Neural computational models underlying coordinate transforms of motion representations in touch

Himanshu Ahuja, Gregory C. DeAngelis, Manuel Gomez-Ramirez

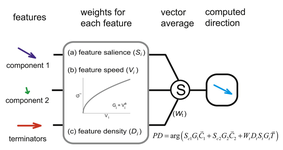
www.haptic-perception-lab.org Department of Brain & Cognitive Sciences; Center for Visual Science, University of Rochester, Rochester, NY

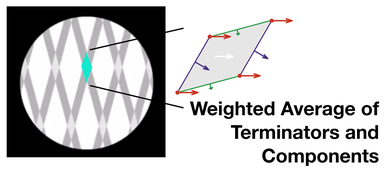
hahuja@ur.rochester.edu

@gomezramirezm

Neuroscience 2022

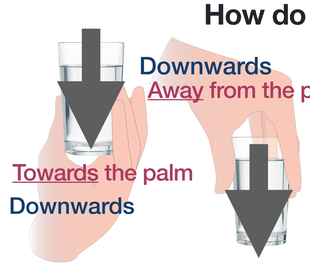
- Integration of tactile motion cues (i.e. speed, saliency, feature density) has been previously described by the Full vector average model. (Pei et. al 2008, 2011)





- However, this model was derived with the hand in only one posture.
- Previous studies (Chen et. al 2020) do not have an explicit instruction of reference frame.
- However, integration of touch and proprioception is dependent on the reference frame.

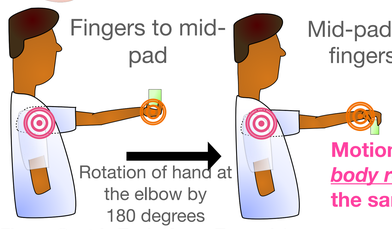
Subjects flexibly perceive motion in multiple reference frames (Ahuja et. al 2021)



How do we perceive motion on the hand?

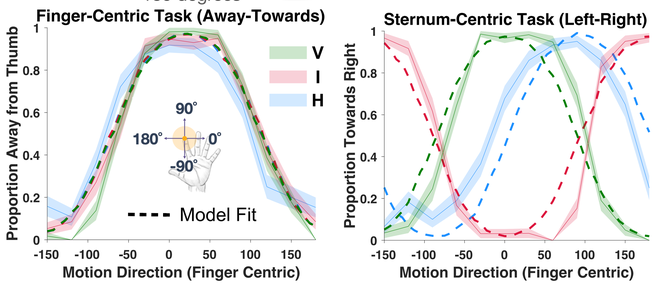
How is tactile motion integrated with posture?

How is this integration controlled by the reference frame?

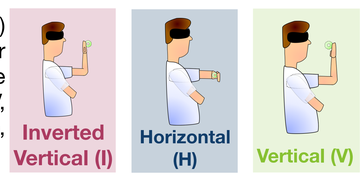


Motion in *hand reference frame* changes

Motion in *center-of-the-body reference frame* stays the same



Population Level (N = 12) Psychometric curves for tactile motion report. The three postures are: vertical (V, green), horizontal (H, blue), and Inverted Vertical (I, red).

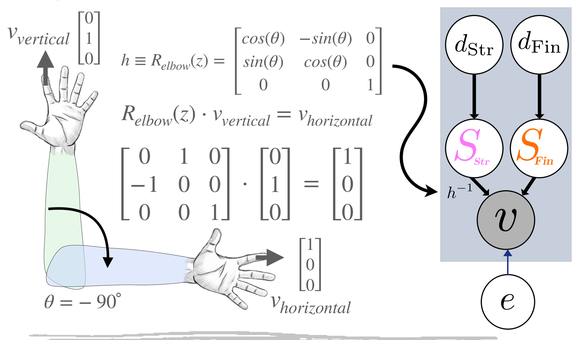


Two-Alternate Force Choice Motion Direction discrimination

LEFT vs RIGHT
w.r.t the center of the body
Sternum-Centric Task

AWAY vs TOWARDS
the thumb-edge of the palm
Finger-Centric Task

Euler Matrix Transformations explain tactile motion report



A Bayesian Computational Model for flexible representations of tactile motion

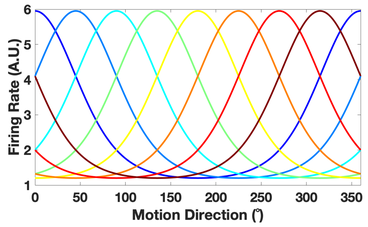
Probability Ratio of decisions made to the right v/s left

$$p(d_{\mathrm{Str}} = r \mid e) = \frac{1}{T} \sum_{v \sim \mathcal{N}(e,\sigma^2)}^{T} I\left(\frac{p(v \mid d_{\mathrm{Str}} = r) \cdot \beta_{\mathrm{Str}}}{p(v \mid d_{\mathrm{Str}} = l) \cdot (1 - \beta_{\mathrm{LR}})} > 1 \right)$$

Likelihood Term for a motion direction v

$$p(v \mid S_{\mathrm{Str}}) = \frac{1}{\sigma_{\mathrm{Str}}\sqrt{2\pi}} \exp\left(\frac{-\left((h \cdot v) - S_{\mathrm{Str}}\right)^2}{2\sigma_{\mathrm{Str}}^2} \right)$$

A Neural implementation for flexible perception of motion in multiple reference frames



$$fr(v, n) = Poisson(e^{G(\alpha_p(P), \alpha_R(R))\cos(v - \mu_n + p(R))})$$

Firing rate

Reference Frame dependent gain

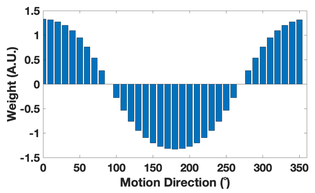
(R)eference frame dependent proprioceptive shift

Posture-dependent gain

Tactile Motion Direction

Preferred motion direction of neuron n

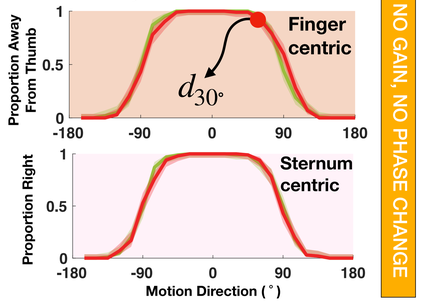
Optimal Decision Readout



$$w = \Sigma^{-1}(\overline{fr}_{0^{\circ}} - \overline{fr}_{180^{\circ}})$$

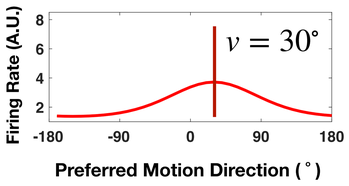
$$d_{30^{\circ}} = w \cdot \overline{fr}_{30^{\circ}}$$

Psychometric Results



NO GAIN, NO PHASE CHANGE

Neural Population Response at a sample stimulus

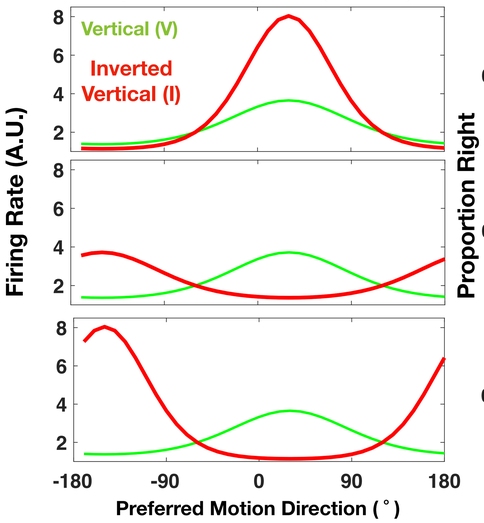


POSTURE DEPENDENT GAIN CHANGE ONLY

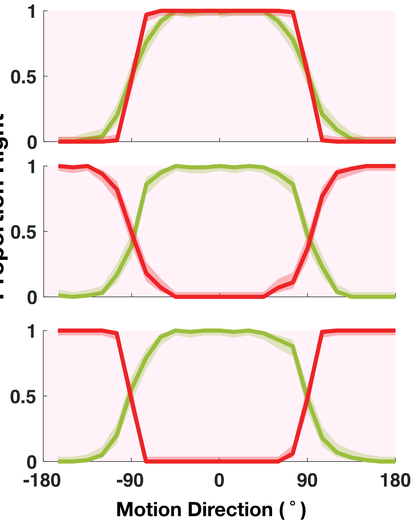
PHASE CHANGE ONLY

POSTURE DEPENDENT GAIN CHANGE WITH PHASE CHANGE

Population Response $(v = 30^{\circ})$



Predictions by the decoder (Left/ Right)



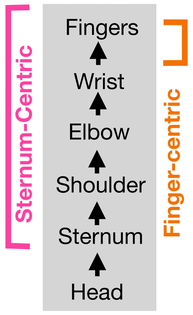
How does the brain select proprioceptive states based on the reference frame

$$R_{sternum}(x) \cdot R_{intermediate} \cdots R_{fingers}(z) \cdot v = v'$$

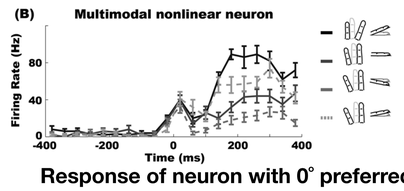
Point of observation

Point of stimulation

Directional dependency of proprioceptive rotations from the **point of observation** to the **point of stimulation.**

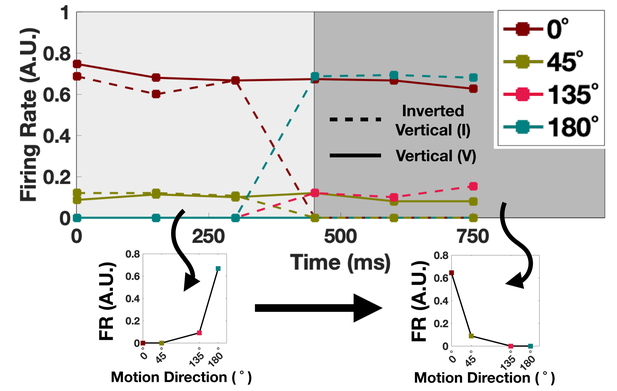


Time dependent integration of proprioceptive state with motion information (Kim et. al 2014)



Kim et. al showed that neurons in the Somatosensory cortex integrates orientation with finger posture after a time delay.

Response of neuron with 0° preferred direction at 2 Postures



CONCLUSION

- ❖ An Euler matrix transformations-based method explains the behavioral results
- ❖ A gain-based neural population can distinguish between different reference frames and proprioceptive states.
- ❖ A phase-shifting neural population is required to explain psychophysical behavior.
- ❖ $p(R)$ can be computed using a directional dependency map from the point of observation to point of stimulation.
- ❖ A temporal decoder might be employed for computing tactile motion in different reference frames.

ACKNOWLEDGEMENTS

Members of the Haptics Lab
Alfred P. Sloan Foundation