Neural computational models underlying coordinate transforms of motion representations in touch

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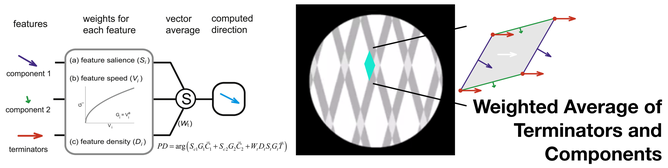
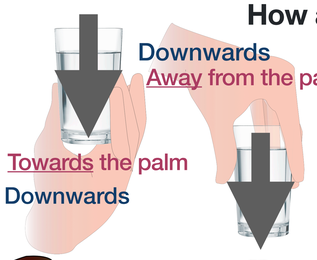
- Integration of tactile motion cues (i.e. speed, saliency, feature density) has been previously described by the Full vector average model. (Pei et. al, 2008, 2011)



Weighted Average of Terminators and Components

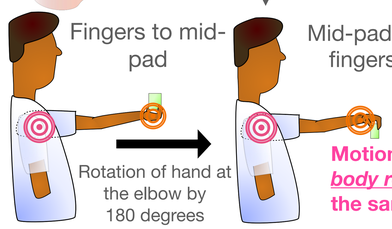
- **However, this model was derived with the hand in only one posture.**
- Previous studies do not have an explicit instruction of reference frame (Chen et. al, 2020)
- **However, integration of touch and proprioception is dependent on the reference frame.**

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



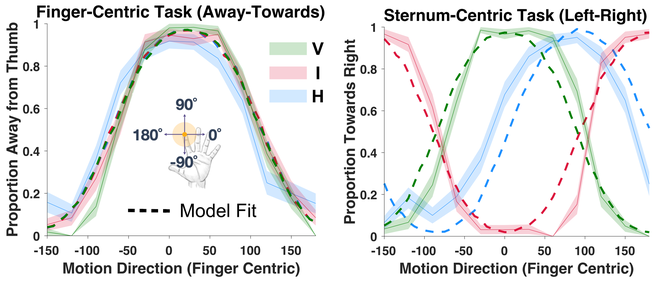
How are tactile inputs on the hand integrated with proprioceptive signals?

How is this integration controlled by the reference frame?

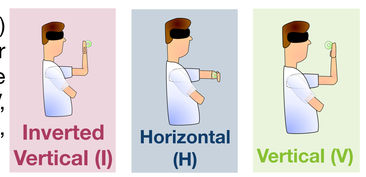


Motion in *hand reference frame* changes

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).

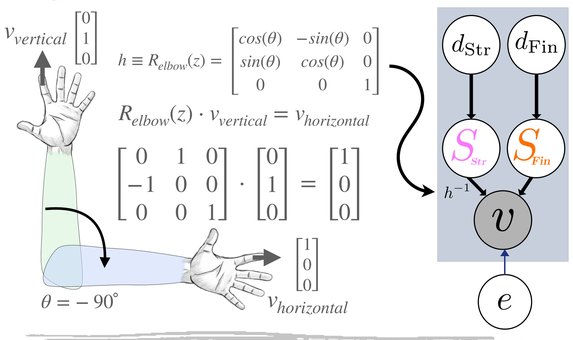


Two-Alternate Force Choice Motion Direction discrimination

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

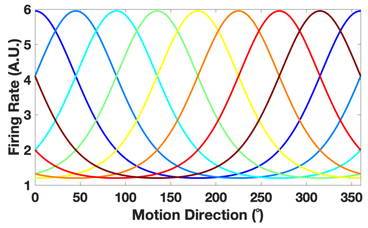
Probability Ratio of decisions made to the right v/s left

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

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

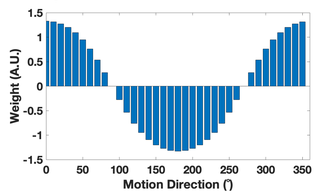
Reference frame dependent proprioceptive shift

Posture-dependent gain

Tactile Motion Direction

Preferred motion direction of neuron n

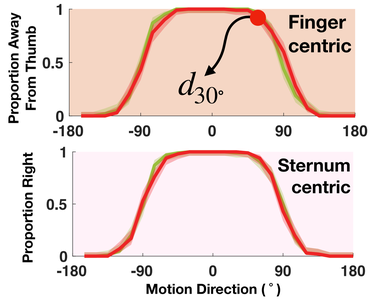
Optimal Decision Readout



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

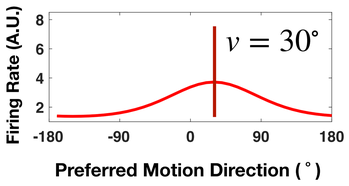
$$d_{30^{\circ}} = w \cdot \overline{fr}_{30^{\circ}}$$

Psychometric Predictions



NO GAIN, NO PHASE CHANGE

Neural Population Response at a sample stimulus

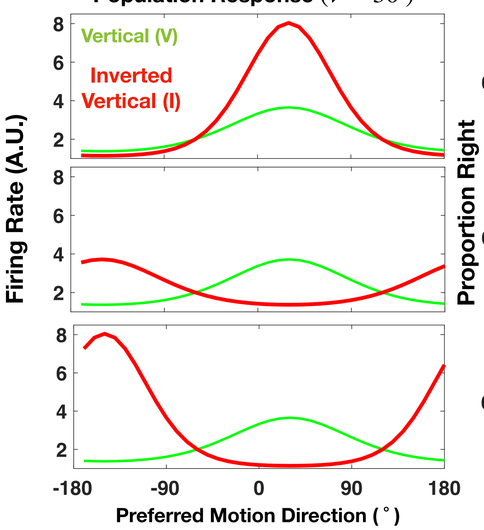


POSTURE DEPENDENT GAIN CHANGE ONLY

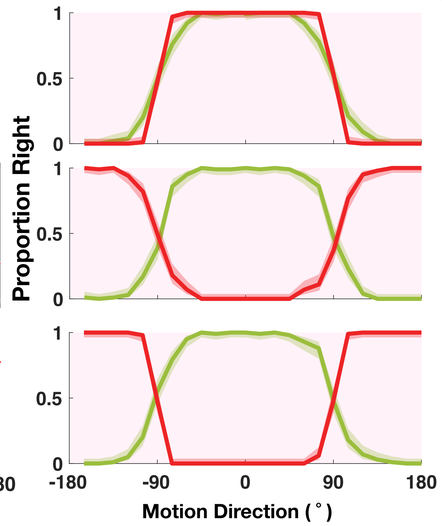
PHASE CHANGE ONLY

POSTURE DEPENDENT GAIN CHANGE WITH PHASE CHANGE

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



Predictions by the decoder (Left/ Right)



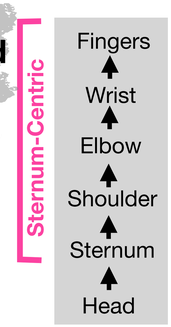
How does the brain select proprioceptive states based on the reference frame

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

Point of observation

Point of stimulation

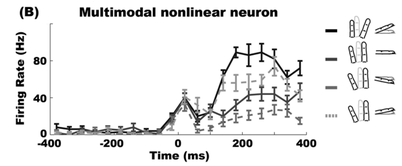
Directional dependency of proprioceptive rotations from the **point of observation** to the **point of stimulation.**



Topographical map of the proprioceptive dependencies

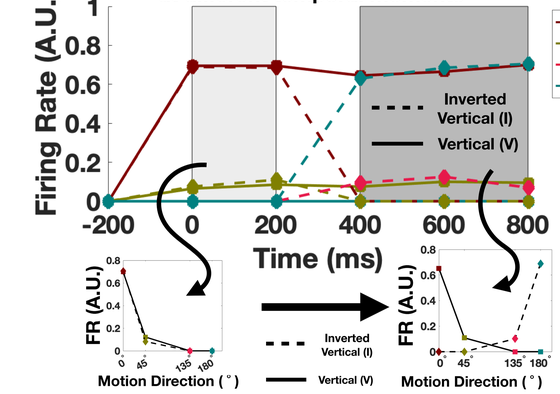
Temporal integration of proprioceptive state with motion information

Kim et. al, 2014



Integration of tactile and proprioceptive inputs is mediated by feedback mechanisms.

A putative neuron encoding reference frame-specific motion at different temporal moments



CONCLUSION

❖ Flexible representations of tactile motion are accounted by a Bayesian-generative model of Euler matrix transforms.

❖ Our computational model proposes that neural and perceptual representations of tactile motion are mediated by gain and phase-shifting mechanisms.

❖ Readout of flexible representations of tactile motion may be achieve by a temporal decoder mechanism.

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