Sensory Re-alignment Model

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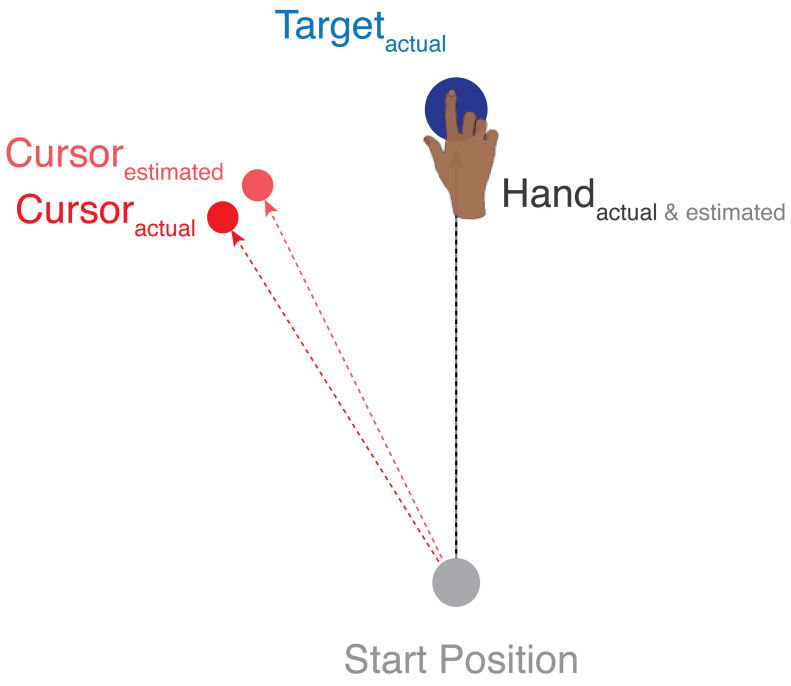
Recent findings challenge a visuo-centric view of motor adaptation

Model attributes	Traditional state-space model	Recent findings
The goal of adaptation	is to nullify a visual error	is also influenced by a proprioceptive error[1]
The rate of adaptation	increases with error size	saturates for large errors, mirroring saturated (visually induced) prop biases[2]
The upper bound of adaptation	is when learning equals forgetting	is correlated with individual differences in proprioception (bias & variability)[3]

[1]Wei & Kording, 2009; Marko et al 2012 ; Bond & Taylor, 2015; Morehead et al 2017; Kim et al, 2018; Kasuga et al, 2013; Modchalingam et al 2019; Tsay et al, 2021
[2]Salomonczyk, et al 2013; Tsay et al, 2020; Rossi et al 2021; Haith et al 2009; Hayashi et al, 2020
[3]Salomonczyk et al, 2013; Tsay et al, 2021; Ruttle et al, 2021, Modchalingam et al 2019; Gastrock et al 2020

Sensory re-alignment model (1st perturb trial)

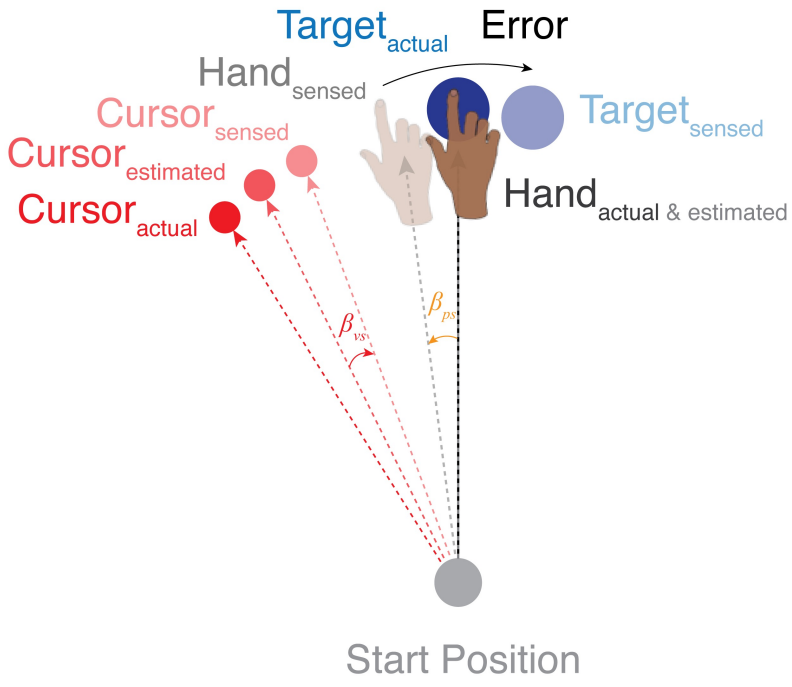
Actual position x sensory prediction = estimated position



*Sensory prediction is assumed to be where people aim (i.e., the target)

Sensory re-alignment model (1st perturb trial)

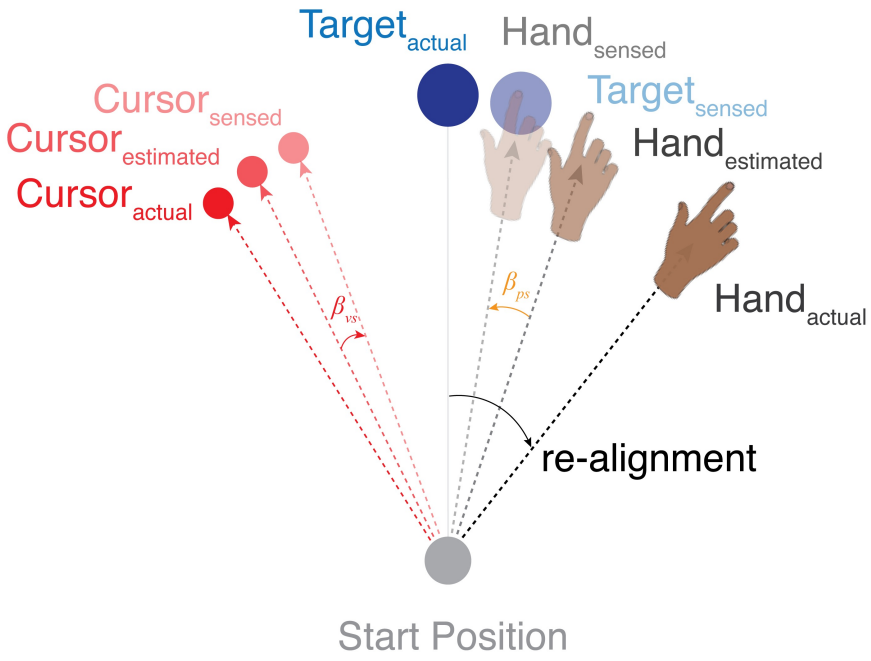
Estimated position + sensory shift = sensed position



*Sensory shifts are elicited by cross-modal (i.e., visuo-proprioceptive) calibration.
Estimated hand position would shift towards the cursor, and the estimated cursor position would shift towards the hand.
These shifts are thought to saturate for large sensory discrepancies (studies from the Prof. Denise Henrique's lab).

Sensory re-alignment model (late adaptation)

Adaptation ceases when sensed hand = sensed target



sensed hand position

actual hand position — $\mu_{p,t+1} = \mu_{p,t} + B(T^s - \mu^s_{p,t})$

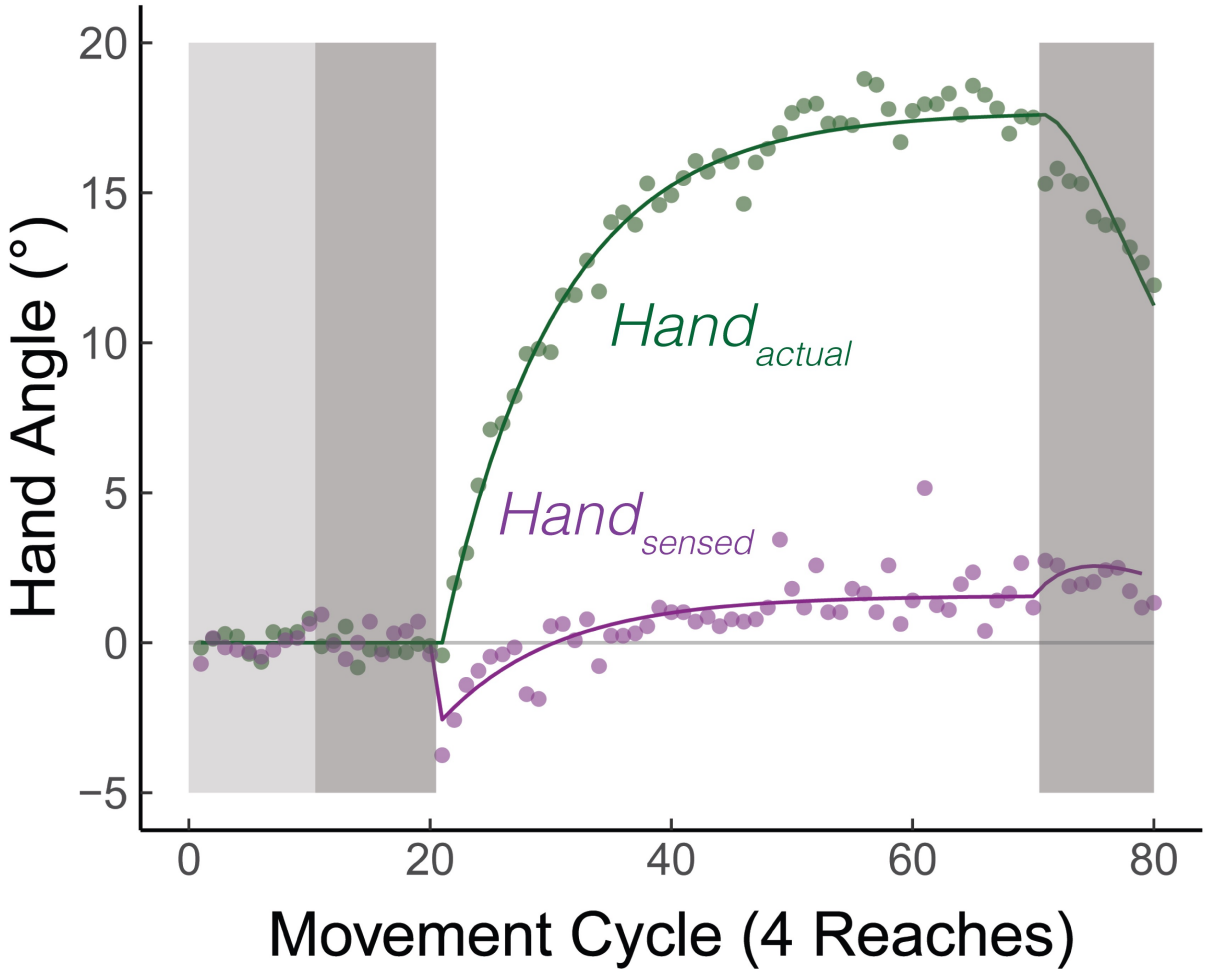
learning rate

sensed target position

The sensory re-alignment model can explain a wide range of features in motor adaptation

#	Feature	**Traditional state space** *Cheng & Sabes (2006)*	**Maximum likelihood estimation** *Ernst & Banks (2002)*	**Relevance estimation** *Wei & Kording (2009)*	**Bayesian estimation** *Haith et al (2009)*	**Sensory re-alignment**
1	Sensed hand position	✗	✗	✗	✓	✓
2	Proprioception predicts upper bound	✗	≠	≠	✓	✓
3	Saturated adaptation rate	✗	✗	✓	✗	✓
4	Common upper bound	✗	✗	✗	✗	✓
5	Visual uncertainty attenuates small errors only	✗	✗	✓	✗	✓
6	Prediction uncertainty attenuates adaptation	✗	✓	✓	✓	✓
7	Passive movements lead to motor aftereffects	✗	✗	✗	✗	✓
8	Generalization patterns	✗	✗	✗	✓	✓

Feature #1: Sensed hand position during adaptation



*lines represent model fits to Tsay et al (2020)

Feature #2: Prop shift and prop variability are correlated with upper bound of adaptation

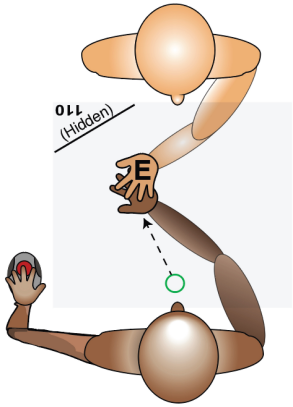
Passive proprioceptive probes for proprioceptive shift/variance

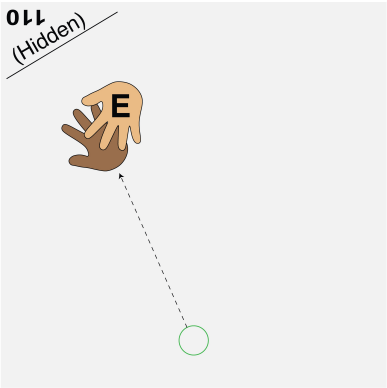
Proprioceptive variance

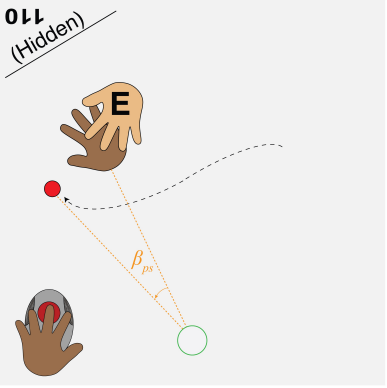
$$\text{Upper bound} \sim \frac{(\sigma_{prior}^2 + \sigma_p^2)}{\sigma_{prior}^2} \beta_{p,t}$$

Prediction variance

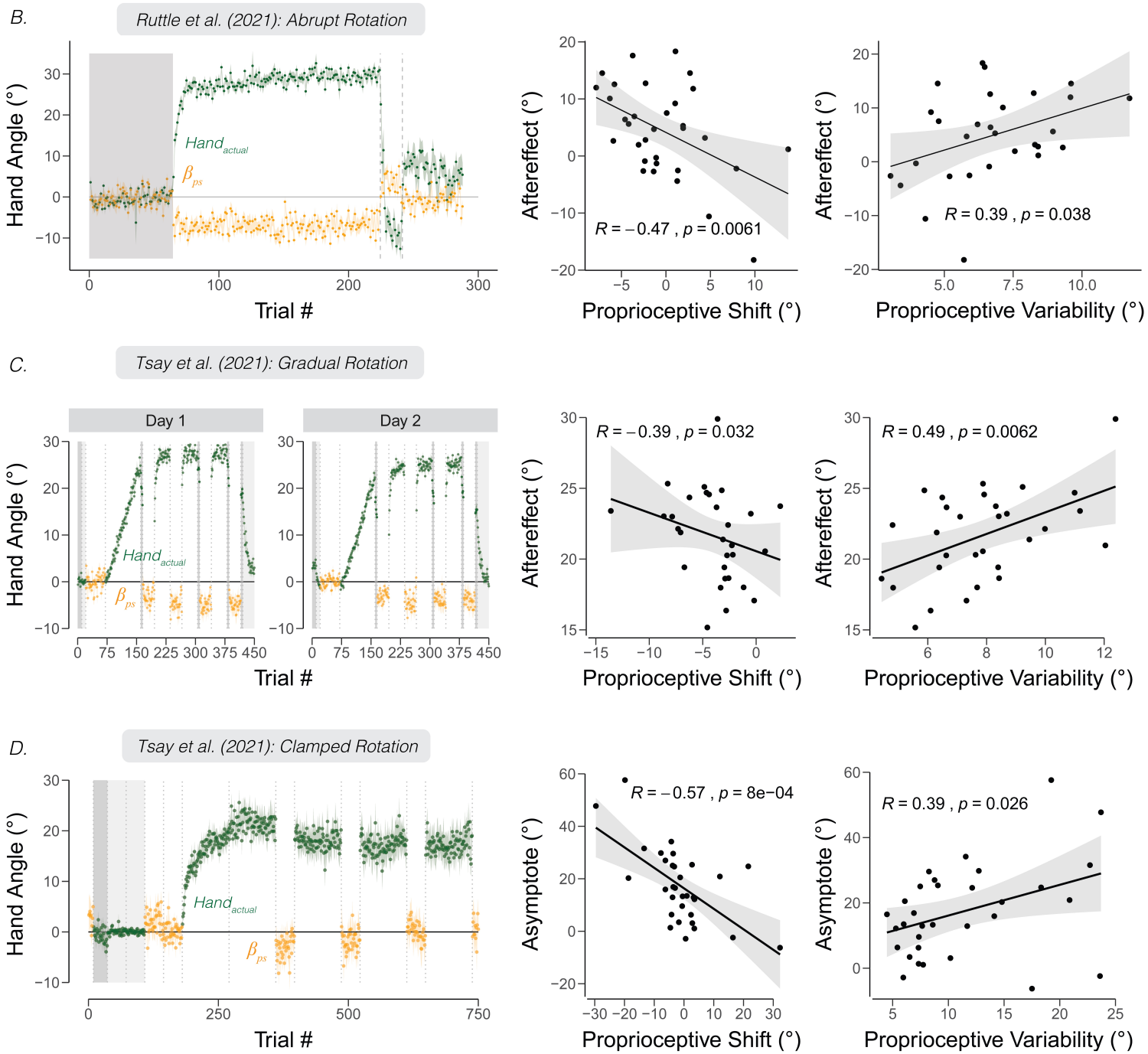
Proprioceptive shift



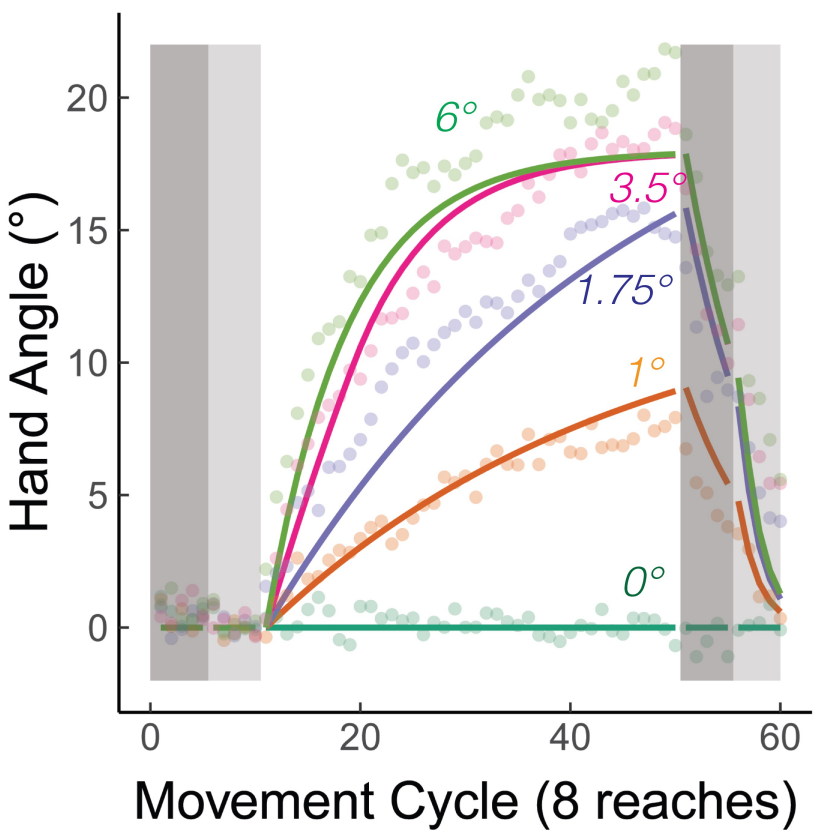


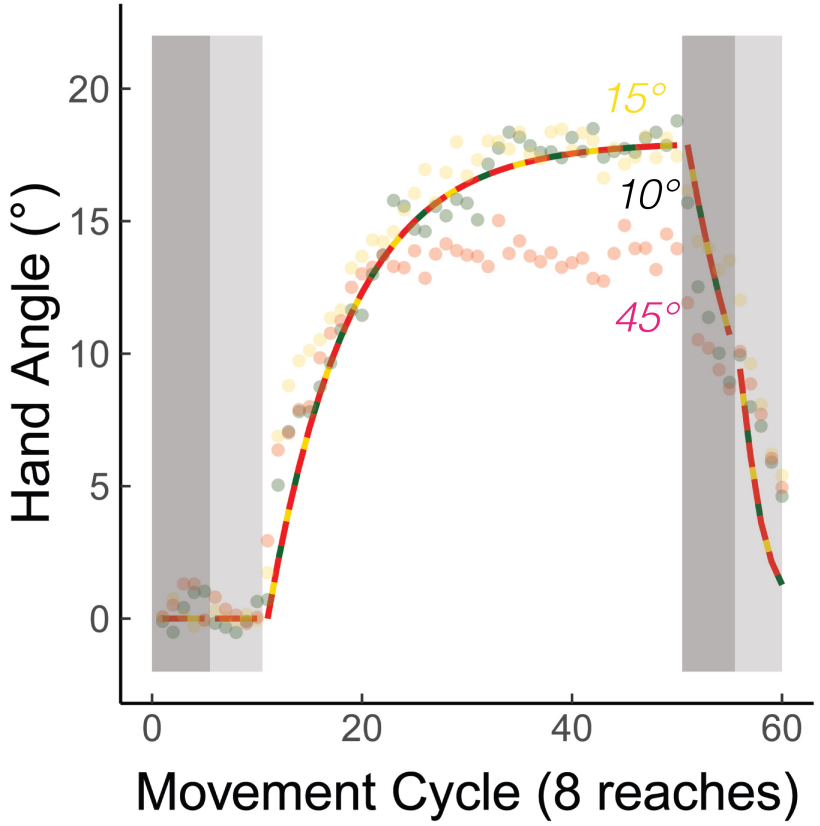


Correlations remain robust across different adaptation tasks



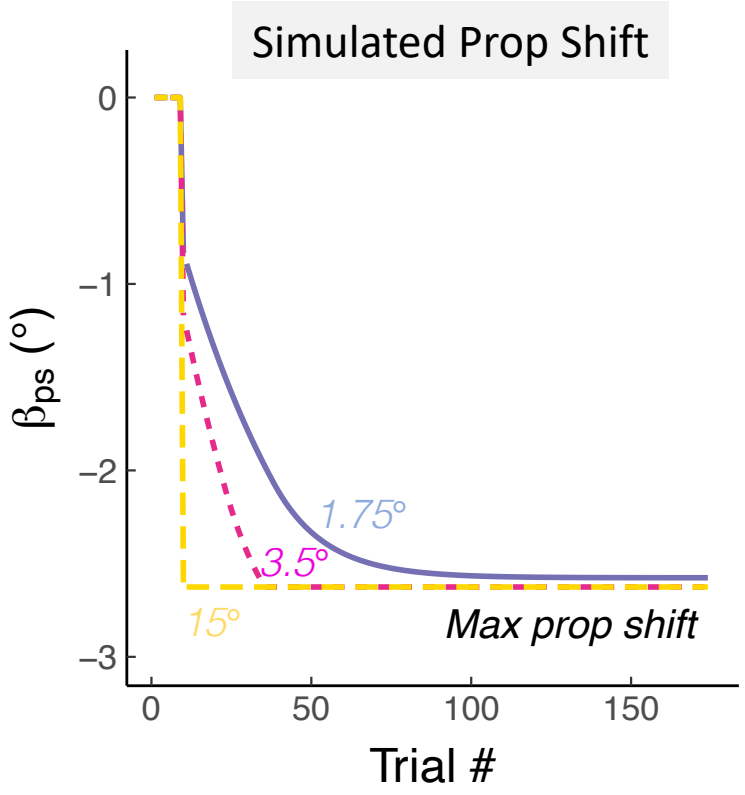
Feature #3: since prop shift saturates for large visual errors, the rate of adaptation would also saturate

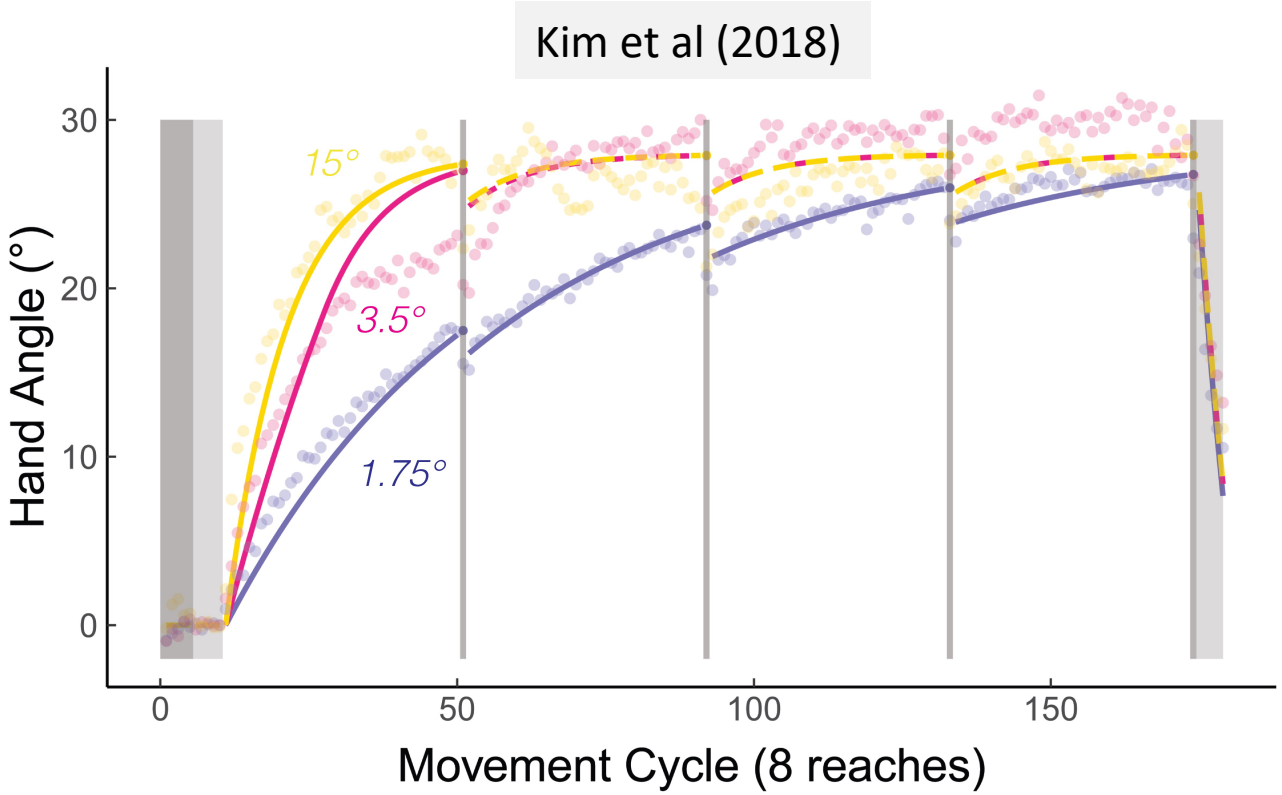




*lines represent model fits to Kim et al (2018)

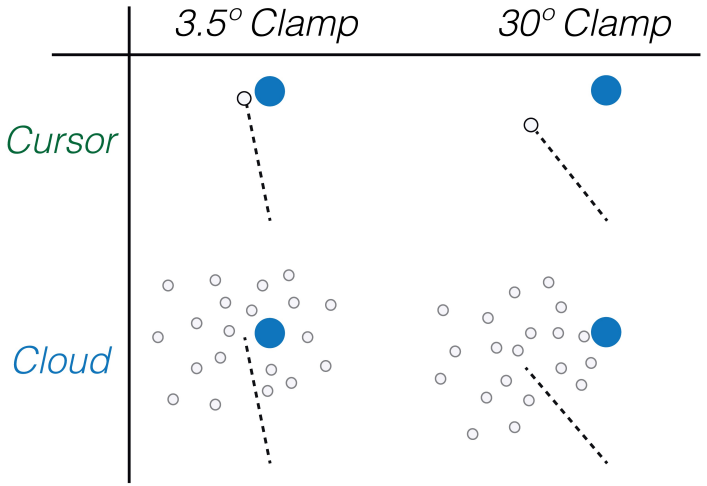
Feature #4: since prop shift saturates at different rates for different visual errors, hand angle would also reach a common upper bound at different rates

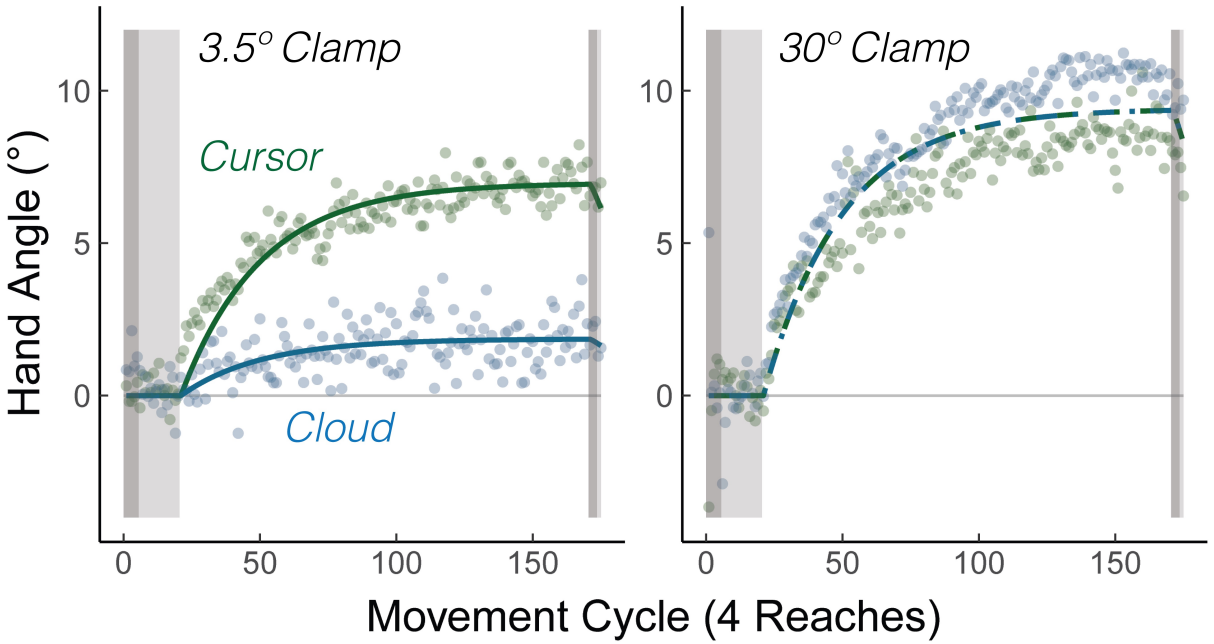




Assume a maximum proprioceptive shift of 2.5°. Size of shift is driven by a difference between estimated cursor and hand positions. For large rotations (15°), maximum shift is reached very fast (first trial). For small rotations (1.75°), shift will increase until estimated hand position results in difference sufficient to produce maximum shift.

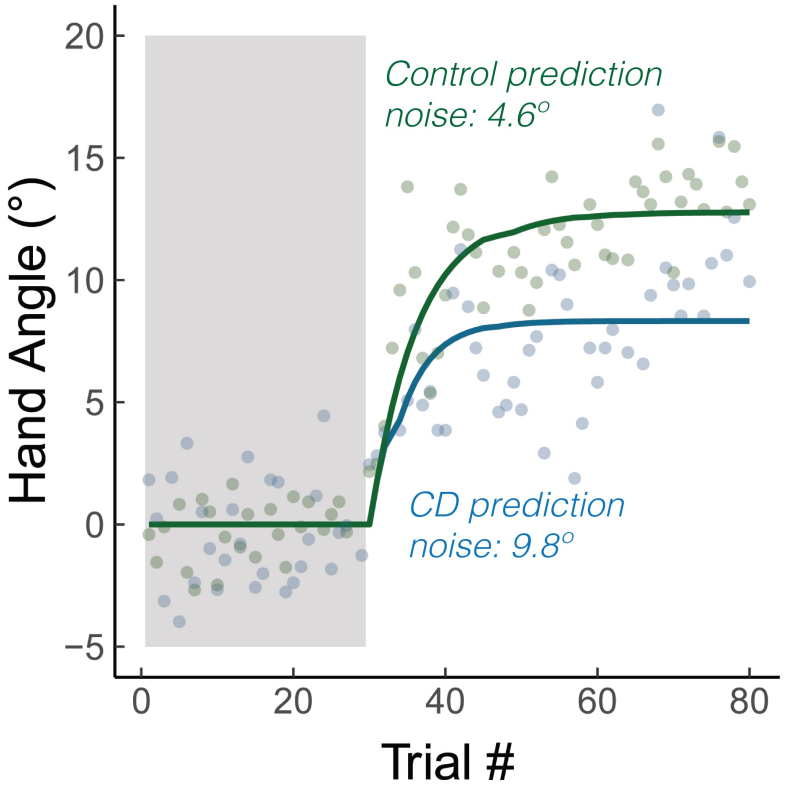
Feature #5: Since prop shift saturates for large visual errors, visual uncertainty would not attenuate adaptation for large errors





Lines represent model fits to Tsay et al, 2020 (different mechanism proposed in the paper)

Feature #6: Greater prior uncertainty in hand position attenuates adaptation

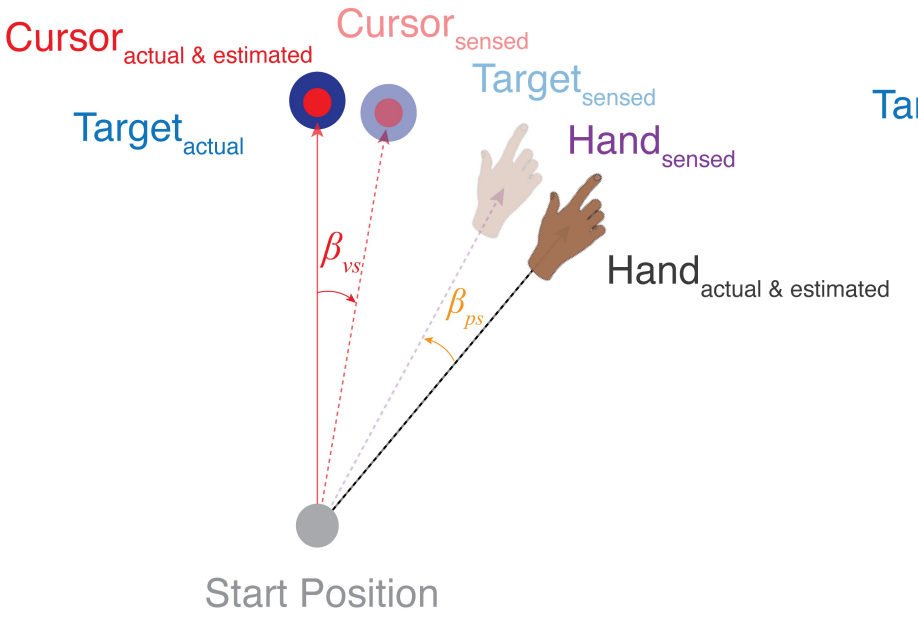


Greater sensory prediction uncertainty (e.g., Cerebellar degeneration) can result from uncertainty in prior about hand and/or cursor position. For example, increased uncertainty in the prior belief of hand position will result in sensed hand position being closer to actual hand position. This will result in reduced adaptation (less change in hand angle needed to achieve re-alignment).

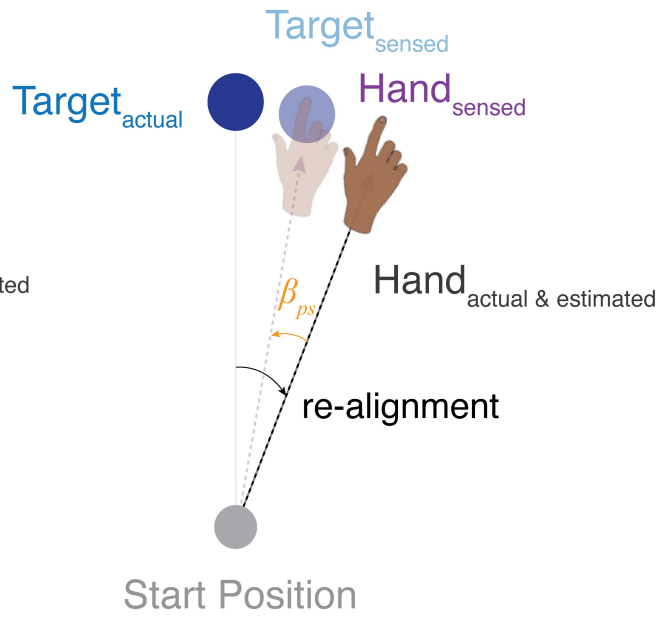
Lines represent model fits to Tseng et al (2007)

Feature #7: The proprioceptive shift during the exposure block induces an aftereffect

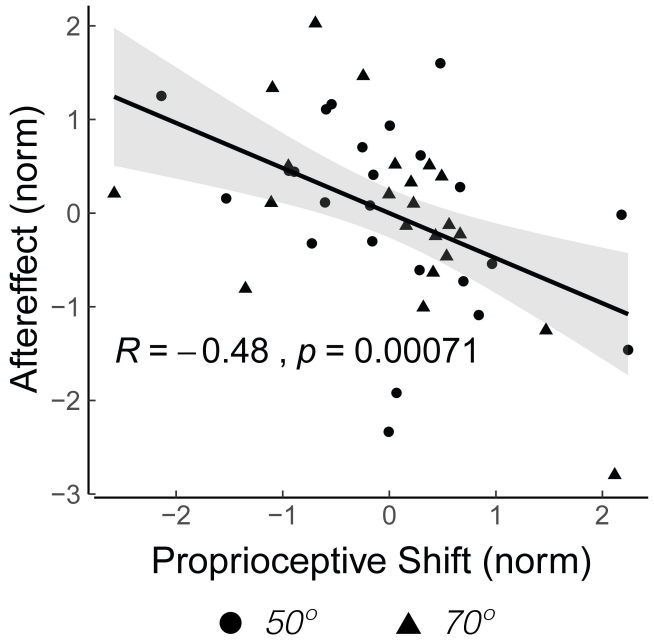
Exposure Block



Aftereffect Block



Salomonczyk et al (2013)

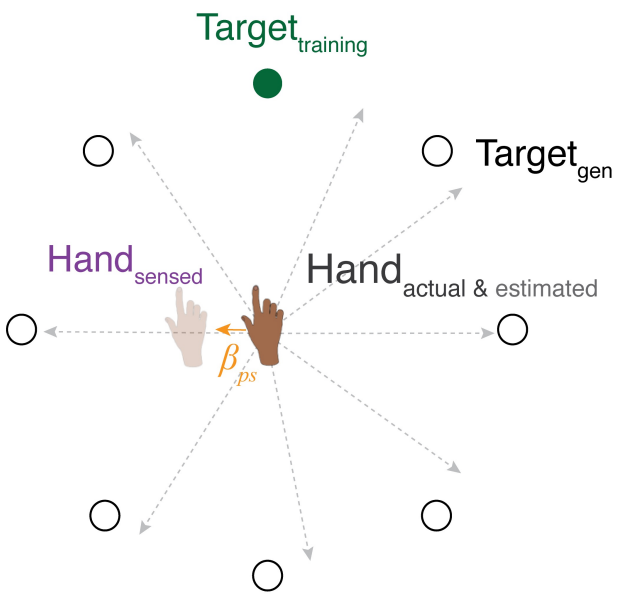


*during the exposure block, participants are passively moved 30° away from the target, while a visual cursor moves invariantly (clamped) to 0 ° (i.e., target). The exposure block results in a proprioceptive shift.

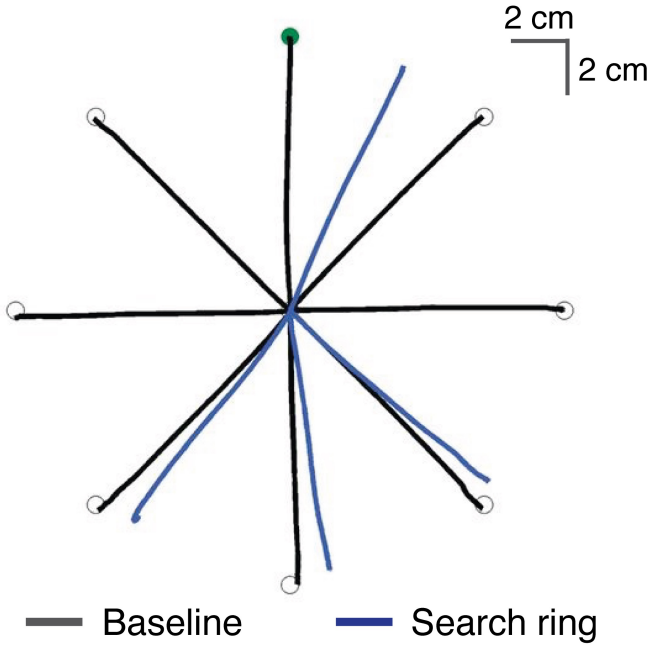
*during the aftereffect block, participants are instructed to reach directly to the target without visual feedback. The proprioceptive shift during the exposure block may have elicited an aftereffect

Feature #8: Generalization pattern resembles a shift in sensed hand position

Predicted generalization: 45° CCW Rotation



Generalization from Taylor & Ivry (2013)



Re-evaluating the sensory constraints underlying motor adaptation

Model attributes	Traditional state-space model	Sensory re-alignment model
The goal of adaptation	is to nullify a visual error	is to nullify a proprioceptive error
The rate of adaptation	increases with error size	increases with error size but saturates
The upper bound of adaptation	is when learning equals forgetting	is when the hand is sensed at the target

Challenges to the sensory re-alignment model

- How does adaptation occur with tools (e.g., joystick)?

- How does adaptation occur when the visual and proprioceptive space are divorced (e.g., trackpad + vertical computer screen)?

- Why do deafferent individuals show intact adaptation?

Thank you for your attention!

Create your own online motor learning experiment:
https://github.com/alan-s-lee/OnPoint

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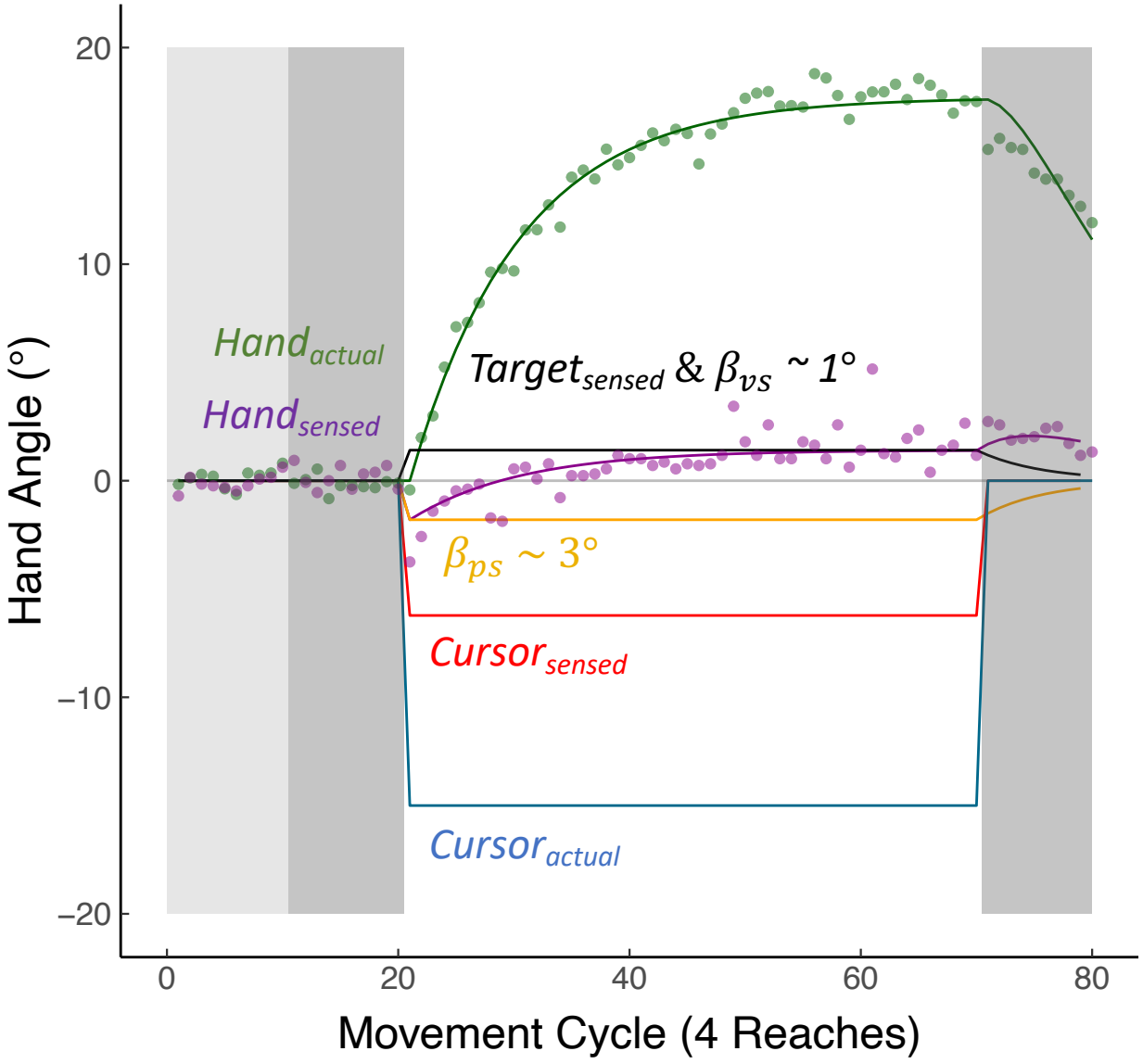
Formalizing the sensory re-alignment model

	Proprioception	Vision
Estimate	$\mu^e_{p,t} = \frac{\sigma^2_{prior}}{\sigma^2_{prior} + \sigma^2_p}\mu_{p,t}$	$\mu^e_{v,t} = \frac{\sigma^2_{prior}}{\sigma^2_{prior} + \sigma^2_v}\mu_{v,t}$
Calibrate	$\beta_{p,t} = \eta_p(\mu^e_{p,t} - \mu^e_{v,t})\rceil_{sat}$	$\beta_{v,t} = \eta_v(\mu^e_{p,t} - \mu^e_{v,t})\rceil_{sat}$
Sense	$\mu^s_{p,t} = \mu^e_{p,t} - \alpha\beta_{p,t}$	$\mu^s_{v,t} = \mu^e_{v,t} + \alpha\beta_{v,t}$
Update	$\mu_{p,t+1} = \mu_{p,t} + \frac{\sigma^2_{prior}}{\sigma^2_{prior} + \sigma^{e\,2}_p}(\mu^s_{p,t} - T^s)$	

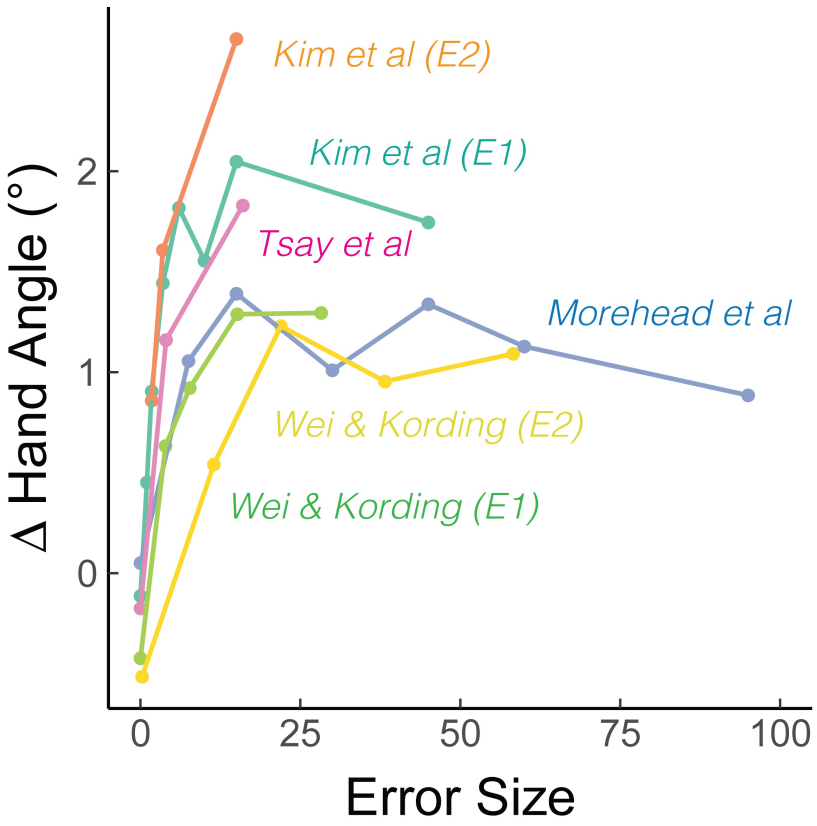
Empirically observable

Latent parameters

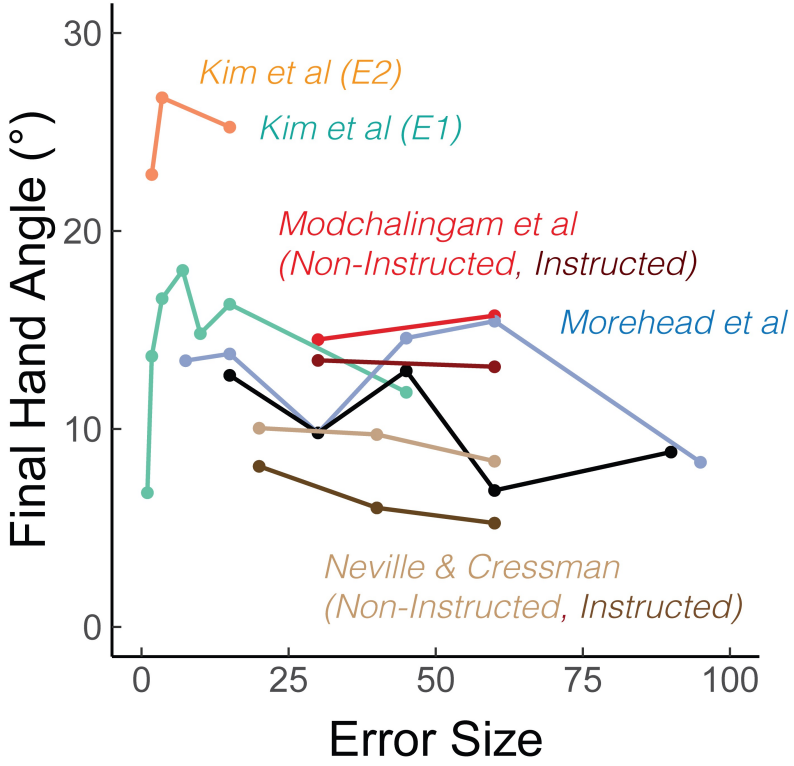
Actual position	$\mu_p\ \mu_v$	Sensory Shift	$\beta_p\ \beta_v$	Sensory noise	$\sigma_v\ \sigma_p$
Estimated position	$\mu^e_p\ \mu^e_v$	Shift ratio	$\eta_p\ \eta_v$	Prediction noise	σ_{prior}
Sensed position	$\mu^s_p\ \ \mu^s_v\ T^s$	Saturated shift	Sat	Sensory decay	α


20
10
0
−10
−20
Hand Angle (°)
0
20
40
60
80
Movement Cycle (4 Reaches)
$Hand_{actual}$
$Hand_{sensed}$
$Target_{sensed}$ & β_{vs} ~ 1°
β_{ps} ~ 3°
$Cursor_{sensed}$
$Cursor_{actual}$

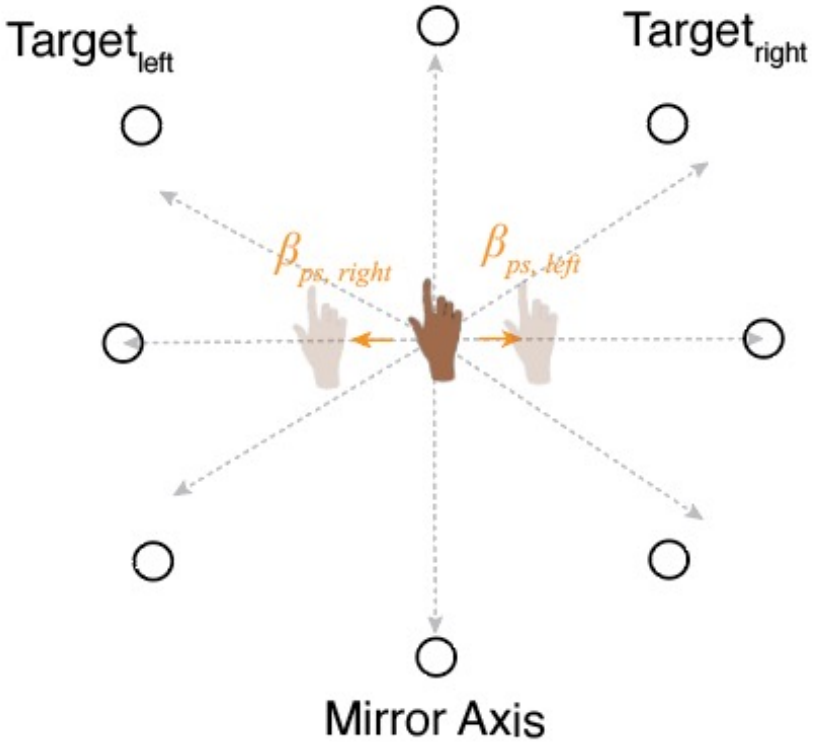
Other studies where rate saturates

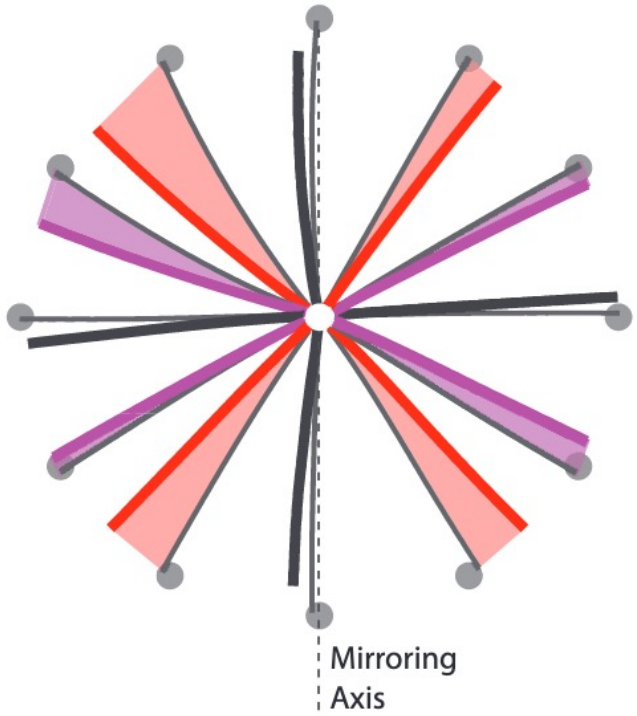


Other studies with a common upper bound



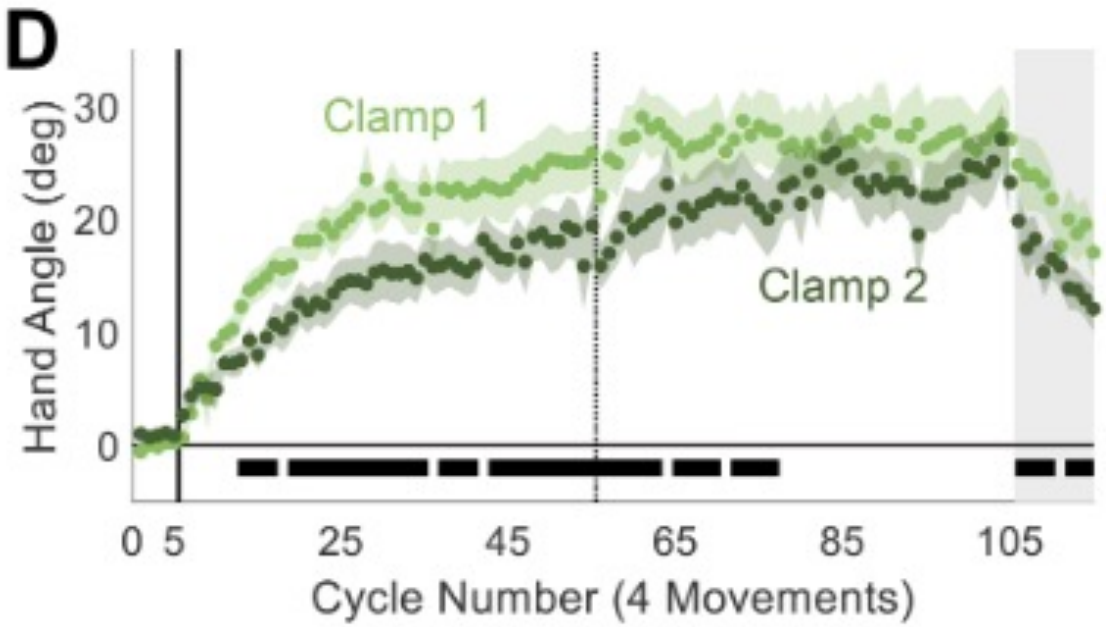
Same line of reasoning applied to adaptation to mirror reversal





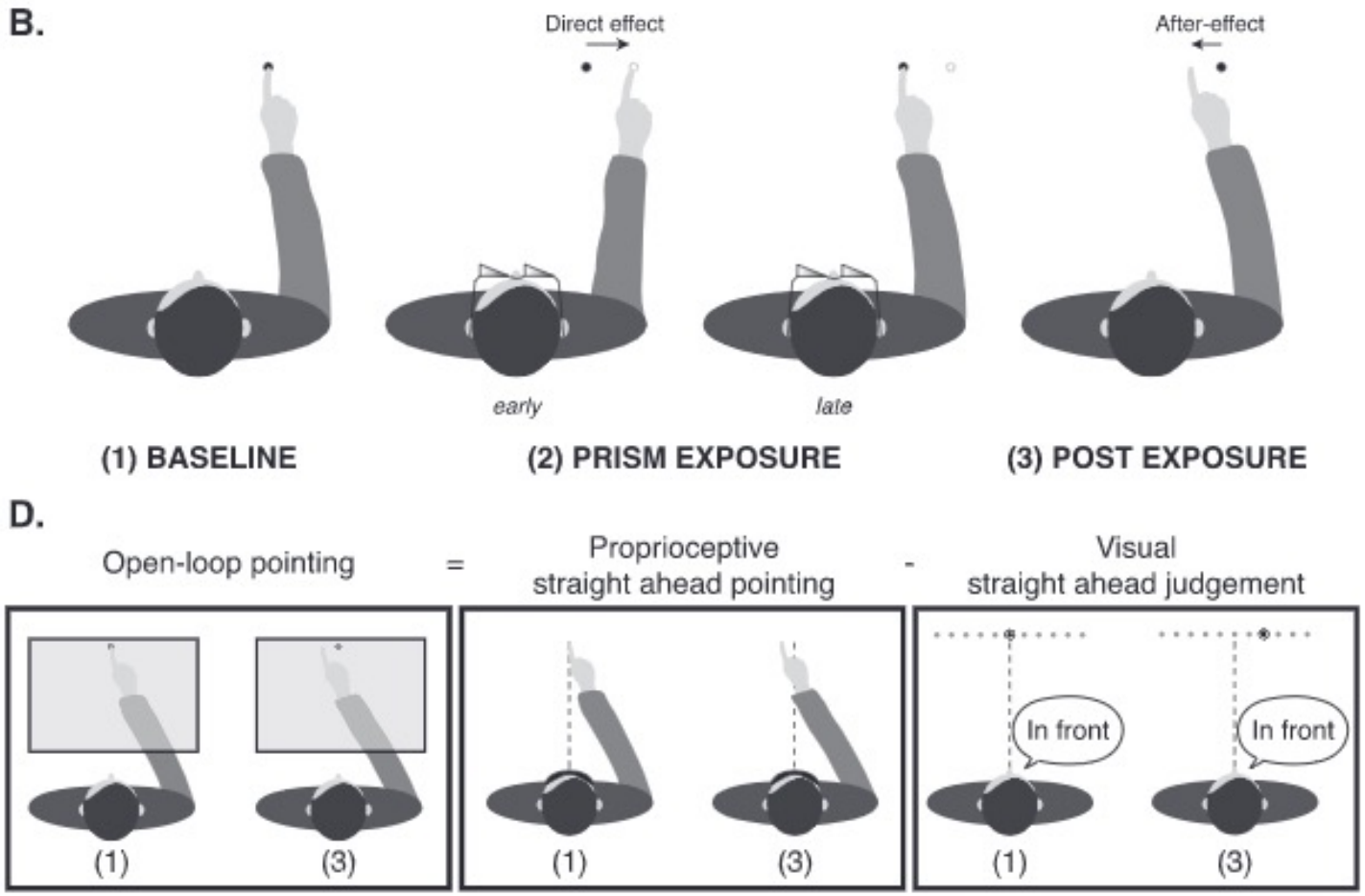
Hadjiosif et al (2020)

Disc #2: Opposite sensory re-alignment = forgetting



Avraham et al (2021)

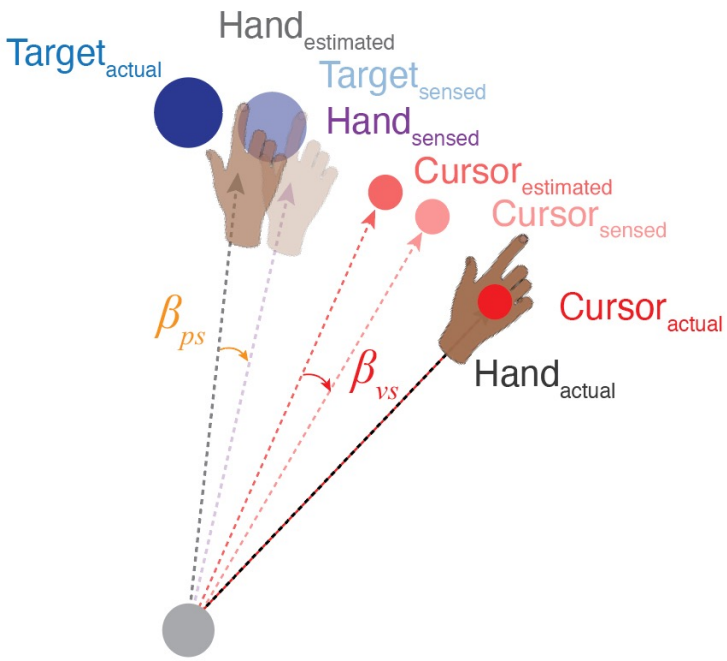
Disc #3: Sensory re-alignment in other motor domains



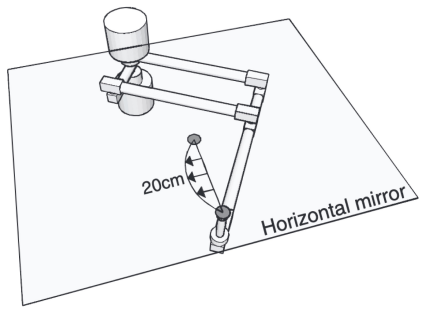
Petitet et al, 2018

Disc #3: Sensory re-alignment in other motor domains

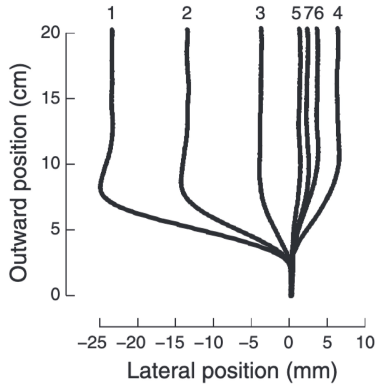
A.



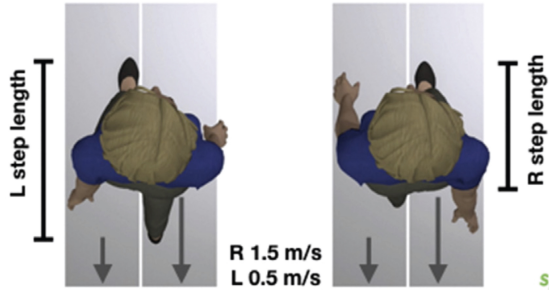
A.



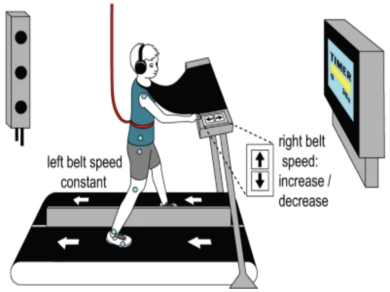
B.



D.

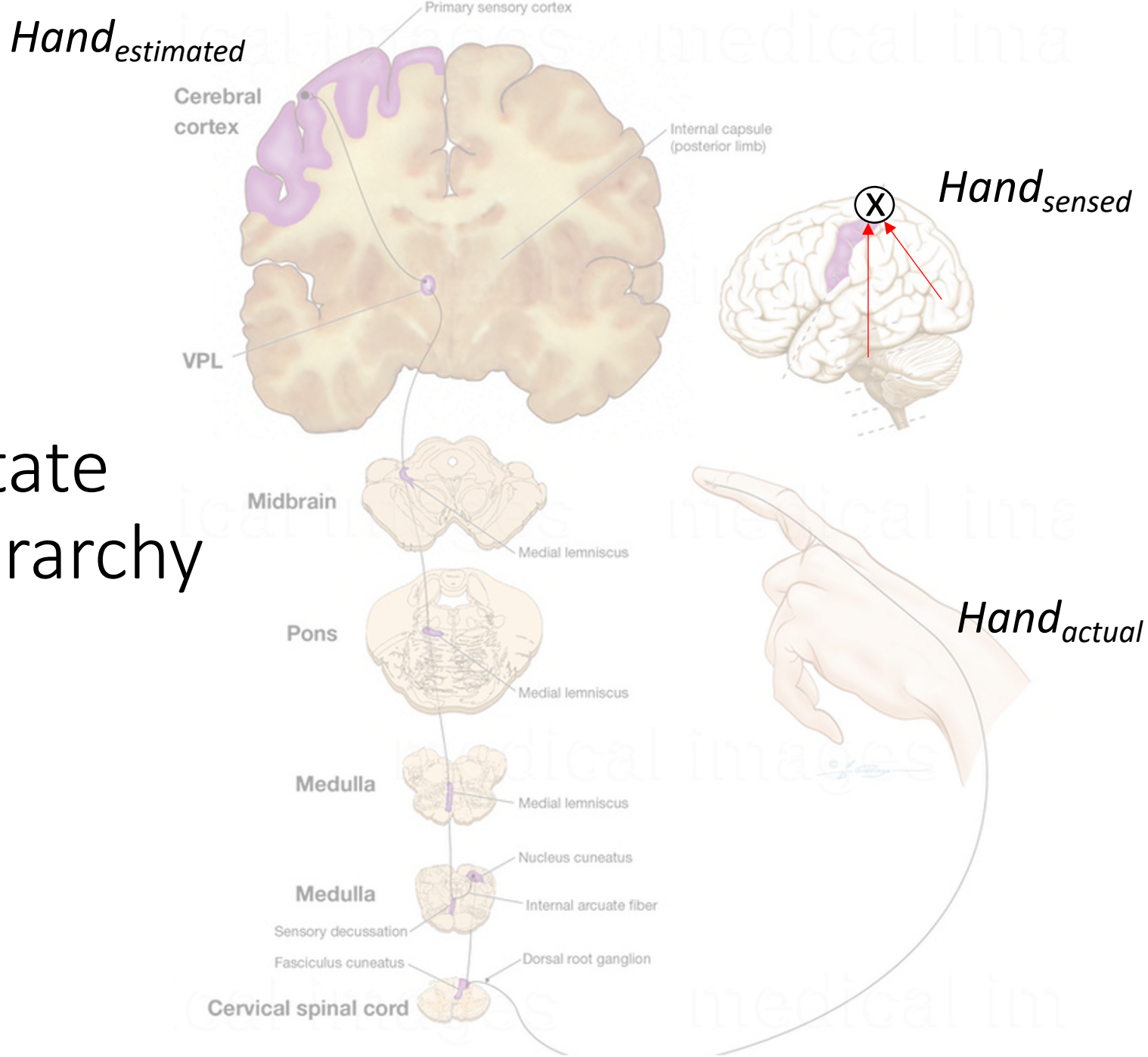


E.

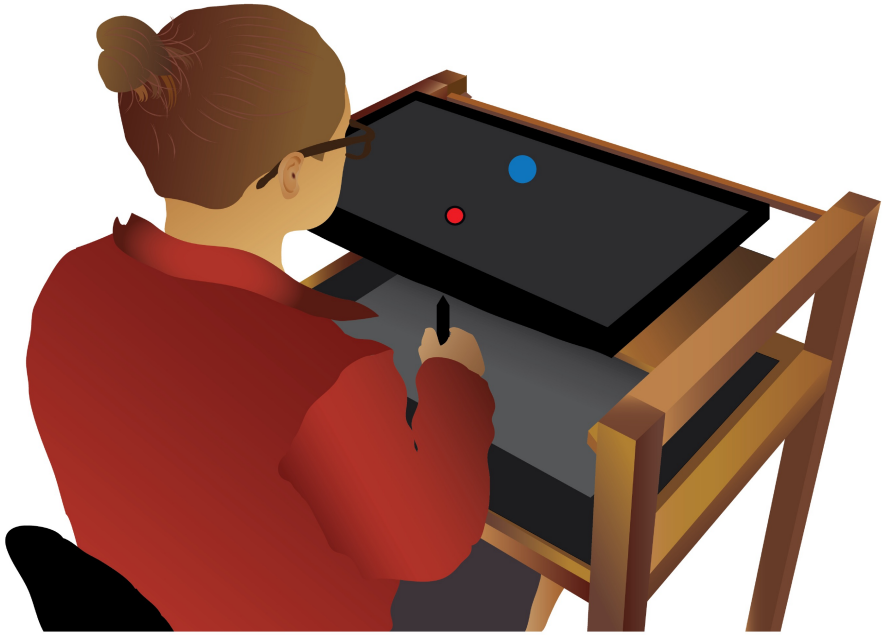


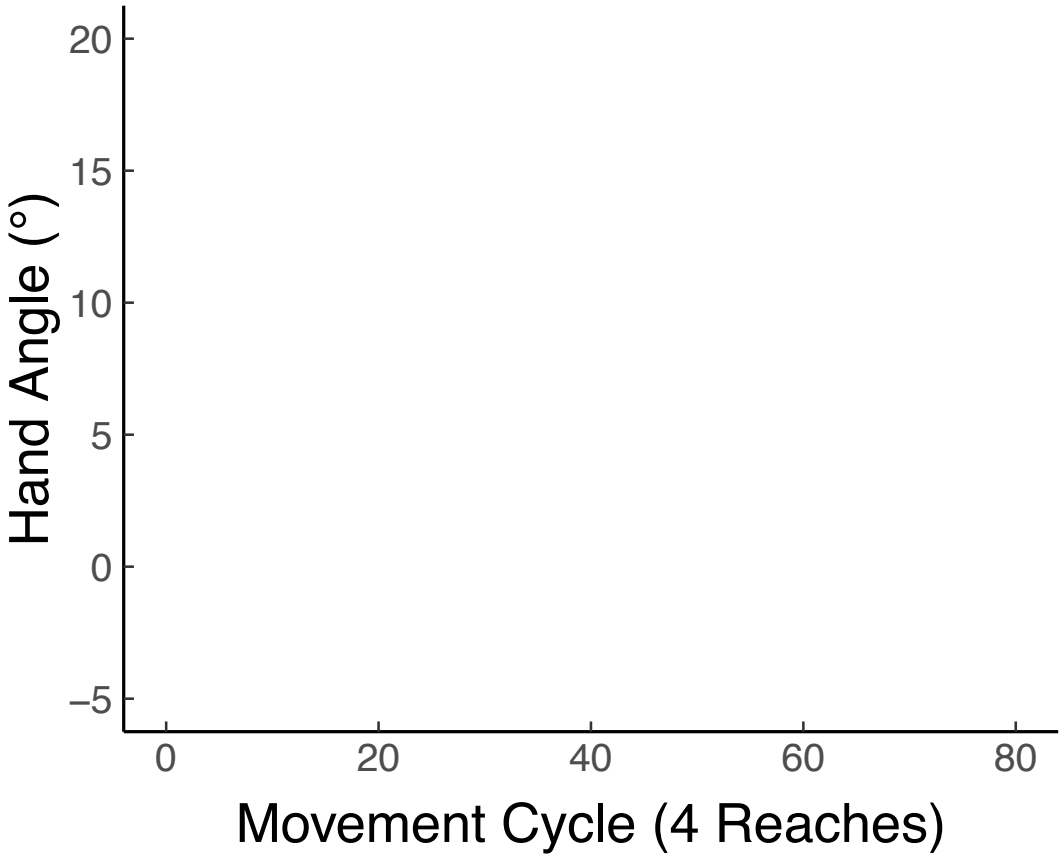
Haith et al (2009); Rossi et al (2021); Ostry et al (2010)

Disc #4: The state estimation hierarchy

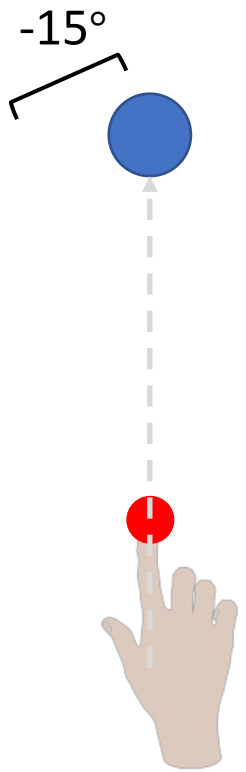


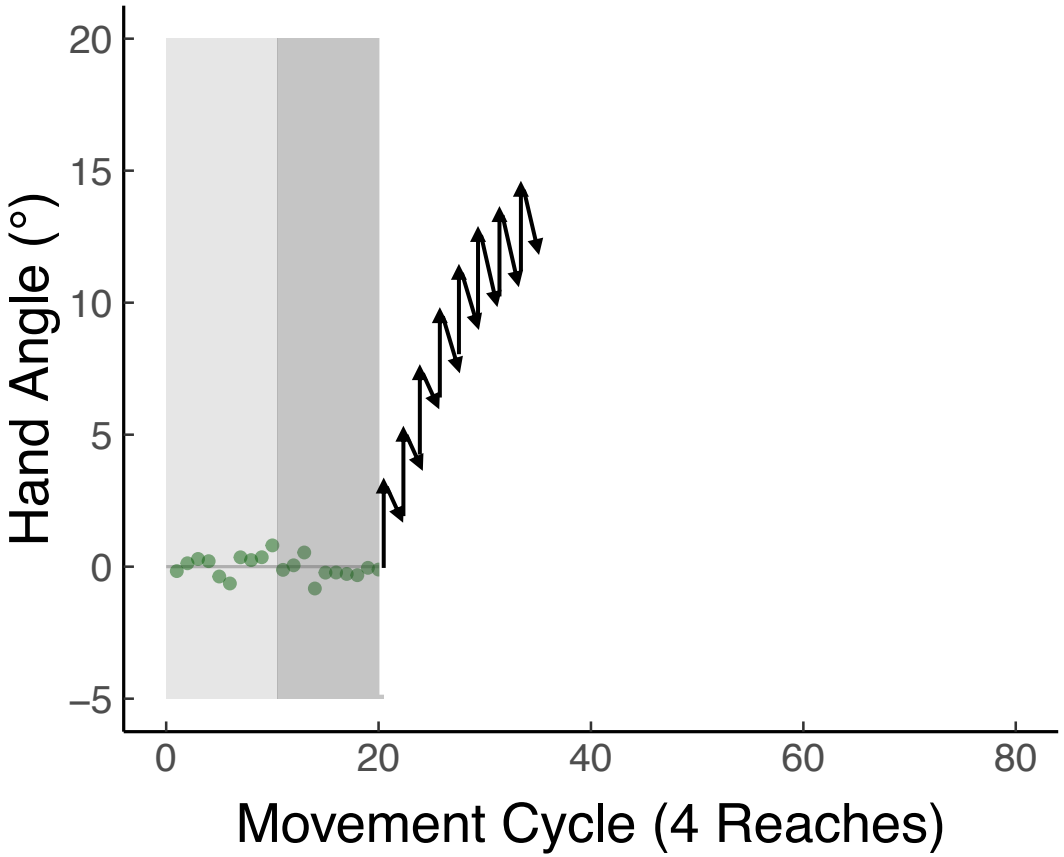
Motor adaptation in the lab





Perturbation block



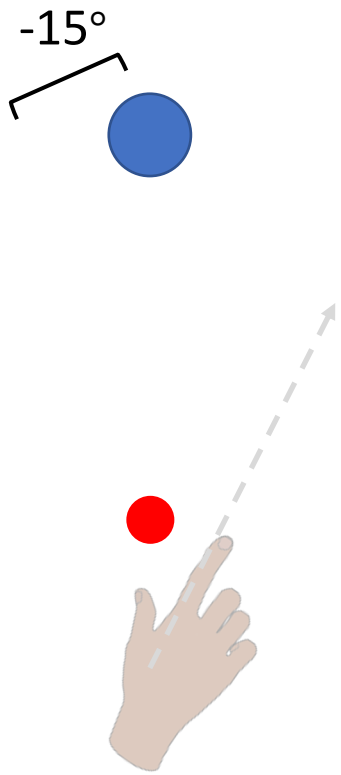


Forgetting $\sim [0, 1]$

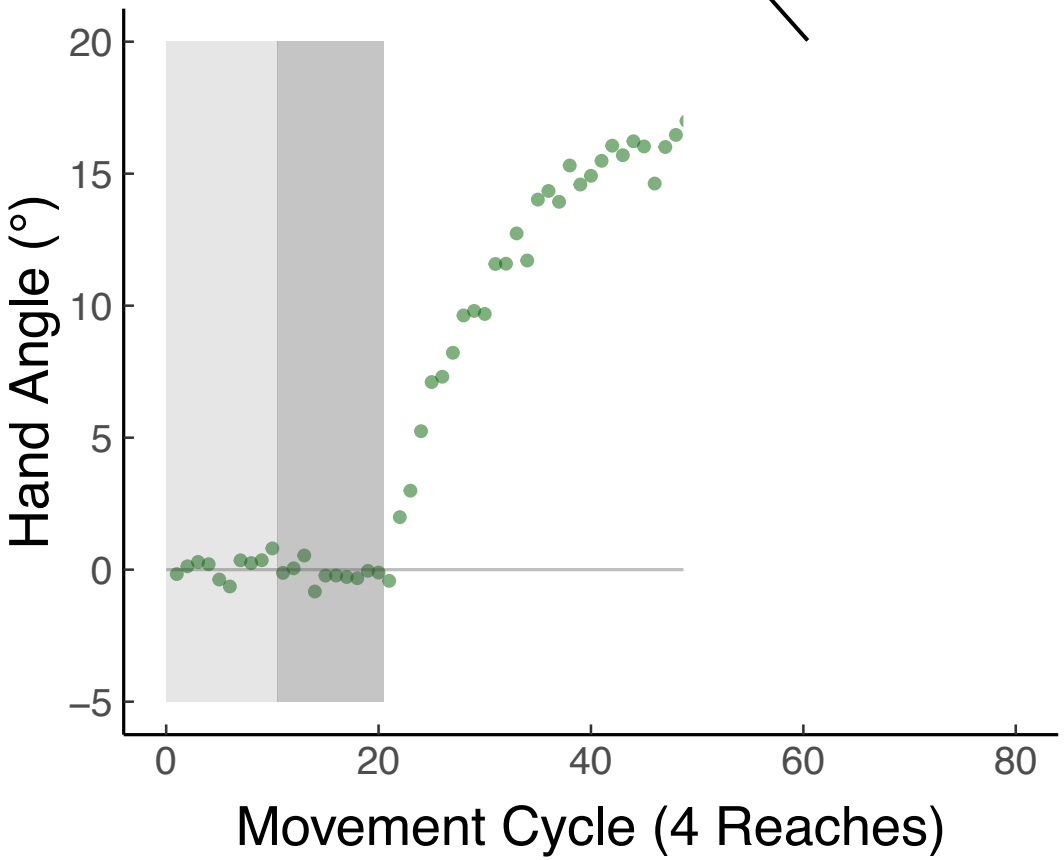
$$\mu_{p,t+1} = A\mu_{p,t} + B(T - \mu_{v,t})$$

Learning $\sim [0, 1]$

Perturbation block



Upper bound:
learning = forgetting

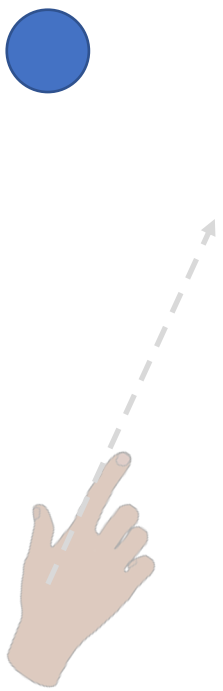


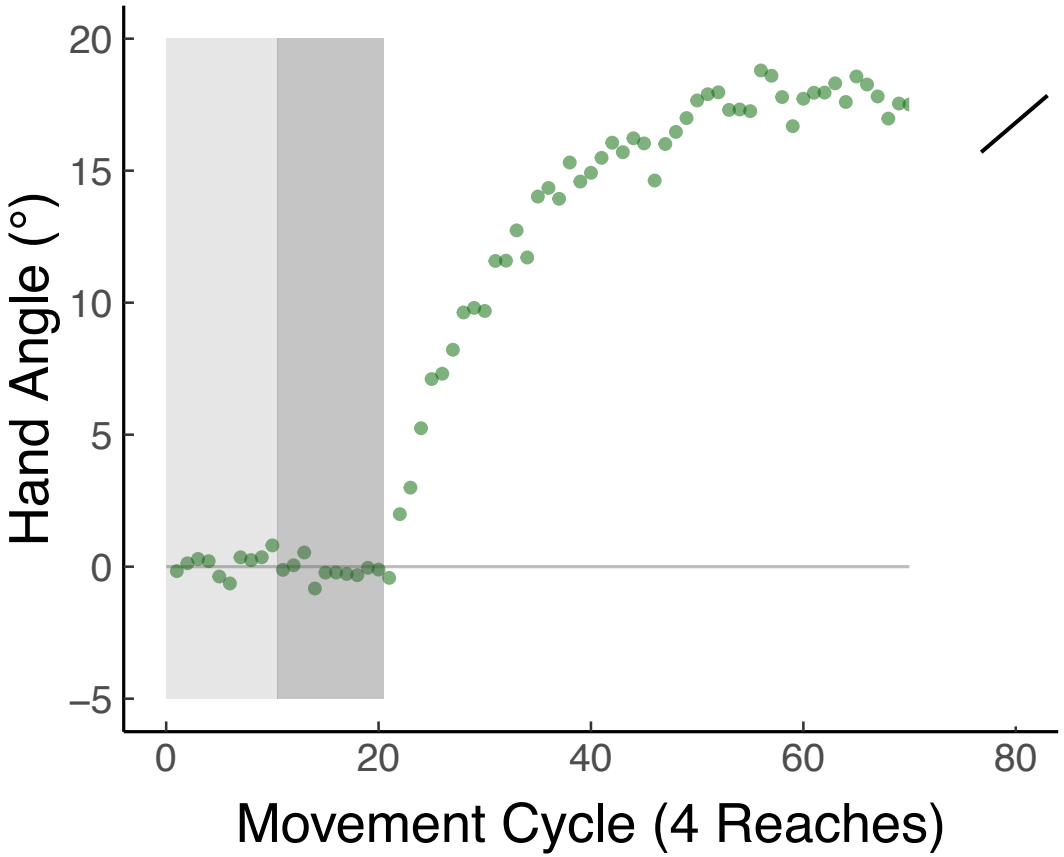
Forgetting $\sim [0, 1]$

$$\mu_{p,t+1} = A\mu_{p,t} + B(T - \mu_{v,t})$$

Learning $\sim [0, 1]$

Washout



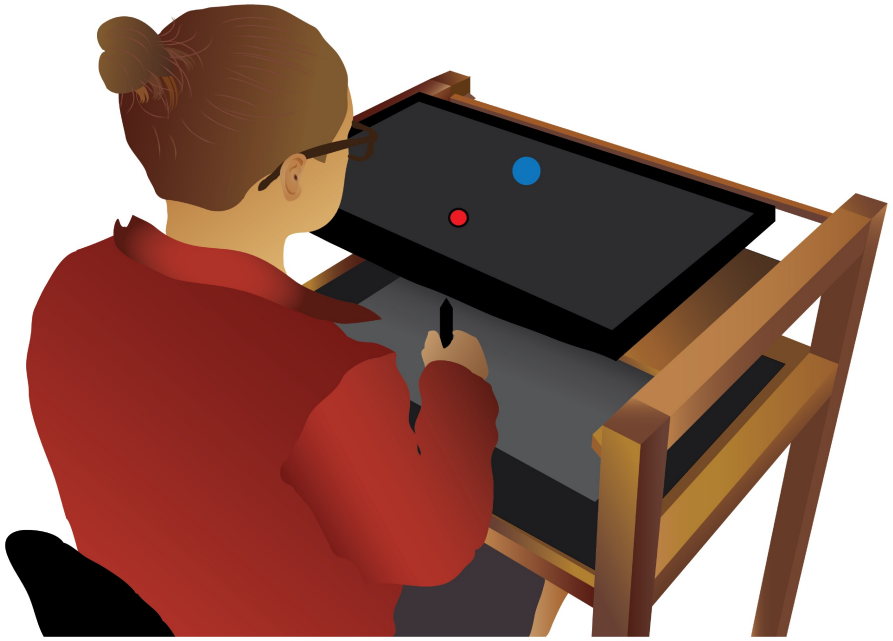


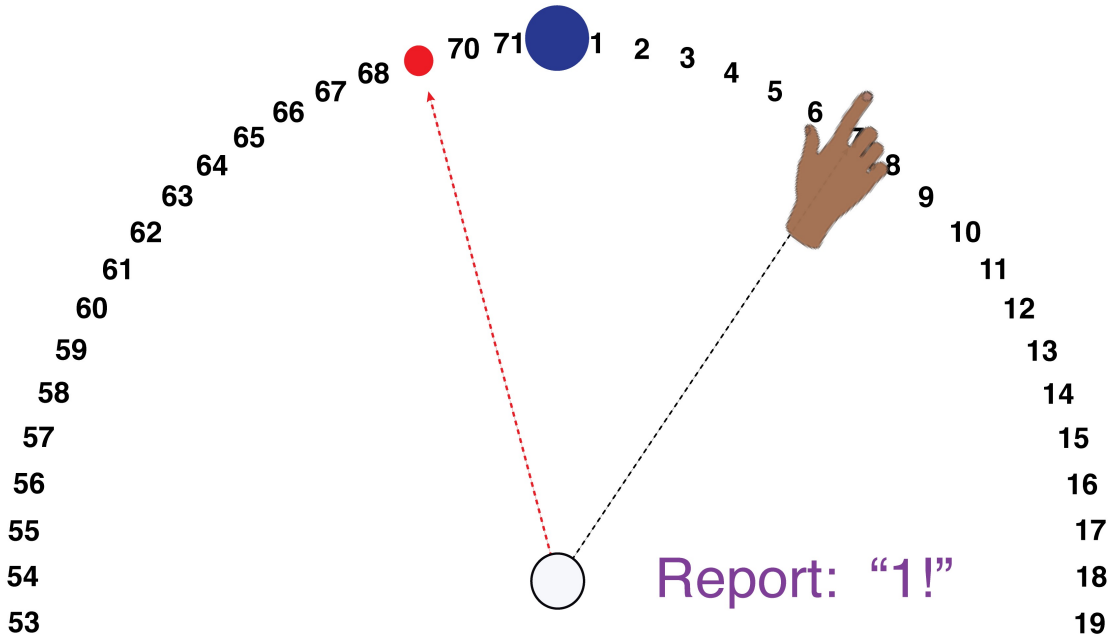
Forgetting $\sim [0, 1]$

$$\mu_{p,t+1} = A\mu_{p,t} + \cancel{B(T - \mu_{v,t})}$$

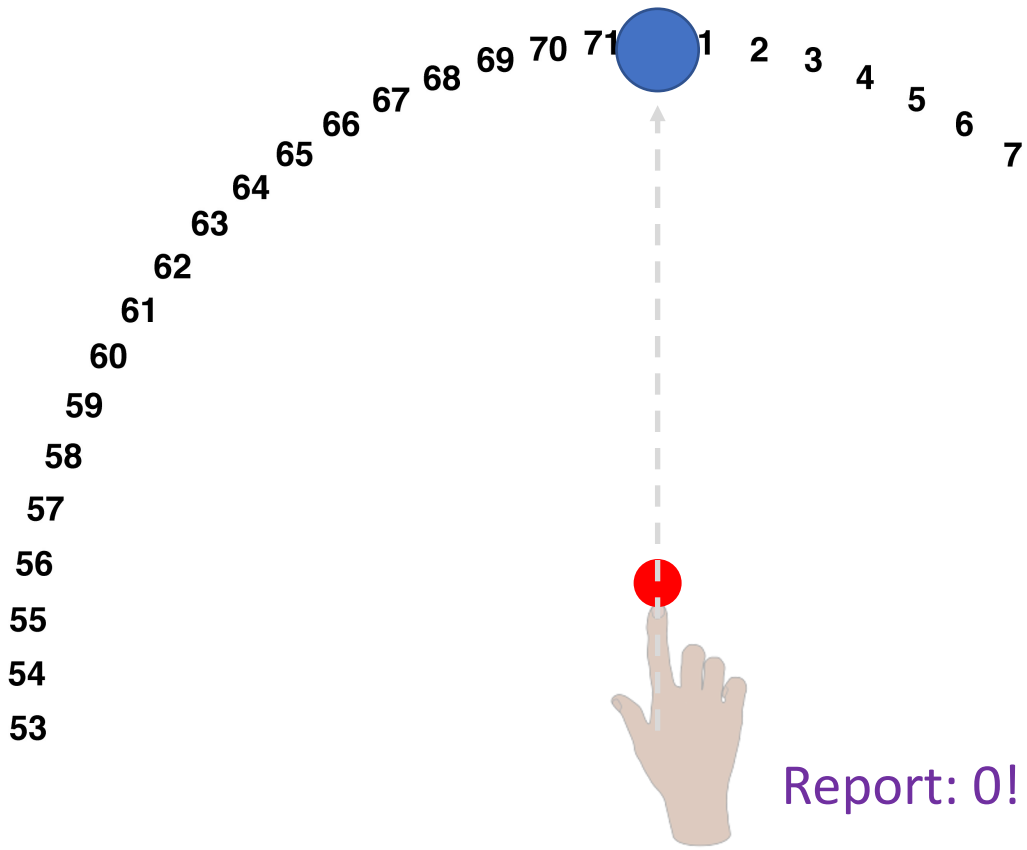
Learning $\sim [0, 1]$

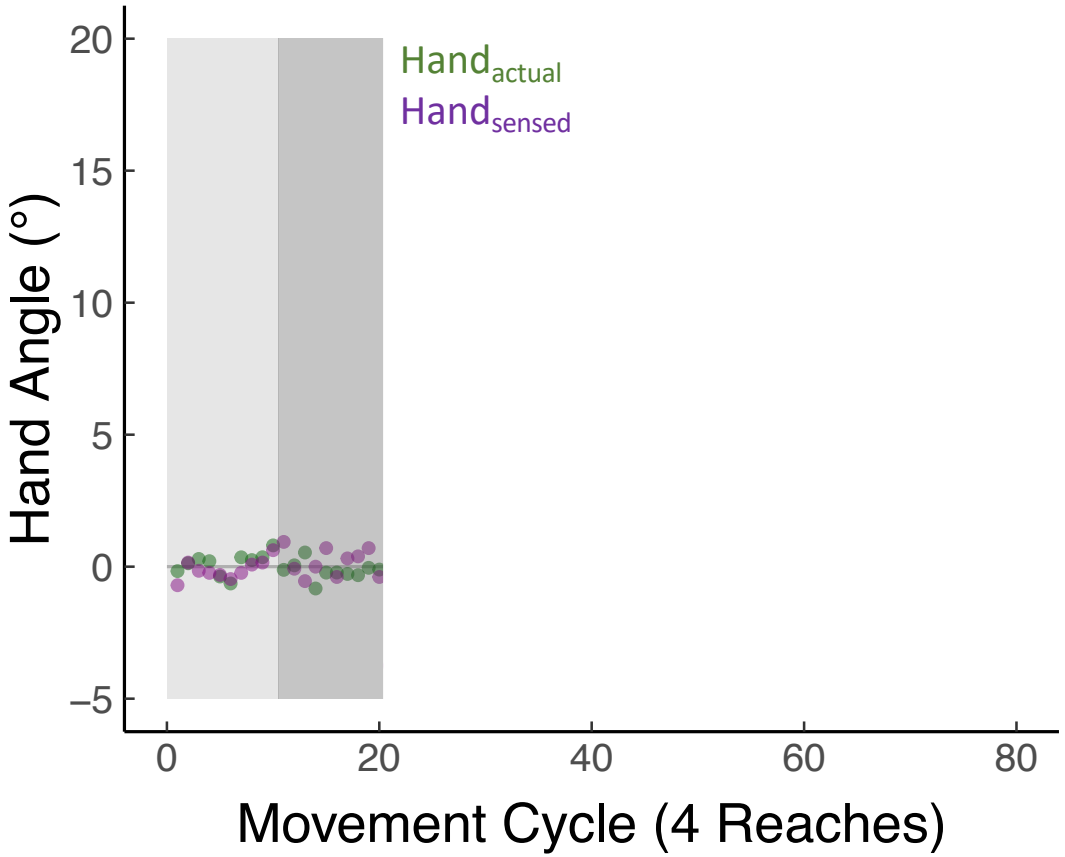
Adaptation may reduce a proprioceptive error



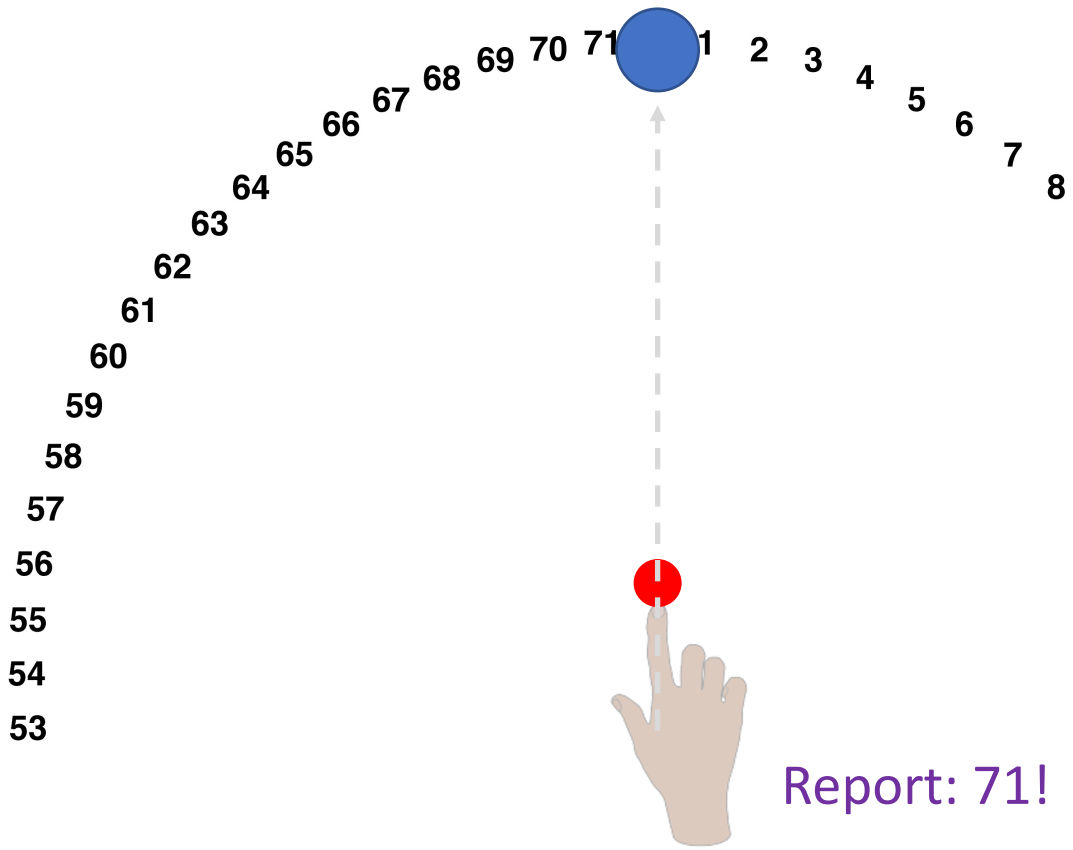


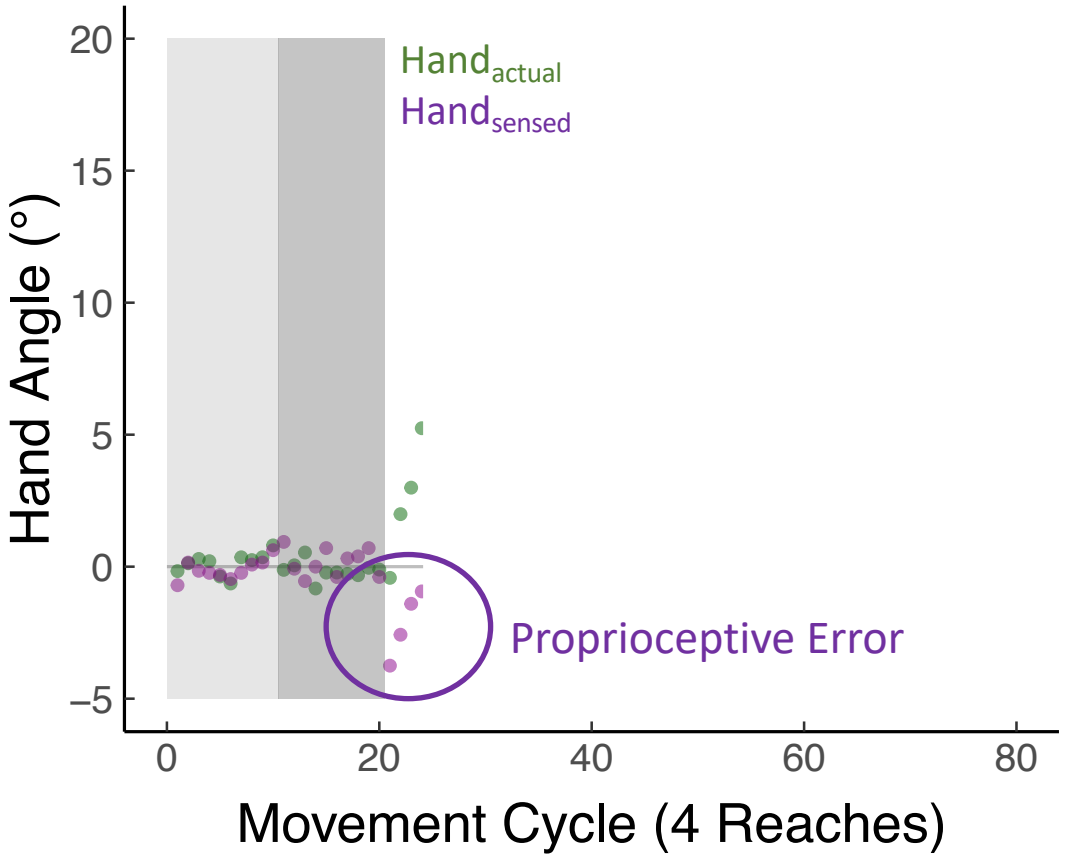
Baseline


53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
1
2
3
4
5
6
7
8
Report: 0!

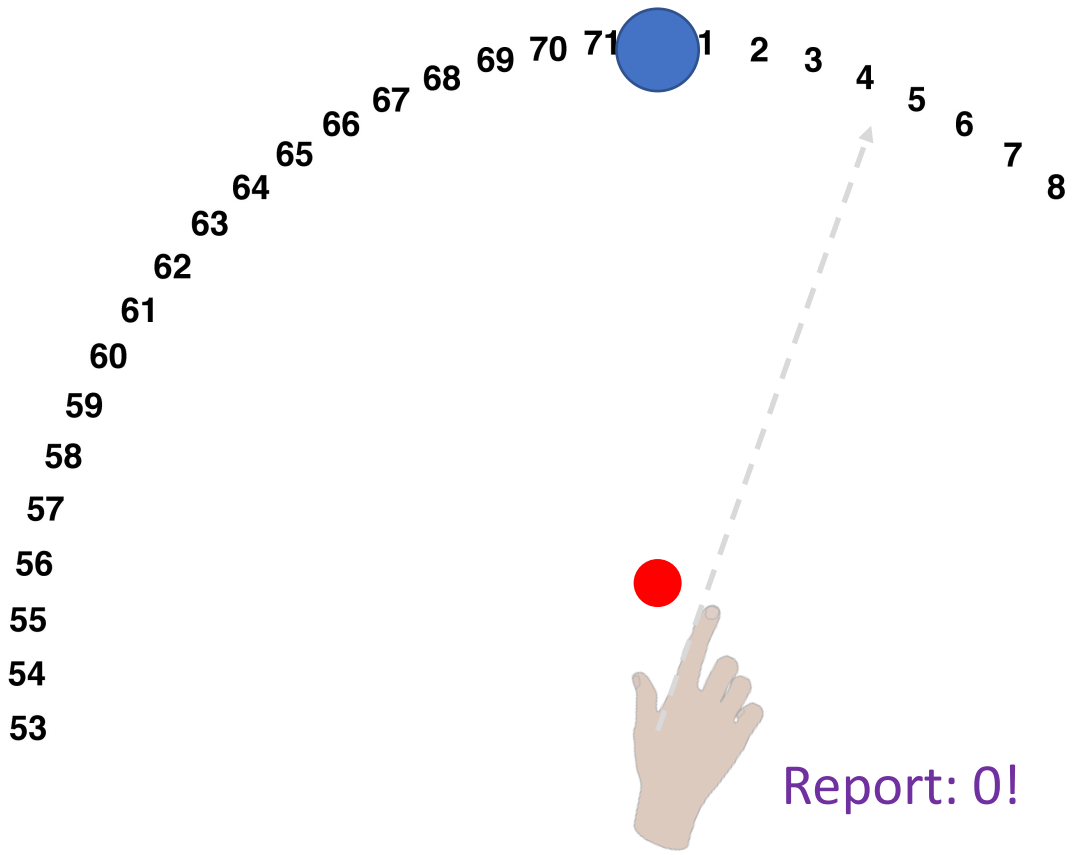

Hand$_{actual}$
Hand$_{sensed}$
Hand Angle (°)
20
15
10
5
0
−5
0
20
40
60
80
Movement Cycle (4 Reaches)

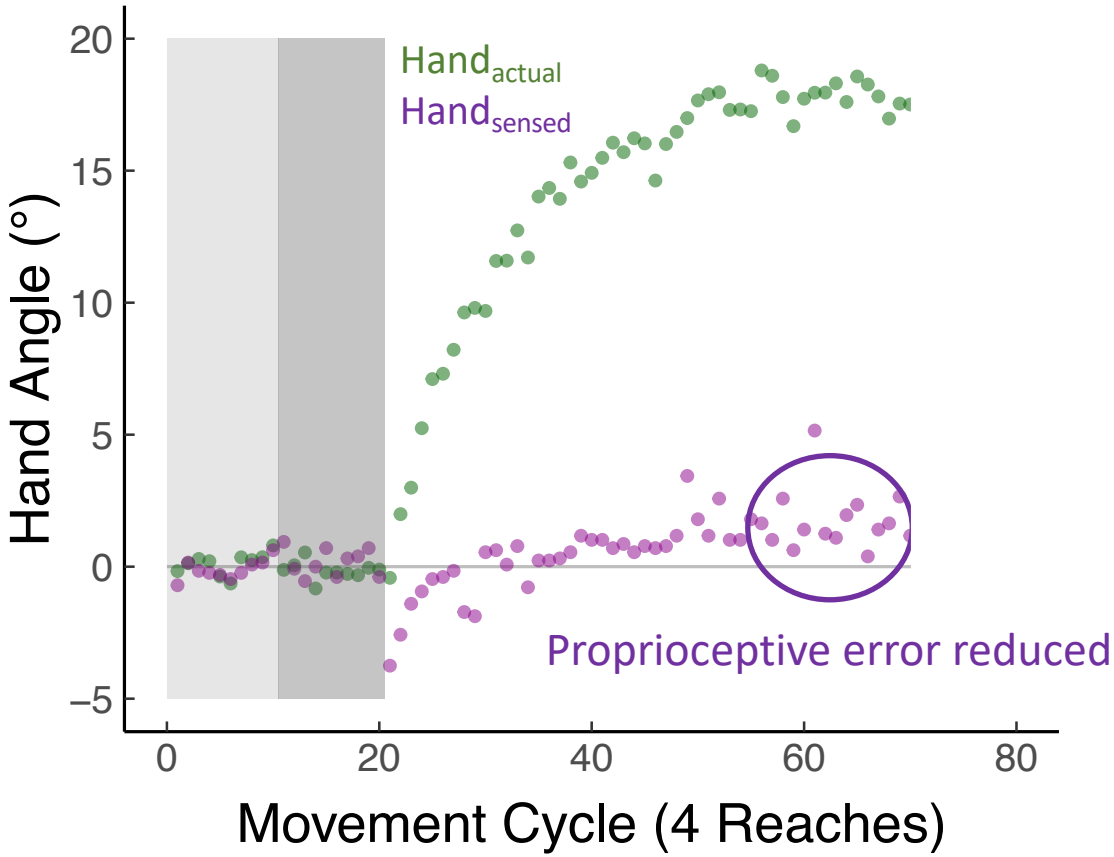
Perturbation block



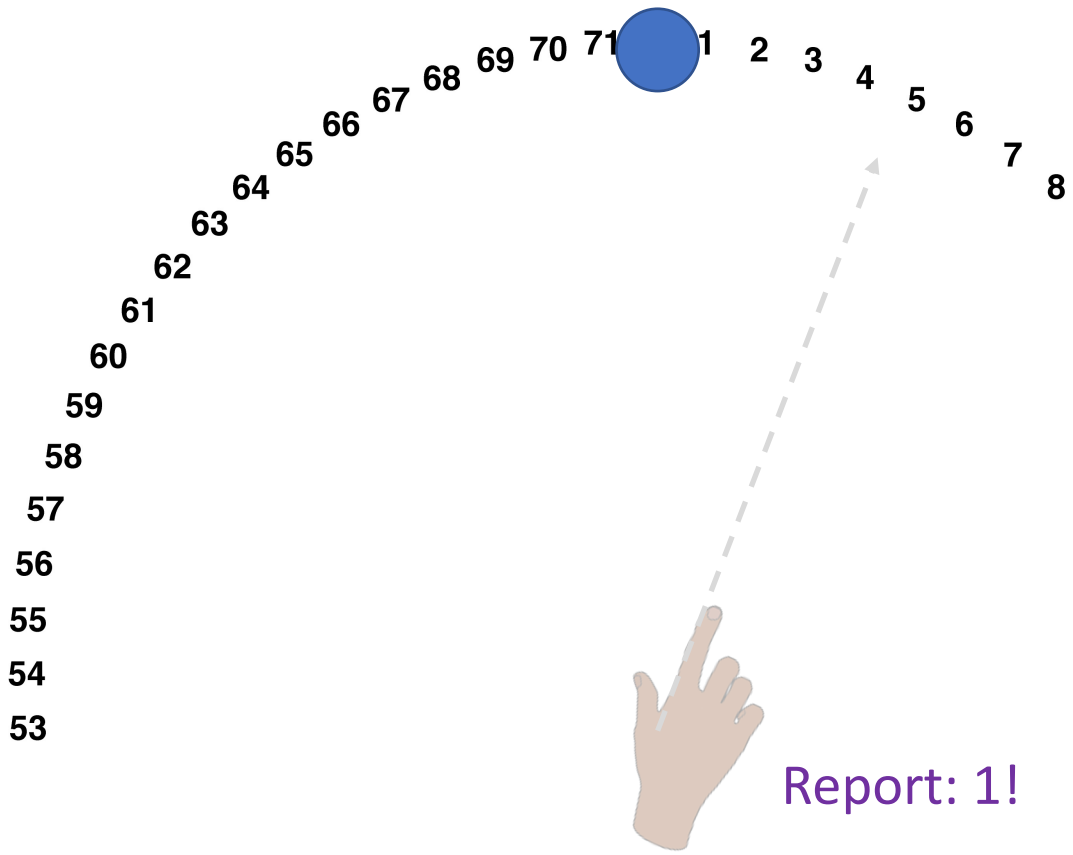


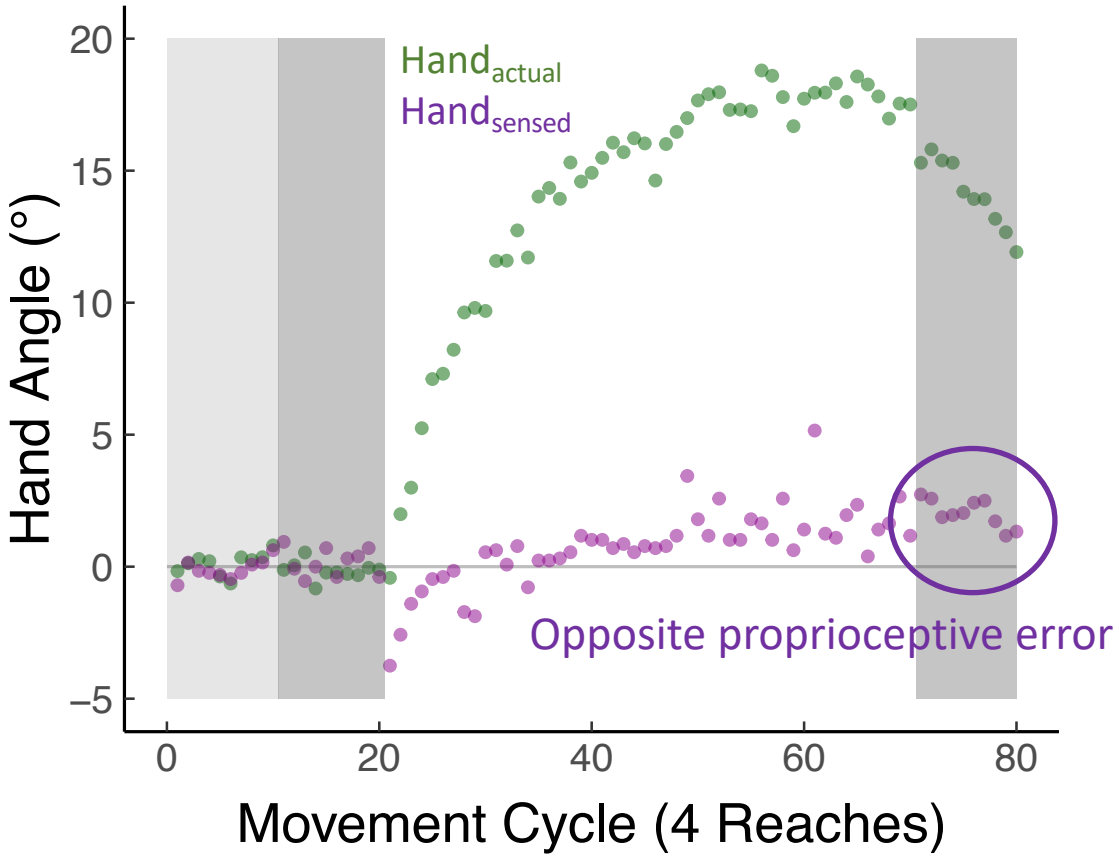
Perturbation block





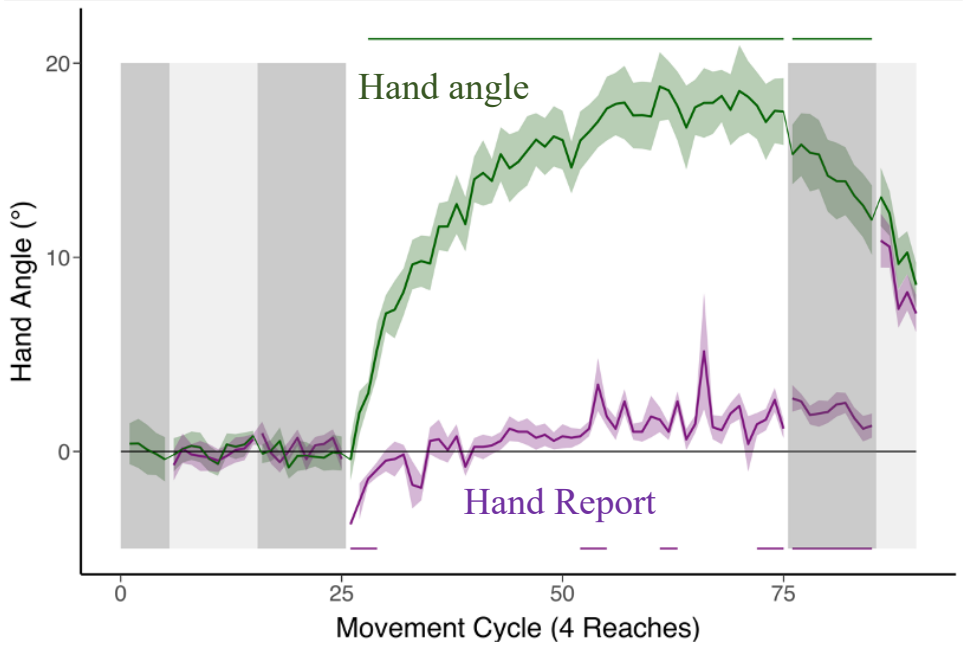
Washout block



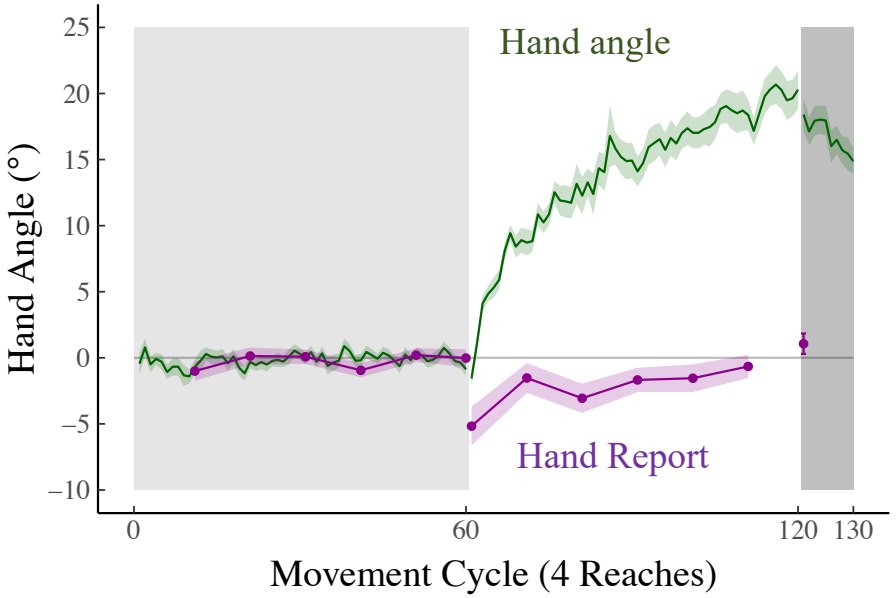


Pilot: Hand angle + reports largely reproduced online

In Person (n = 16, Tsay et al 2020)



Online (n = 31)



Exp 1: WL was reporting her sensed hand position, not simply the visual cursor position

Individual without proprioception of her moving limb