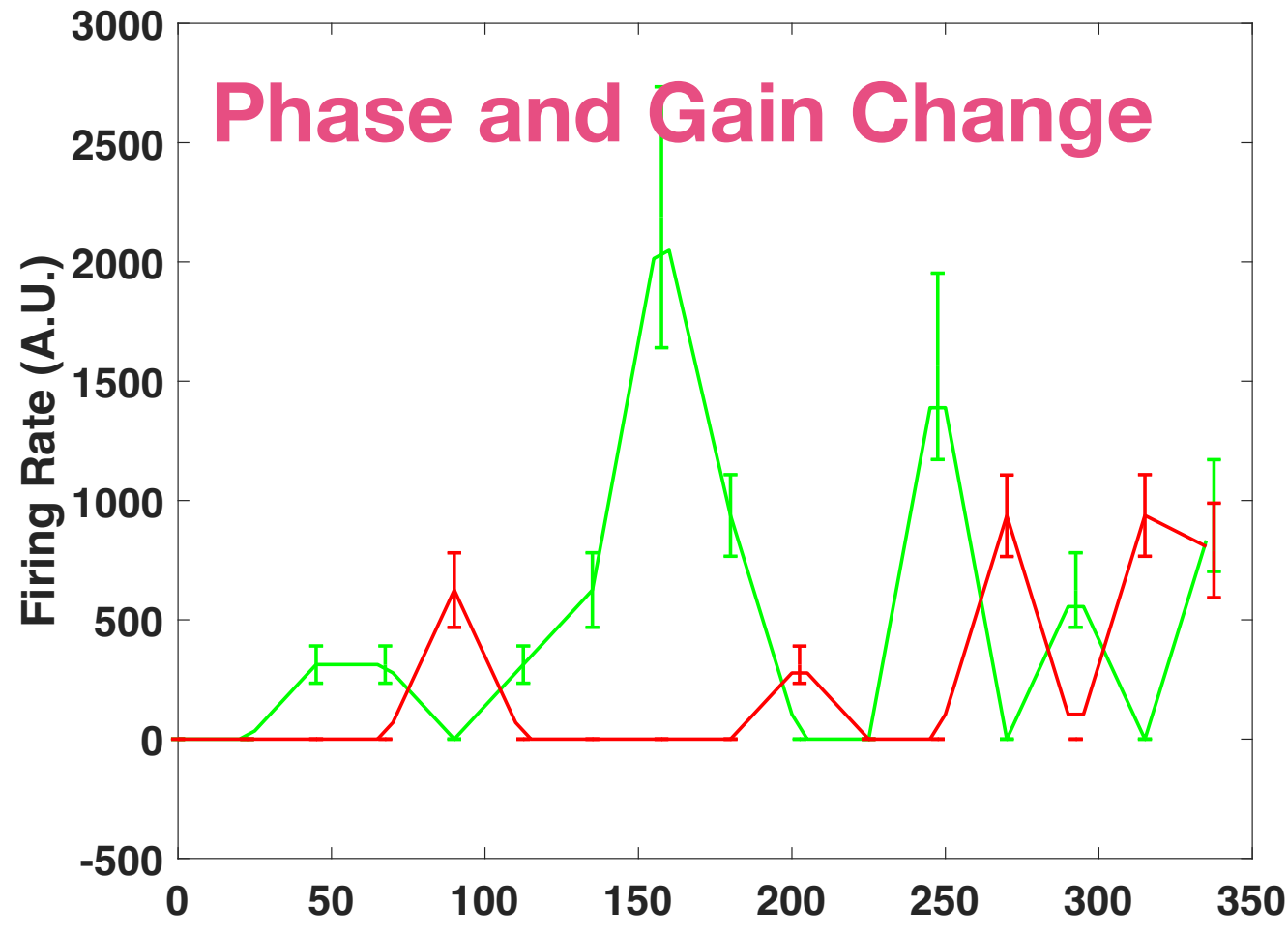
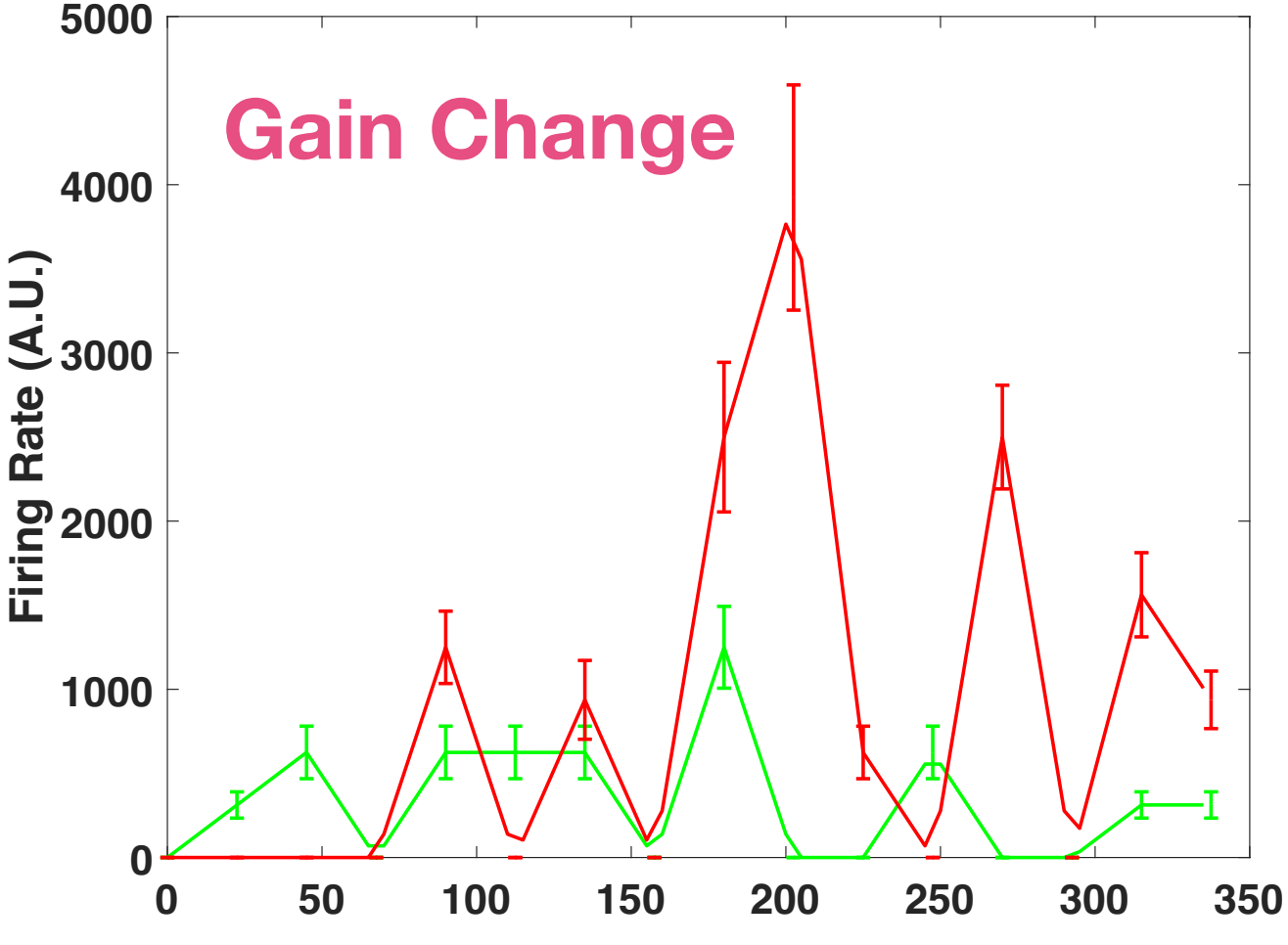
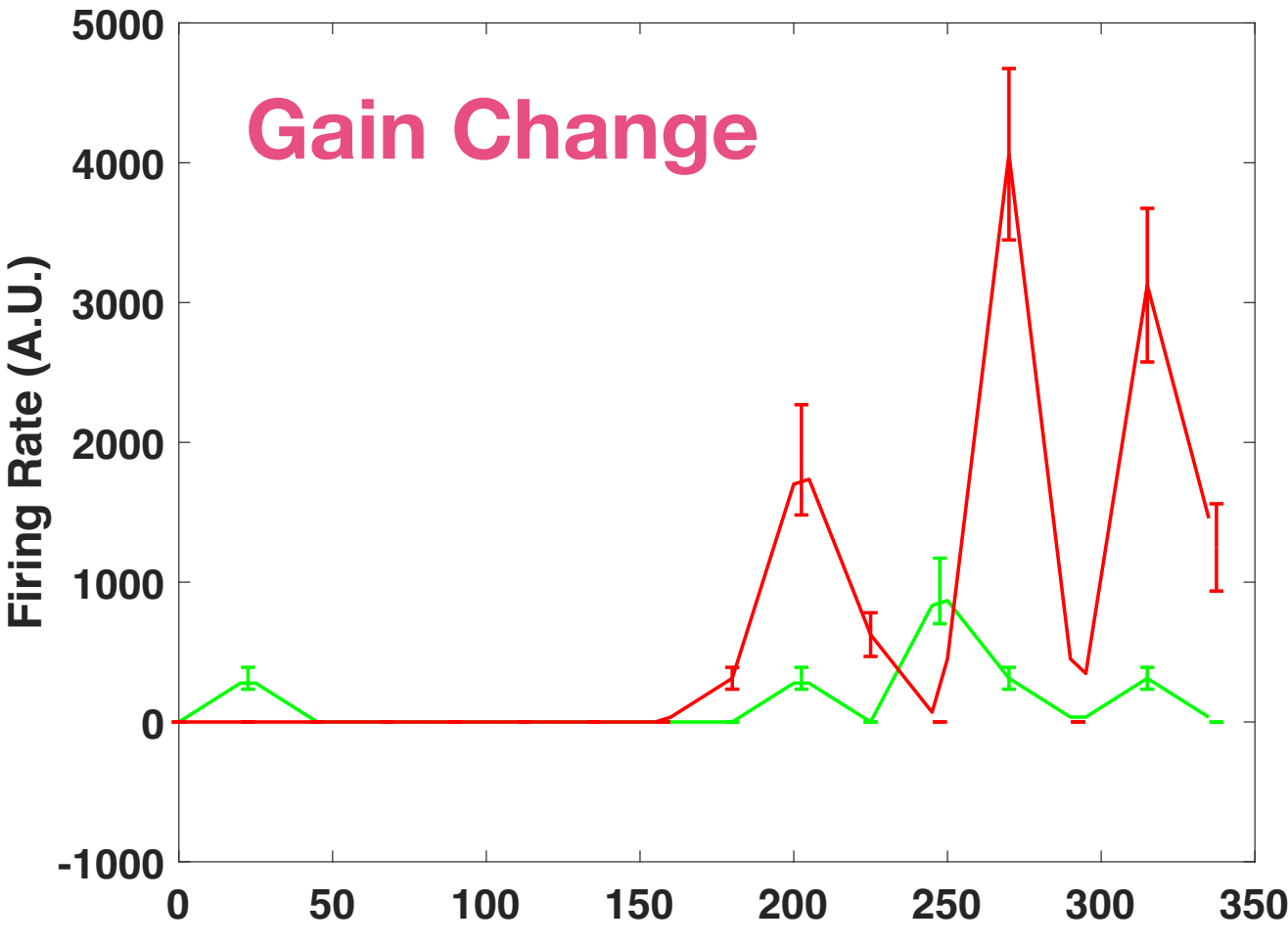
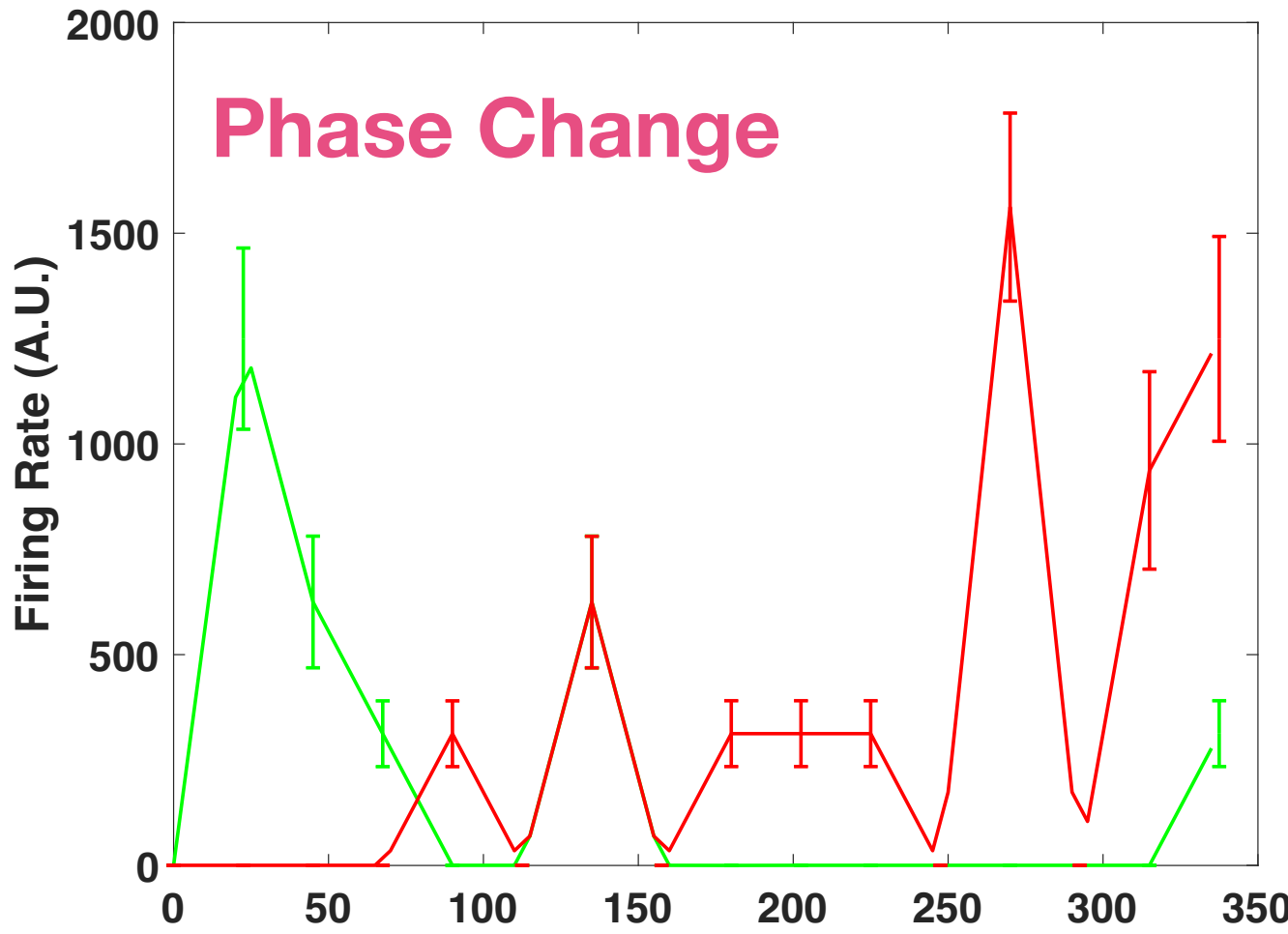
Gain change only

Phase change only

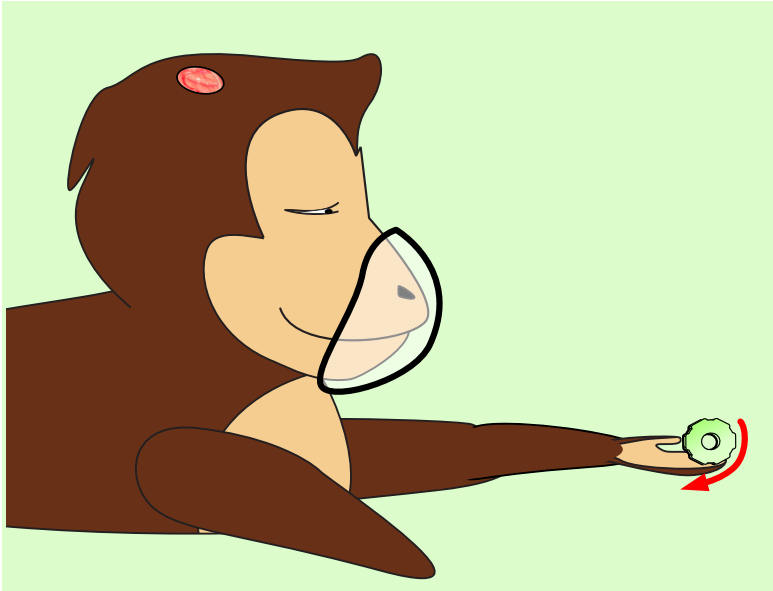
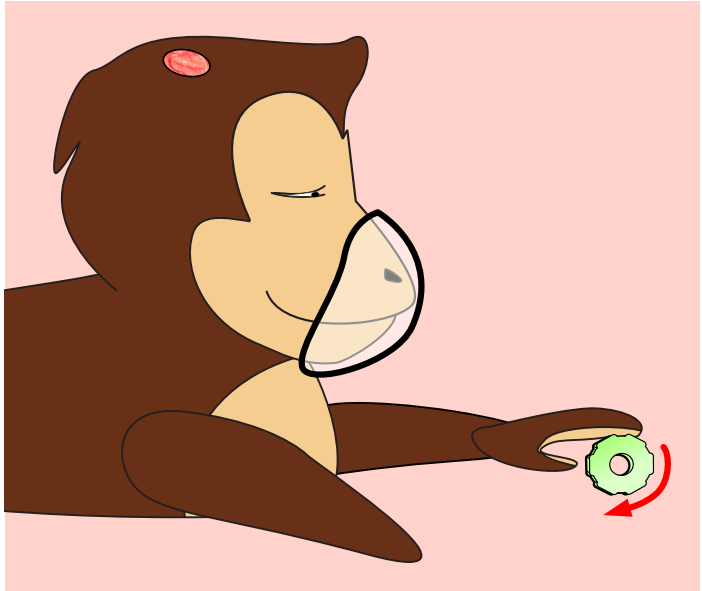
Phase and gain change combination



# Multi-unit activity shows phase and gain shifts



Motion Direction (°)

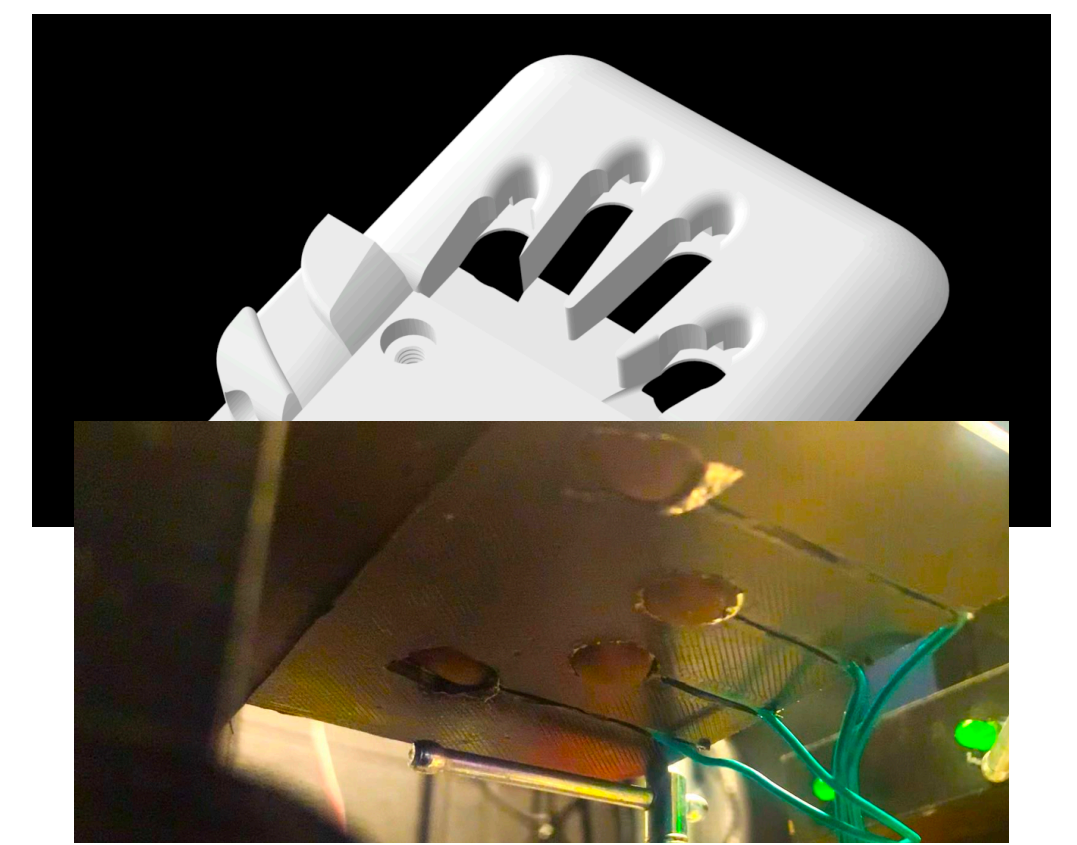


**Goal 3:** Determine how tactile motion information is modulated by proprioception in the brain?

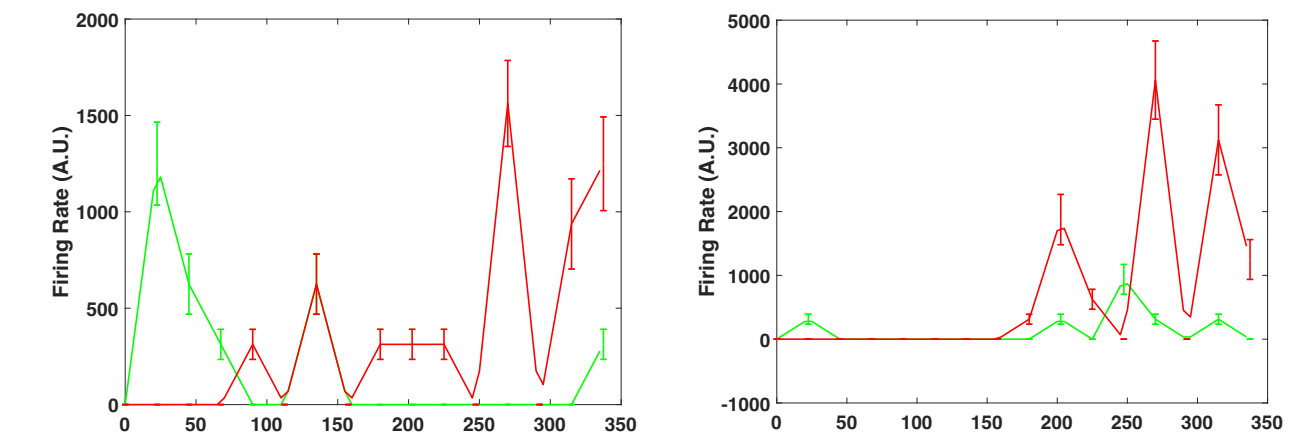


COMING UP

- Training the monkey to perform a naturalistic reach to receive tactile motion in different proprioceptive states.



- Multi-unit activity shows phase shift and gain shifts across postures.



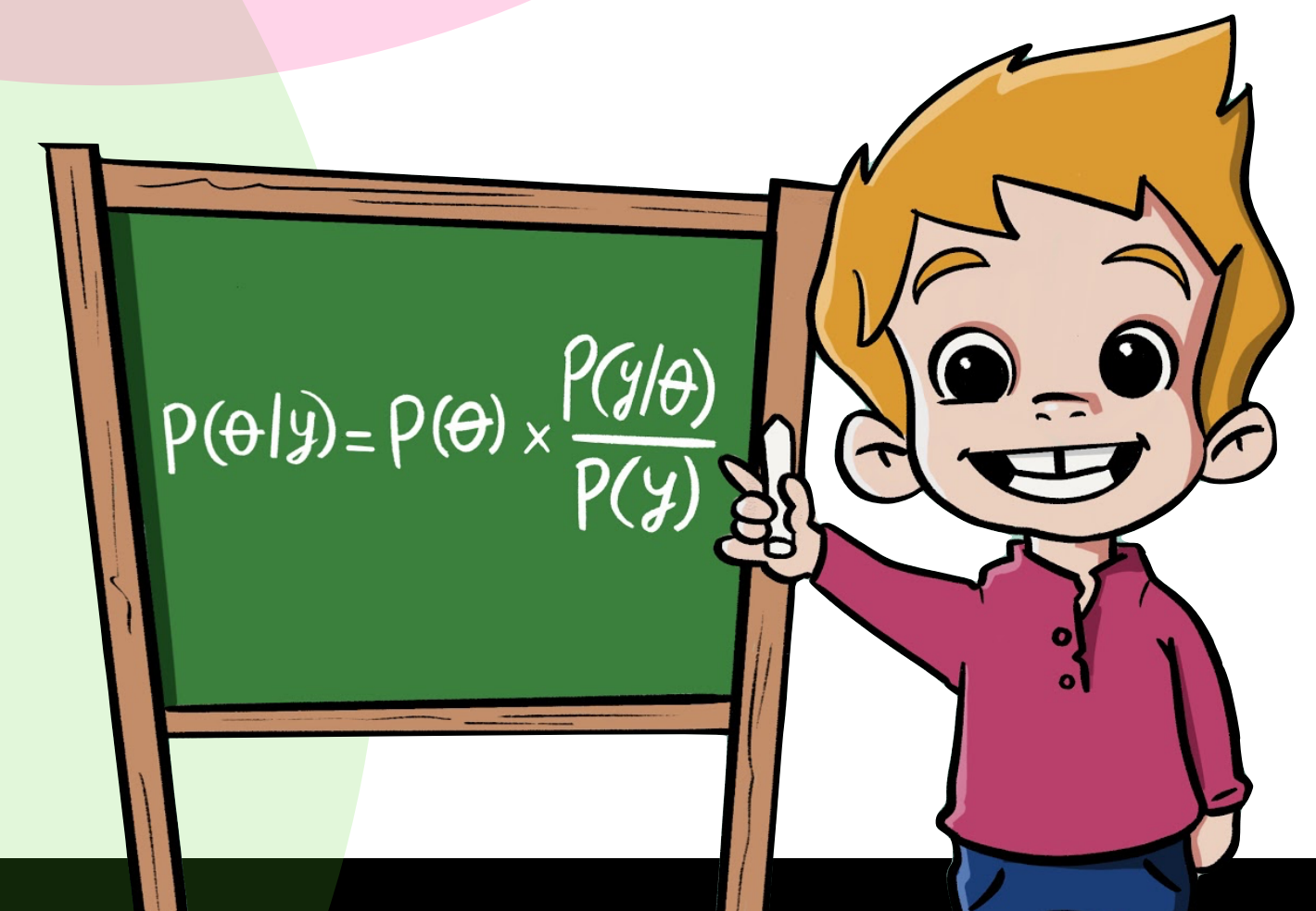
- Training the monkey to perform tactile motion discrimination in two reference frames.
- Individual unit motion tuning across postures.

# Research questions of interest

**Goal 1:** Determine if humans can flexibly perceive tactile motion in different proprioceptive states and reference frames?

**Goal 3:** Determine how tactile motion information is modulated by proprioception in the brain?

**Goal 2:** Develop a generalizable computational model that explains human behavioral report.



# Acknowledgements

- **Prof. Manuel Gomez-Ramirez, Prof. Ralf Haefner, Prof. Gregory DeAngelis** for their continual guidance throughout these project.
- **Sabyasachi Shivkumar:** For modeling and fitting the behavioral results
- **Catalina Feistritzer, Amy Fuller, Yihan Xie:** Processing data and running human participants
- Haptics Lab



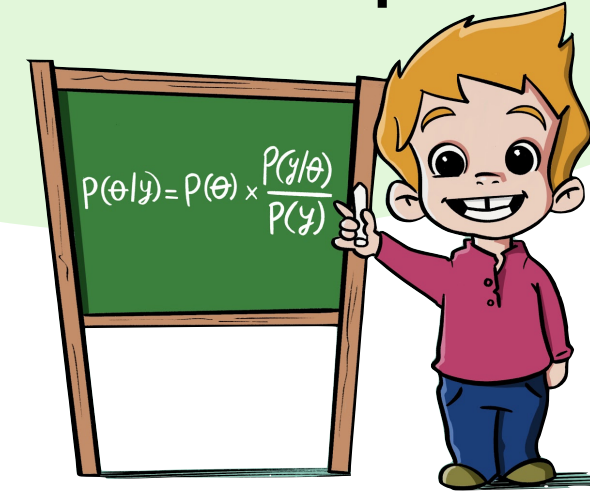
# QUESTIONS AND COMMENTS

**Goal 1:** Determine if humans can flexibly perceive tactile motion in different proprioceptive states and reference frames?



- Proprioception modulates tactile motion perception in a reference-frame dependent manner.
- Sternum-centric task has faster readout.
- Proprioceptive noise in sternum-centric task
- Proprioception biases motion judgement in a reference-frame dependent manner.

**Goal 2:** Develop a generalizable computational model that explains human behavioral report.



- Circular logistic does not generalize to new reference frames and postures.
- Sternum-centric data deviates from standard Euler model
- Bayesian Generative model accommodates individual choice biases and idiosyncratic proprioceptive priors.

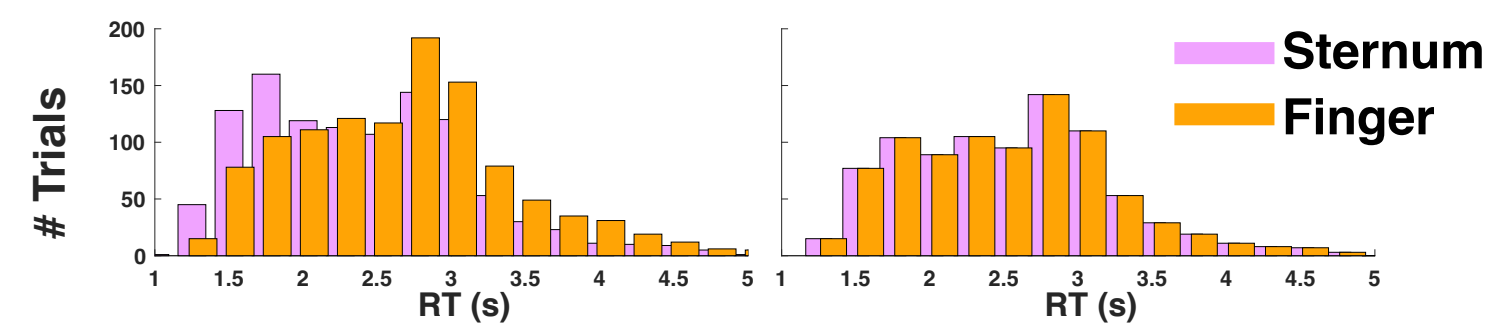
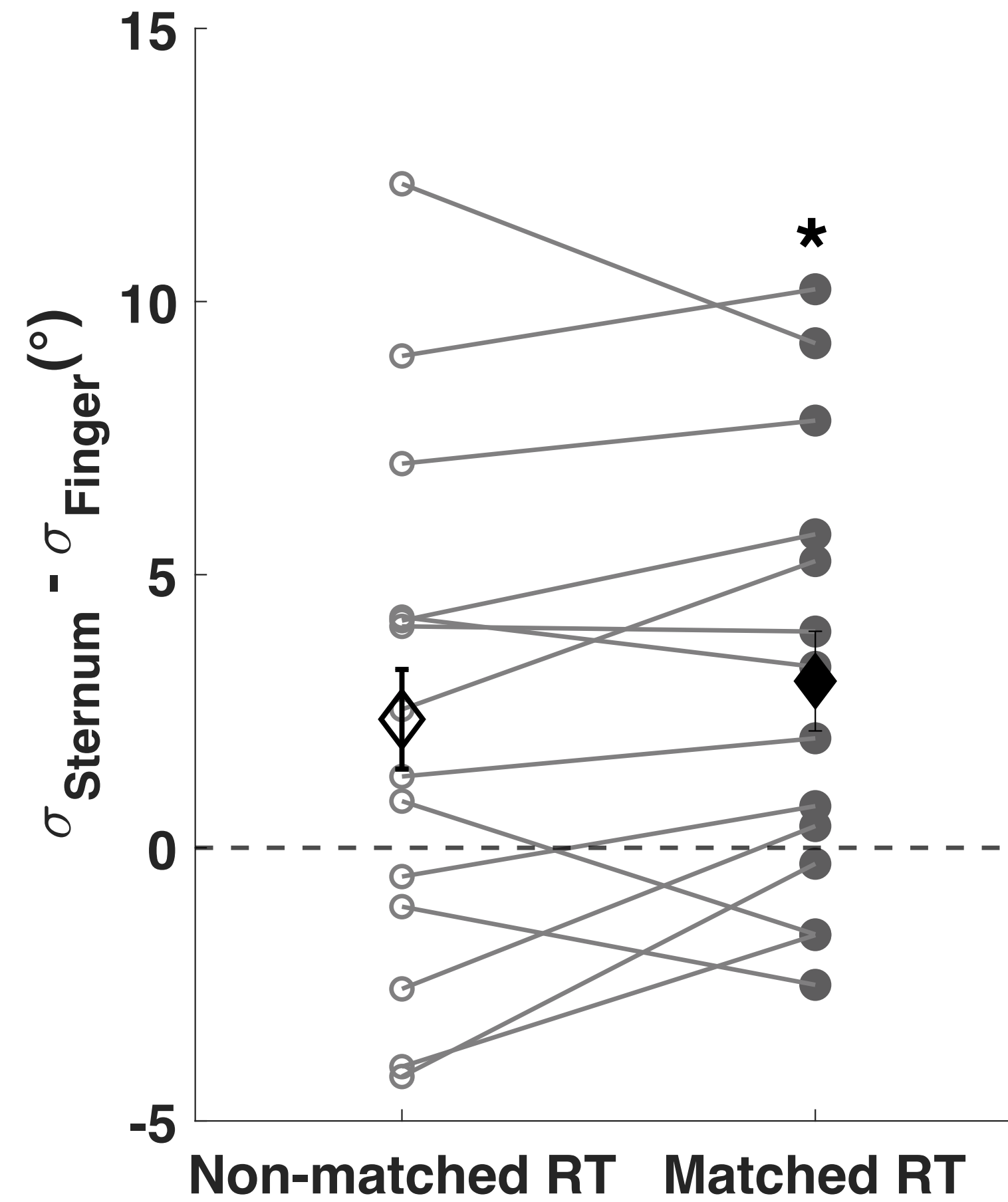
**Goal 3:** Determine how tactile motion information is modulated by proprioception in the brain?



- Training the monkey to perform a naturalistic reach to receive tactile motion in different proprioceptive states.
- Multi-unit activity shows phase shift and gain shifts across postures.

# Supplementary Material

# Difference in variance between reference frames



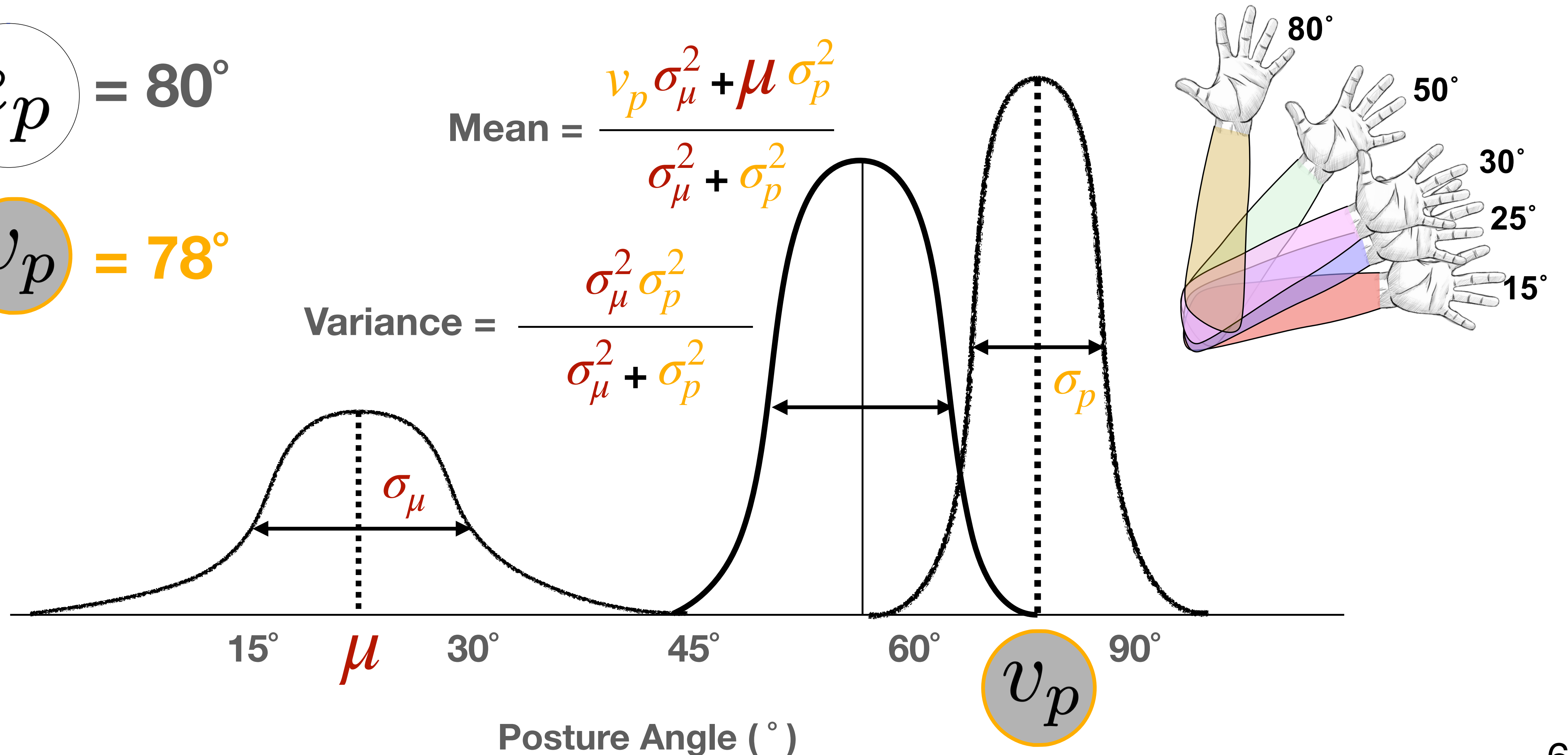
# Mixing prior belief with posture estimate

$$e_p = 80^\circ$$

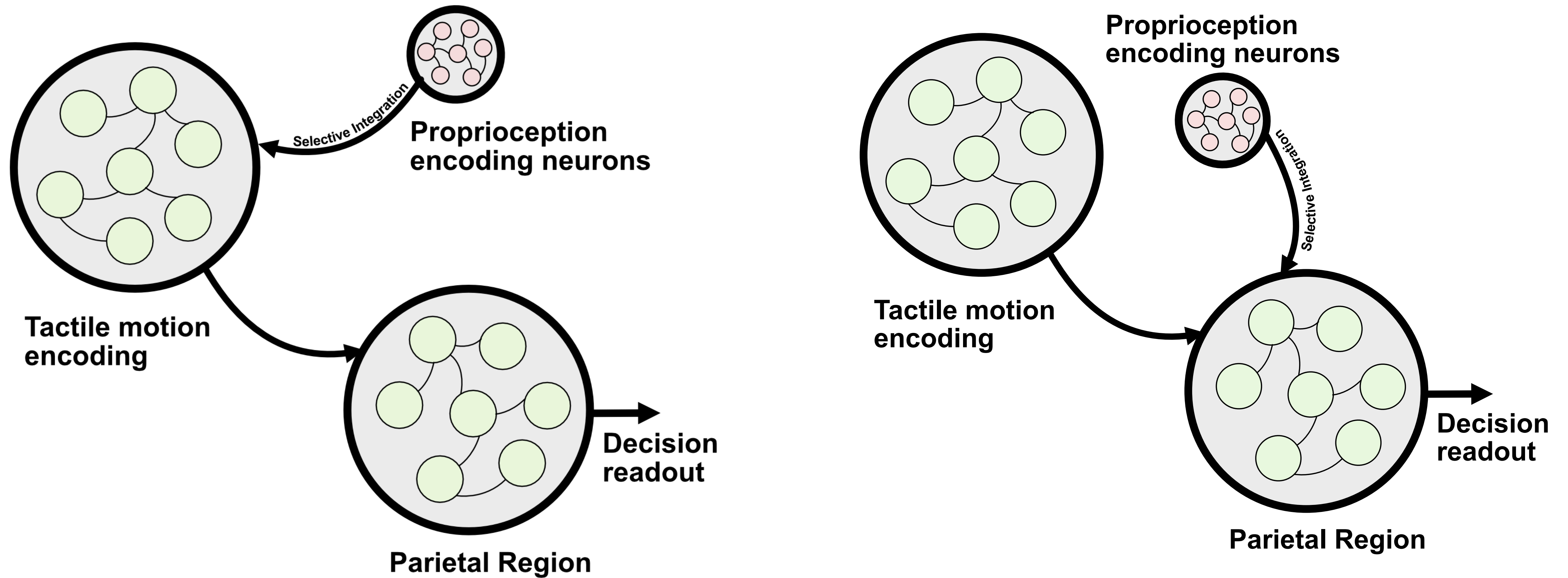
$$v_p = 78^\circ$$

$$\text{Mean} = \frac{v_p \sigma_\mu^2 + \mu \sigma_p^2}{\sigma_\mu^2 + \sigma_p^2}$$

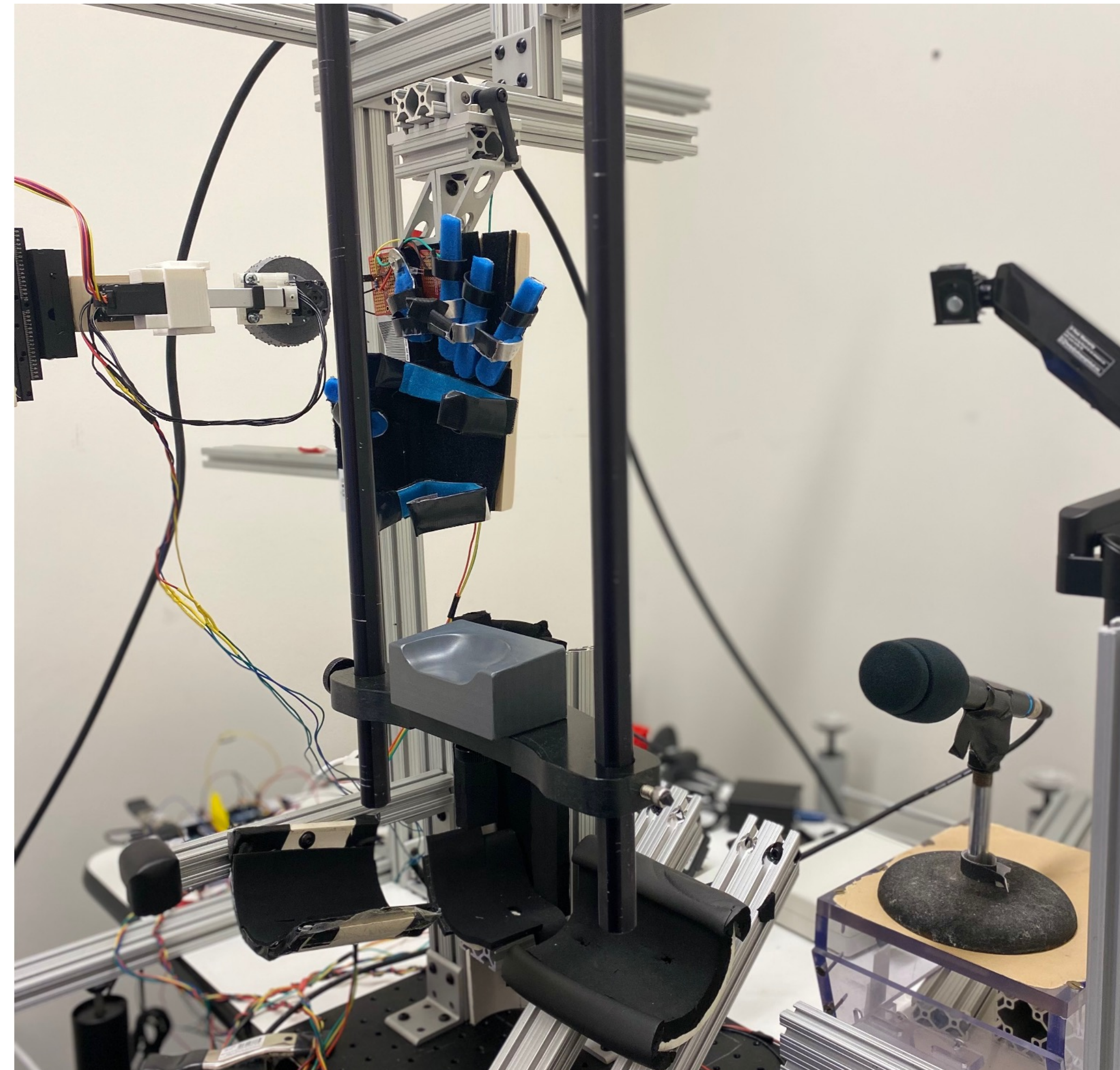
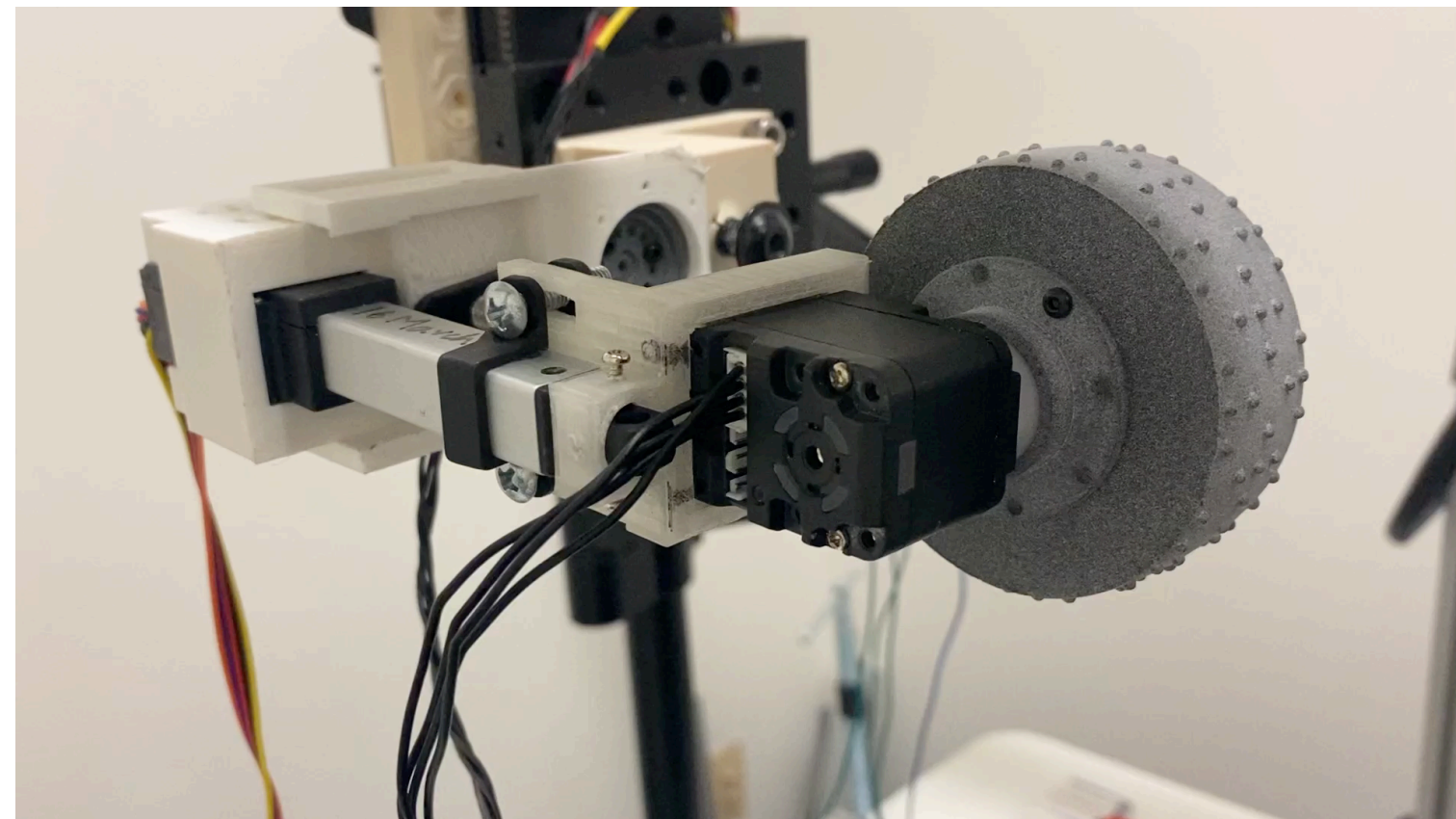
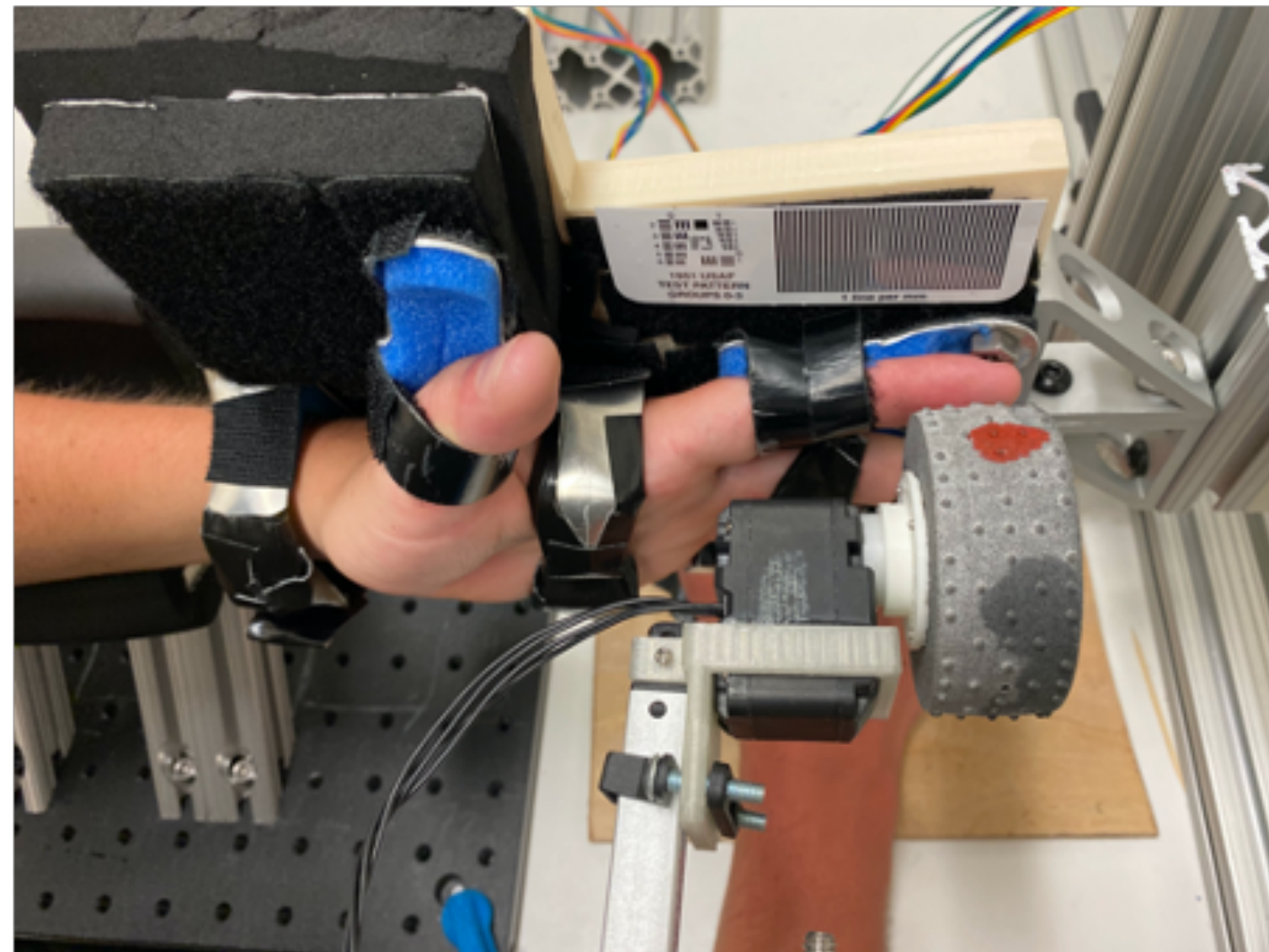
$$\text{Variance} = \frac{\sigma_\mu^2 \sigma_p^2}{\sigma_\mu^2 + \sigma_p^2}$$



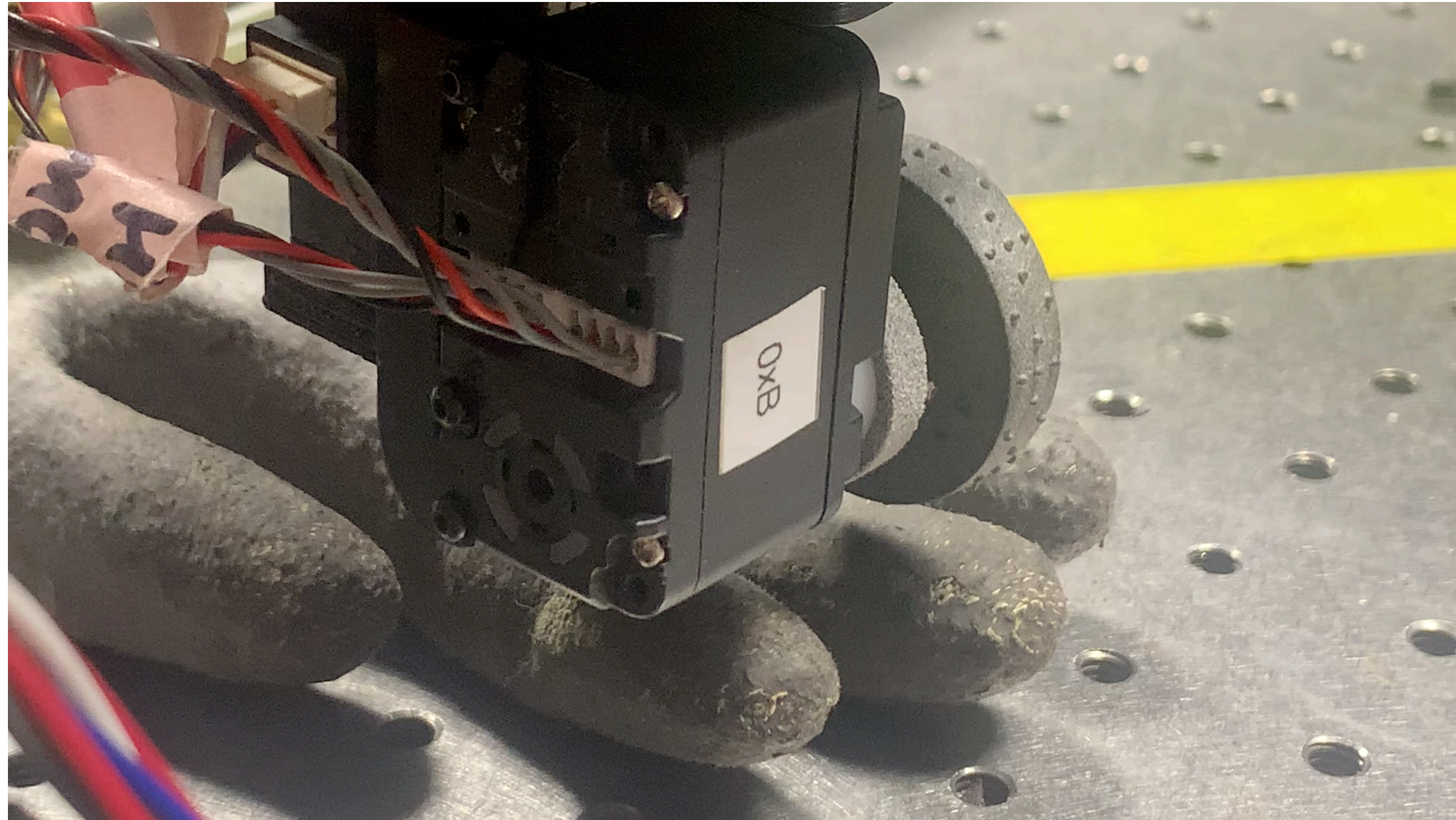
# Neural implementation possibilities



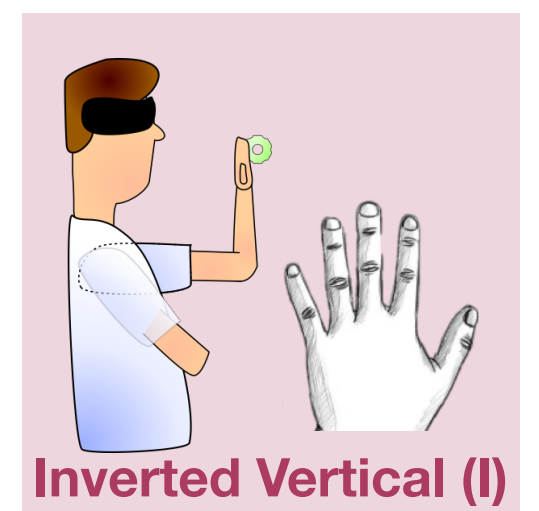
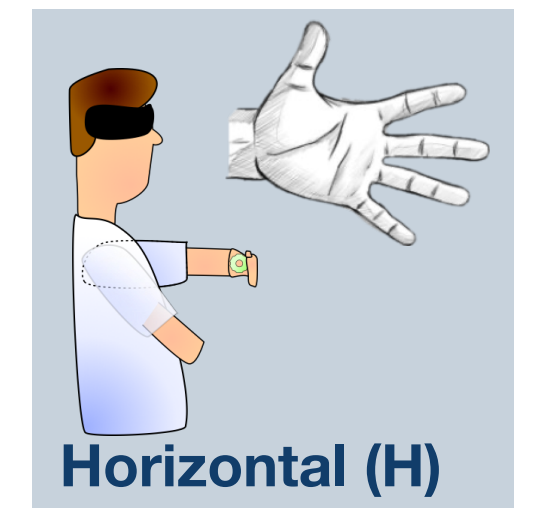
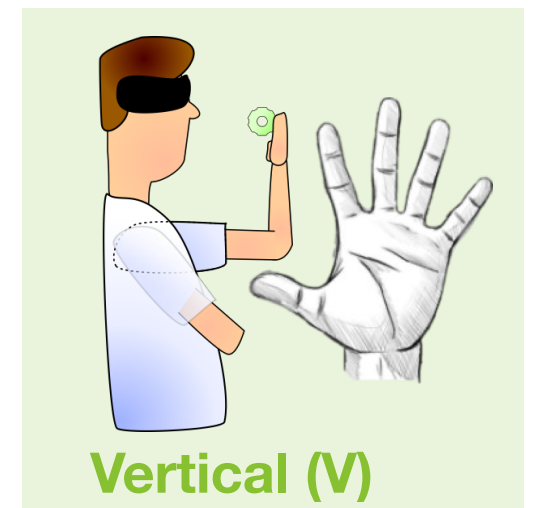
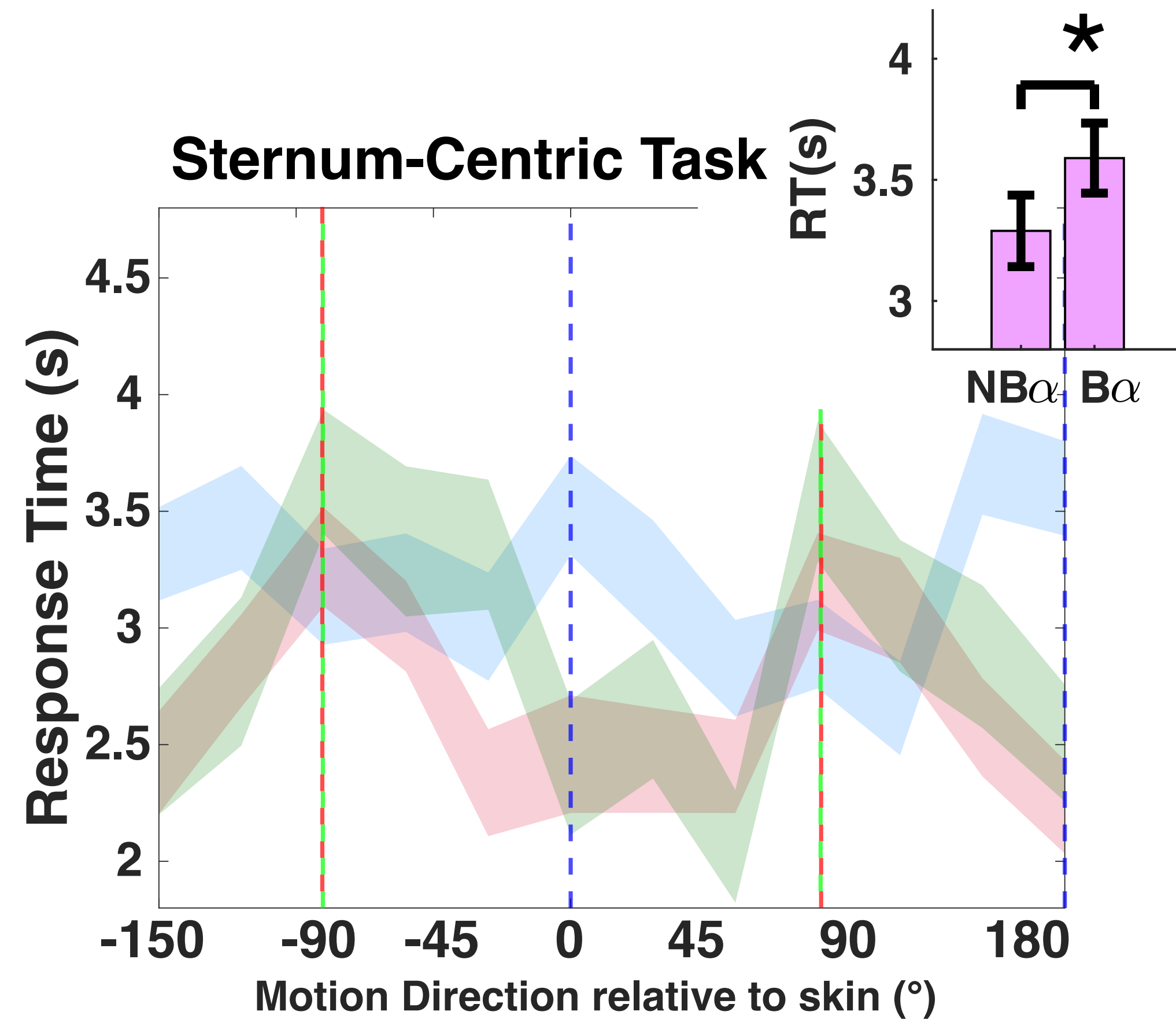
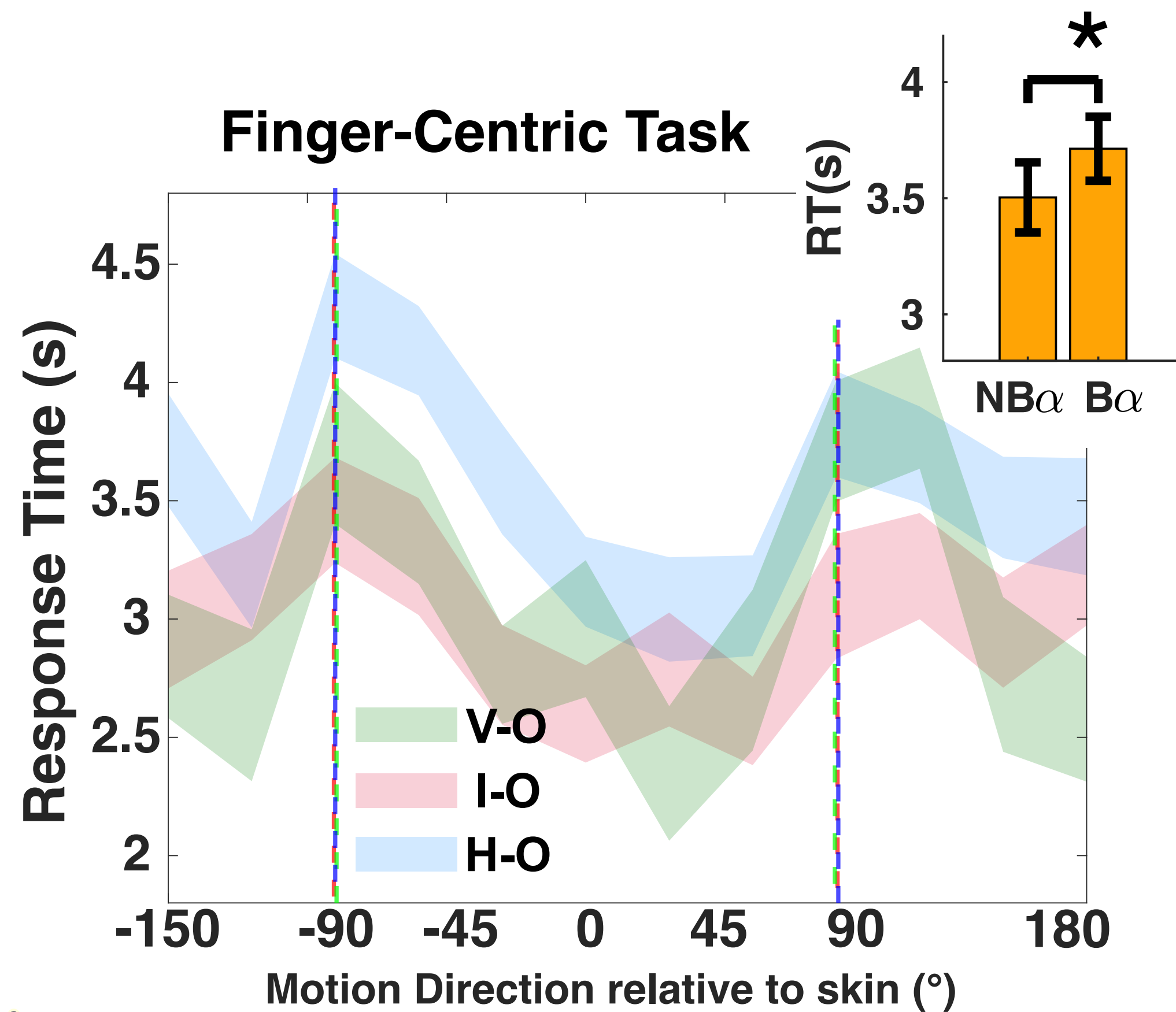
# Old Experiment Design



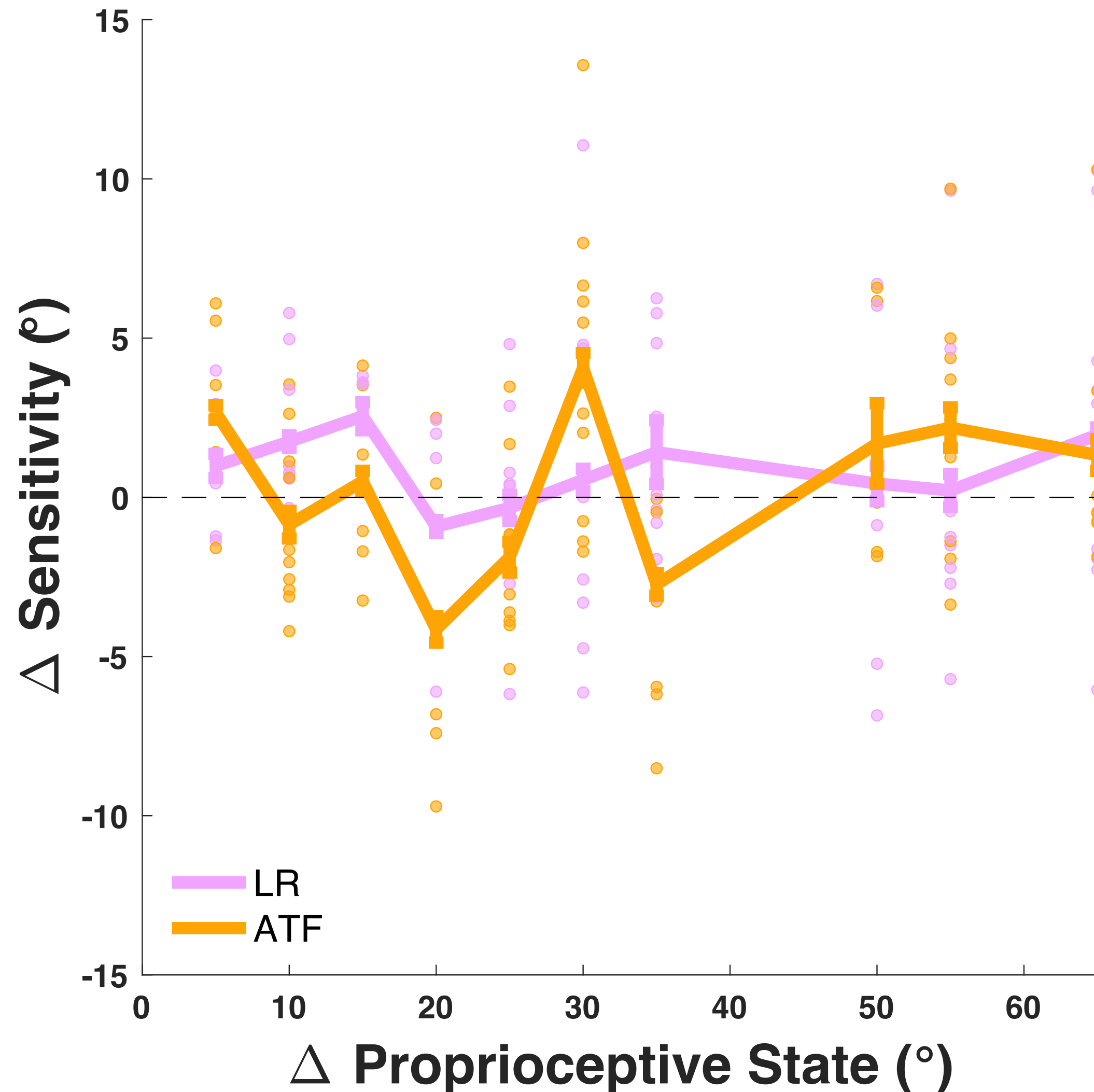
# How does the motor rotation look like?



# How the reaction time changes with the angle measure.

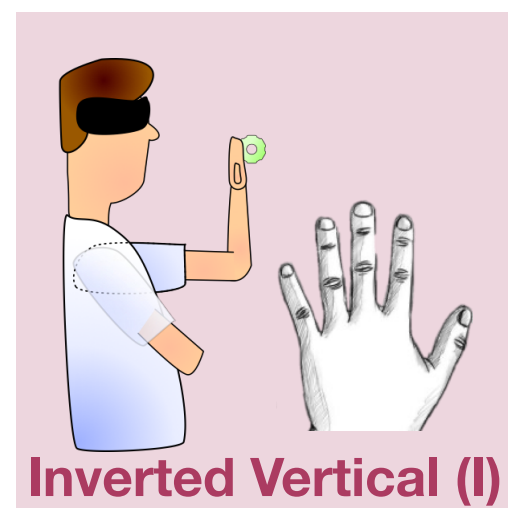
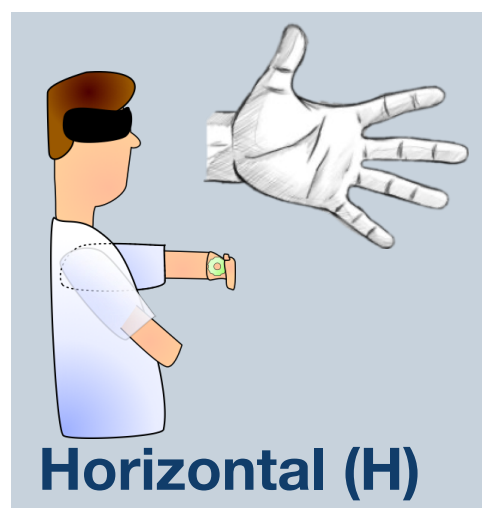
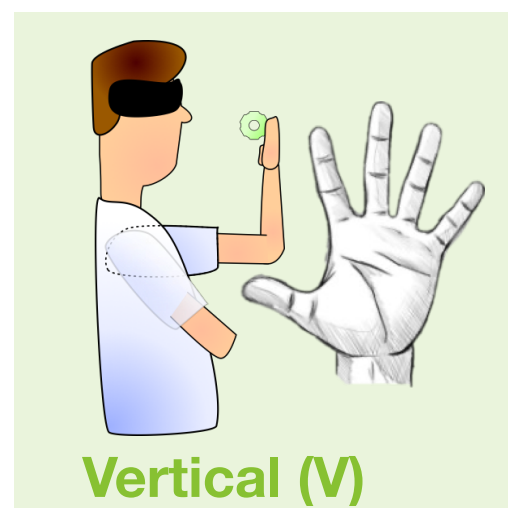
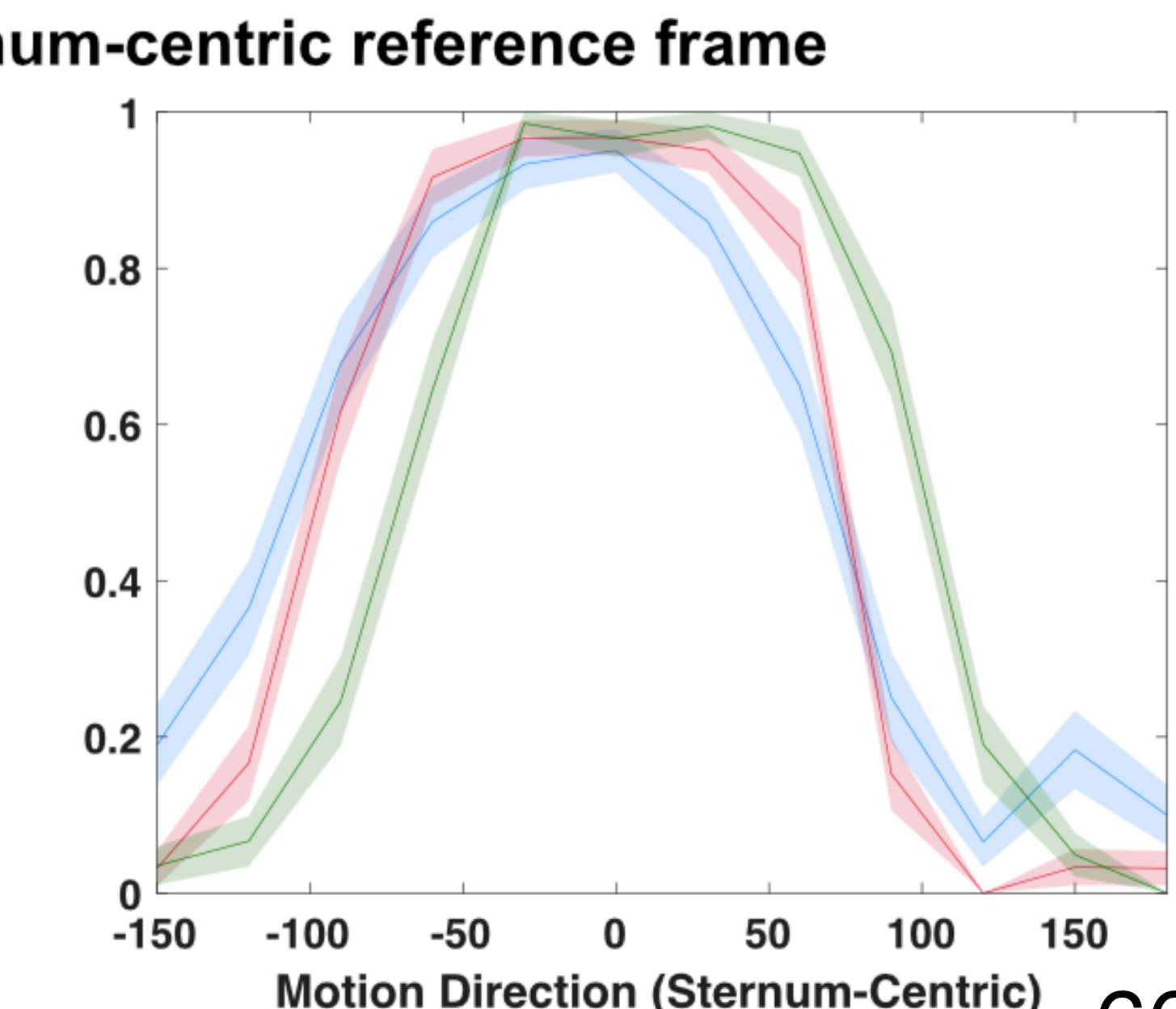
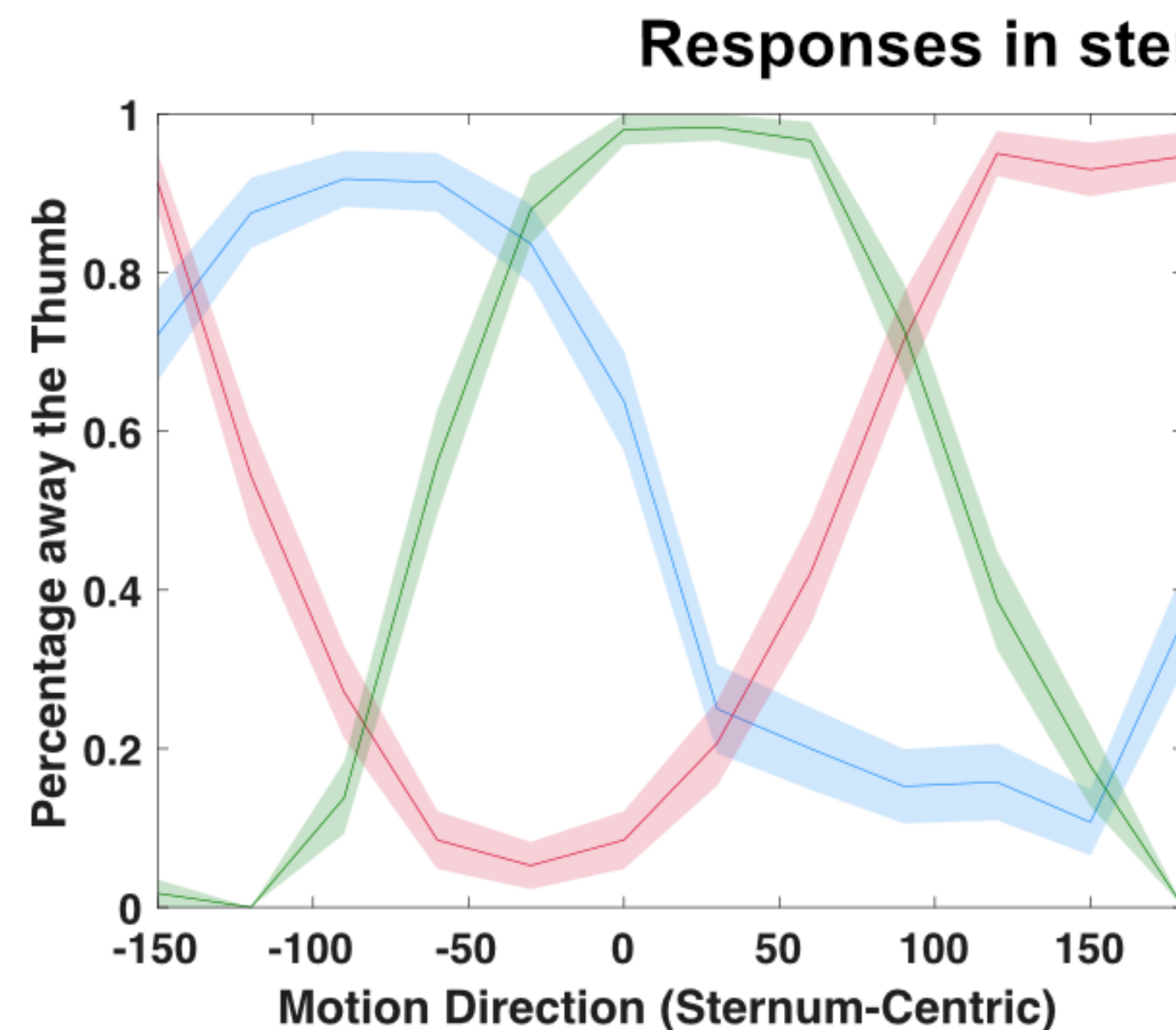
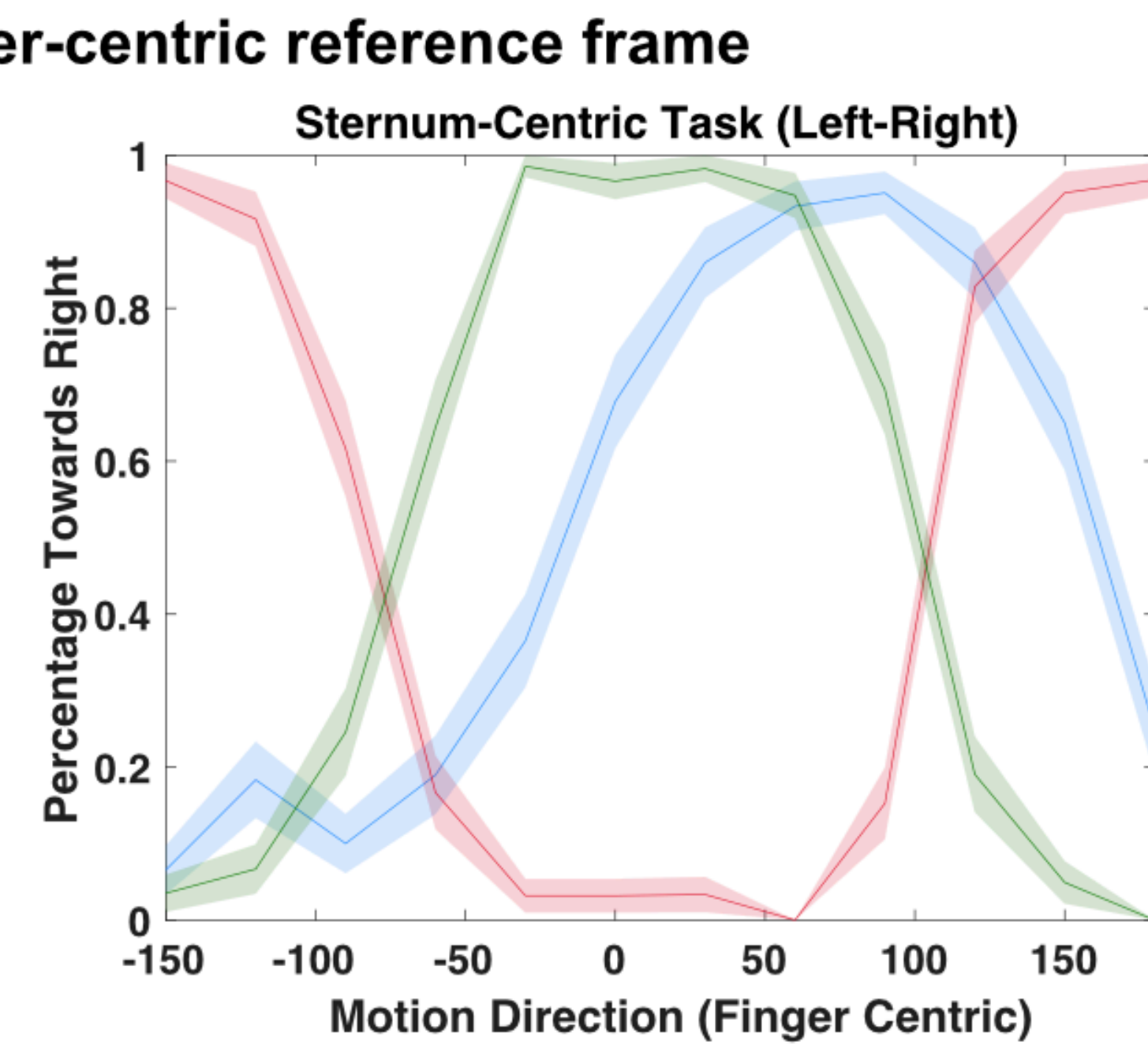
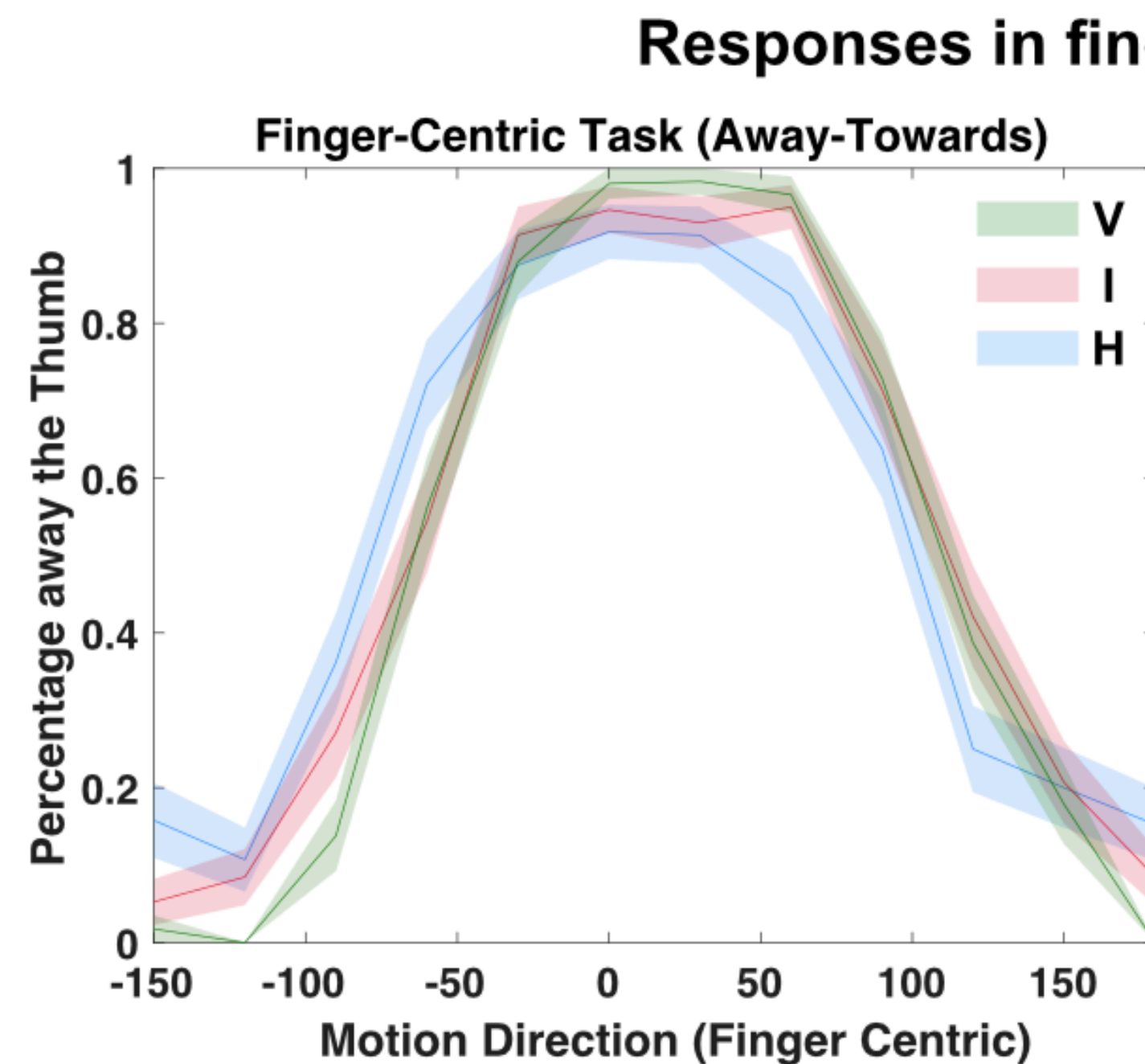


# Why do we only choose one sensitivity term?



**Similar sensitivity difference across different proprioceptive states.**

# Responses of the population in two coordinate systems



**End of Supplementary Material**