Sensory Re-alignment Model

NCM, 2021
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Recent findings challenge a **visuo-centric view of motor adaptation**

<table>
<thead>
<tr>
<th>Model attributes</th>
<th>Traditional state-space model</th>
<th>Recent findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>The goal of adaptation</td>
<td>is to nullify a visual error</td>
<td>is also influenced by a proprioceptive error&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>The rate of adaptation</td>
<td>increases with error size</td>
<td>saturates for large errors, mirroring saturated (visually induced) prop biases&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>The upper bound of adaptation</td>
<td>is when learning equals forgetting</td>
<td>is correlated with individual differences in proprioception (bias &amp; variability)&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>1</sup> 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


Sensory re-alignment model (1\textsuperscript{st} 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

\[ \mu_{p,t+1} = \mu_{p,t} + B(T^s - \mu_{p,t}) \]
The sensory re-alignment model can explain a wide range of features in motor adaptation.

<table>
<thead>
<tr>
<th>#</th>
<th>Feature</th>
<th>Traditional state space</th>
<th>Maximum likelihood estimation</th>
<th>Relevance estimation</th>
<th>Bayesian estimation</th>
<th>Sensory re-alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sensed hand position</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>2</td>
<td>Proprioception predicts upper bound</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>Saturated adaptation rate</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>4</td>
<td>Common upper bound</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>5</td>
<td>Visual uncertainty attenuates small errors only</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>6</td>
<td>Prediction uncertainty attenuates adaptation</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>7</td>
<td>Passive movements lead to motor aftereffects</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>8</td>
<td>Generalization patterns</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
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

\[ \text{Upper bound} \sim \frac{\frac{1}{\sigma_{\text{prior}}^2} + \frac{1}{\sigma_p^2}}{\sigma_{\text{prior}}^2} \beta_{p,t} \]

Proprioceptive variance

Prediction variance  Proprioceptive shift

Passive proprioceptive probes for proprioceptive shift/variance
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.

*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.

Salomonczyk et al. (2013)
Feature #8: Generalization pattern resembles a shift in sensed hand position
Re-evaluating the sensory constraints underlying motor adaptation

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<tr>
<td>The rate of adaptation</td>
<td>increases with error size</td>
<td>increases with error size but saturates</td>
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<tr>
<td>The upper bound of adaptation</td>
<td>is when learning equals forgetting</td>
<td>is when the hand is sensed at the target</td>
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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

Funding support:
National Institute of Health grant R35NS116883
Formalizing the sensory re-alignment model

<table>
<thead>
<tr>
<th></th>
<th>Proprioception</th>
<th>Vision</th>
</tr>
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<tbody>
<tr>
<td>Estimate</td>
<td>$\mu_{p,t}^e = \frac{\sigma_{prior}^2}{\sigma_{prior}^2 + \sigma_p^2} \mu_{p,t}$</td>
<td>$\mu_{v,t}^e = \frac{\sigma_{prior}^2}{\sigma_{prior}^2 + \sigma_v^2} \mu_{v,t}$</td>
</tr>
<tr>
<td>Calibrate</td>
<td>$\beta_{p,t} = \eta_p (\mu_{p,t}^e - \mu_{v,t}^e)_{sat}$</td>
<td>$\beta_{v,t} = \eta_v (\mu_{p,t}^e - \mu_{v,t}^e)_{sat}$</td>
</tr>
<tr>
<td>Sense</td>
<td>$\mu_{p,t}^s = \mu_{p,t}^e - \alpha \beta_{p,t}$</td>
<td>$\mu_{v,t}^s = \mu_{v,t}^e + \alpha \beta_{v,t}$</td>
</tr>
<tr>
<td>Update</td>
<td>$\mu_{p,t+1} = \mu_{p,t} + \frac{\sigma_{prior}^2}{\sigma_{prior}^2 + \sigma_p^2} (\mu_{p,t}^s - T^s)$</td>
<td></td>
</tr>
</tbody>
</table>

- **Actual position**: $\mu_p \mu_v$
- **Estimated position**: $\mu_p^s \mu_v^s$
- **Sensed position**: $\mu_p^s \mu_v^s T^s$
- **Sensory Shift**: $\beta_p \beta_v$
- **Shift ratio**: $\eta_p \eta_v$
- **Saturated shift**: $Sat$
- **Sensory noise**: $\sigma_v \sigma_p$
- **Prediction noise**: $\sigma_{prior}$
- **Sensory decay**: $\alpha$
- **Empirically observable Latent parameters**

Empirically observable
Latent parameters
Movement Cycle (4 Reaches)

Hand Angle (°)

−20
−10
0
10
20
30
40
50
60
70
80

Hand

Hand sensed

Handsensed

Target sensed & βps ~ 1°

b̃p_s ~ 3°

Cursor sensed

Cursor

0
20
40
60
80

Movement Cycle (4 Reaches)
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

Disc #4: The state estimation hierarchy
Motor adaptation in the lab
Perturbation block

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

Forgetting \( \sim [0, 1] \)

Learning \( \sim [0, 1] \)
Perturbation block

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

Forgetting \( \sim [0, 1] \)

Learning \( \sim [0, 1] \)

Upper bound: learning = forgetting
Washout

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

Forgetting \(\sim [0, 1]\)

Learning \(\sim [0, 1]\)
Adaptation may reduce a proprioceptive error
Baseline

Report: 0!

Movement Cycle (4 Reaches)

Hand Angle (°)

Hand_{actual}
Hand_{sensed}
Perturbation block

Report: 71!
Perturbation block

Report: 0!

Proprioceptive error reduced
Washout block

Movement Cycle (4 Reaches)

Hand Angle (°)

Report: 1!

Opposite proprioceptive error
**Pilot:** Hand angle + reports largely reproduced online

![Graphs showing hand angle and report data for in-person and online settings.](image)

- **In Person (n = 16, Tsay et al 2020)**
  - Hand angle
  - Hand Report

- **Online (n = 31)**
  - Hand angle
  - Hand Report
Exp 1: WL was reporting her sensed hand position, not simply the visual cursor position
Individual without proprioception of her moving limb