Dimensions of Motor Control
@TUM 20250320

Motor learning: context dependency, meta-learning, and redundancy

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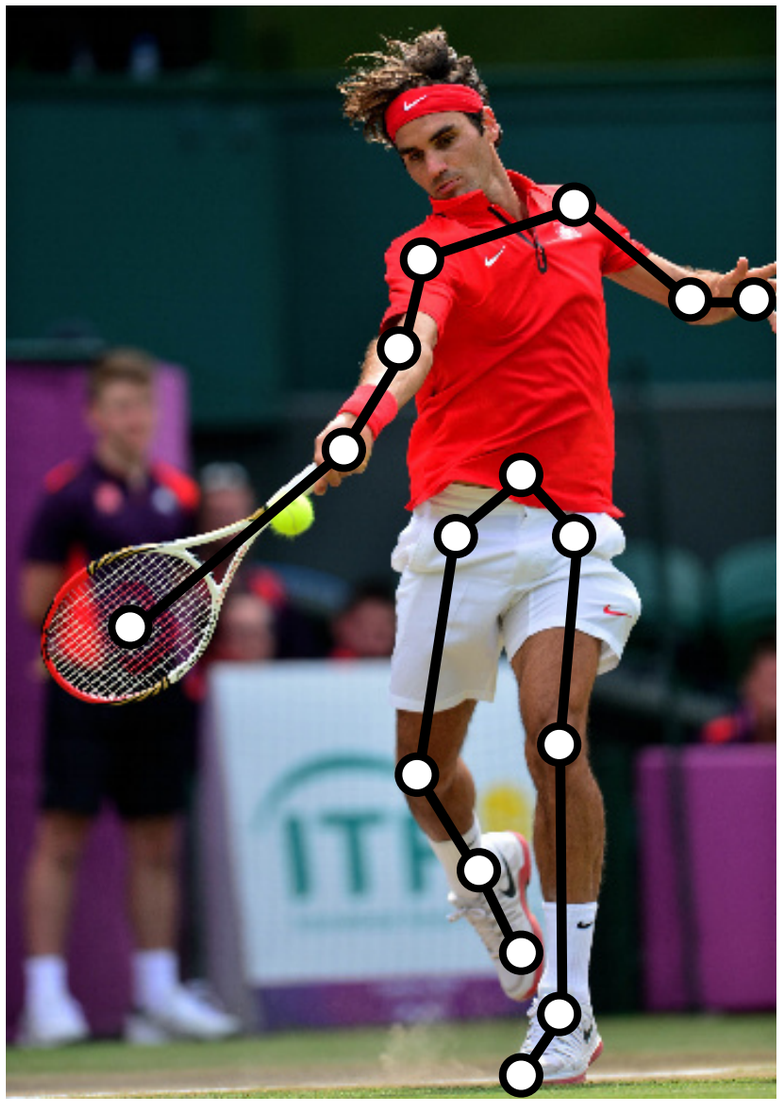
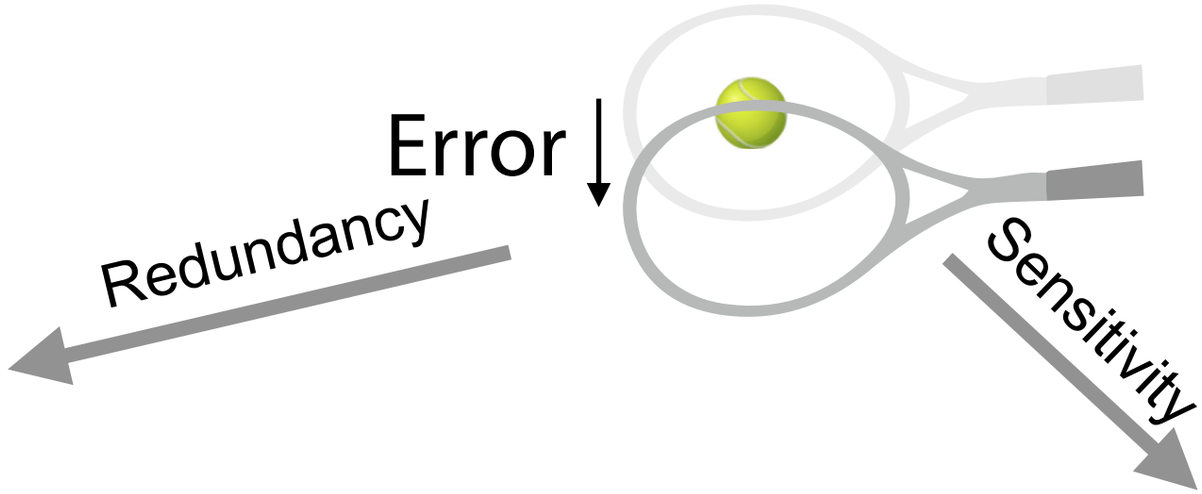
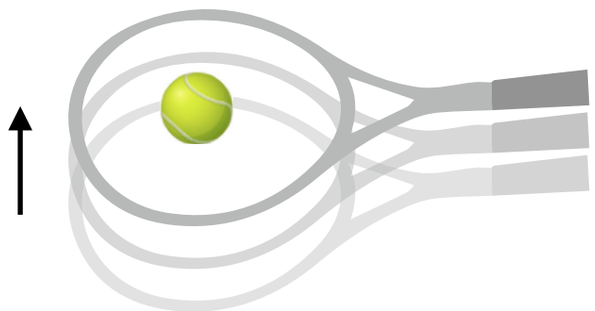
Mechanisms of movement correction



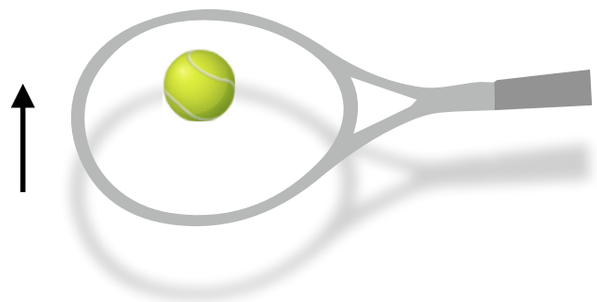


Feedback mechanism



within the swing

Learning mechanism



in the next swing

Transformation

Multimodal sensory integration

Integration between prediction and sensory information…

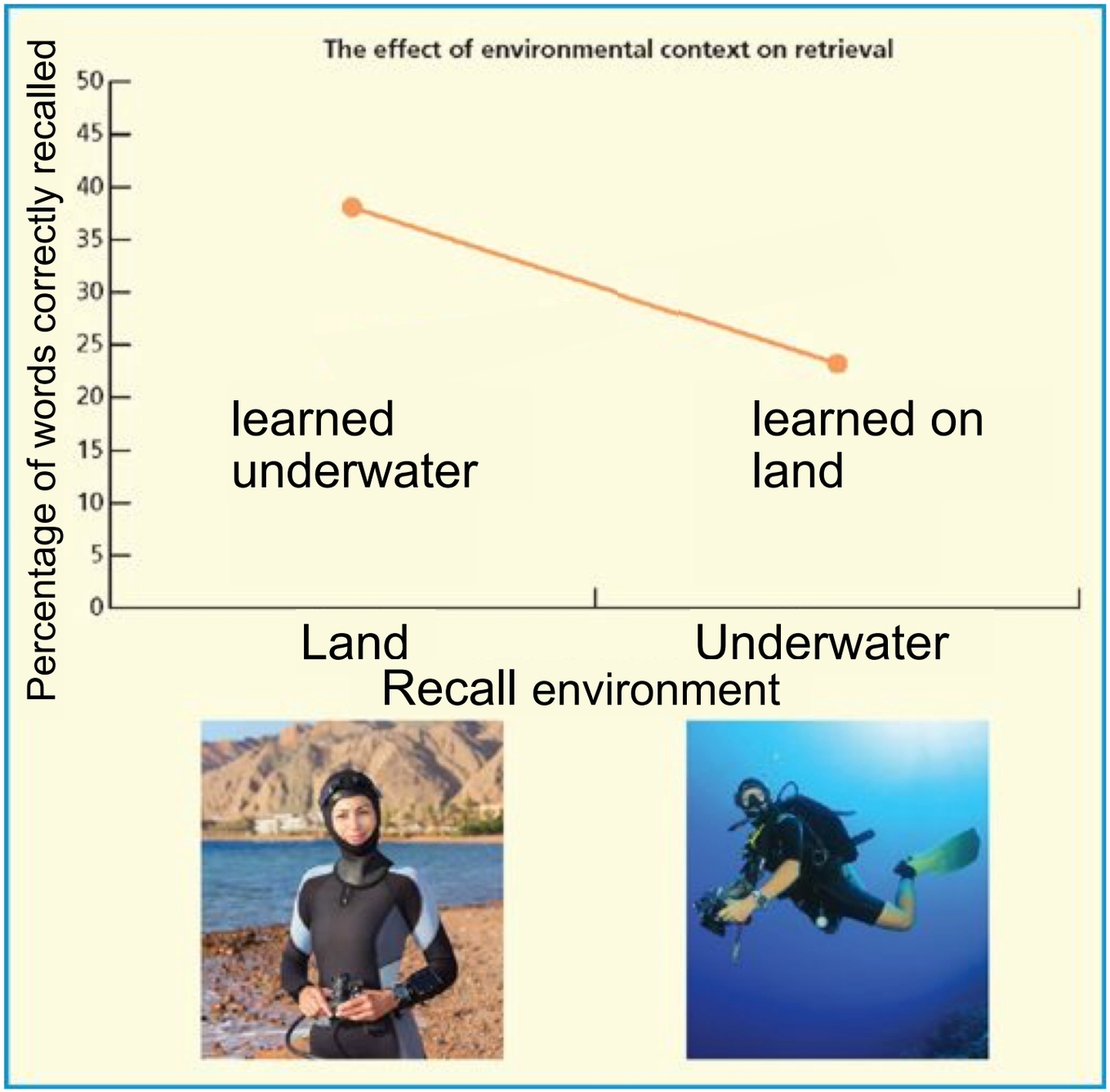
Contents

1. Context dependency: Motor memory is formed and retrieved according to different behavioral contexts.
2. Meta learning: Motor learning alters how motor learning is performed.
3. Redundancy: How does the brain coordinate redundant body movement for adaptations?

Contents

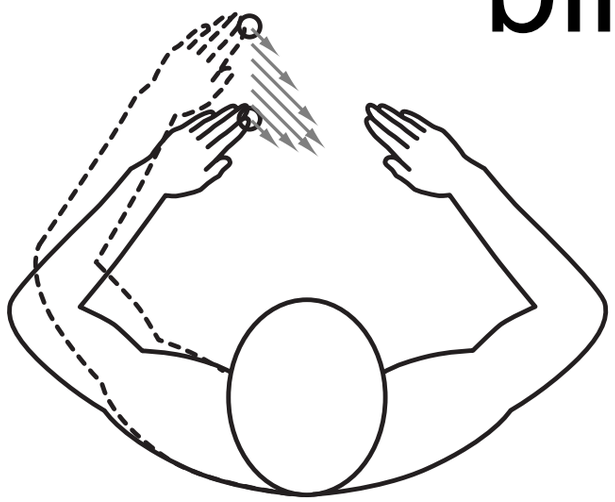
1. **Context dependency: Motor memory is formed and retrieved according to different behavioral contexts.**
2. Meta learning: Motor learning alters how motor learning is performed.
3. Redundancy: How does the brain coordinate redundant body movement for adaptations?

Declarative memory is context dependent

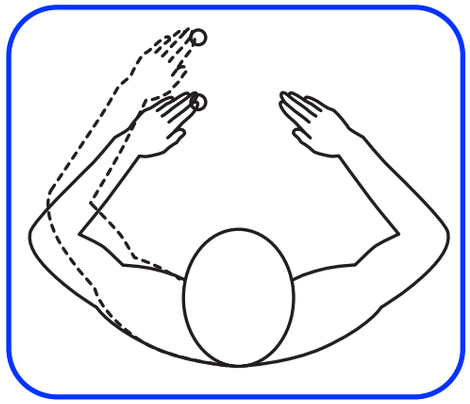


Godden & Baddeley, British Journal of Psychology, 1975

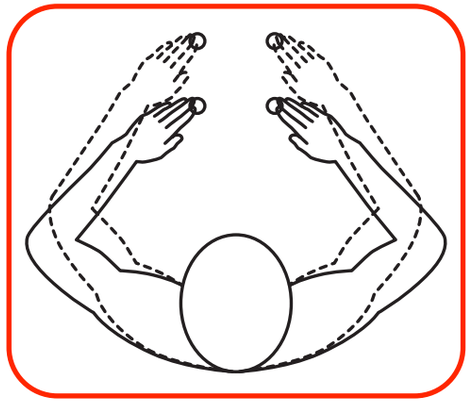
Transfer of learning between uni- and bimanual movements



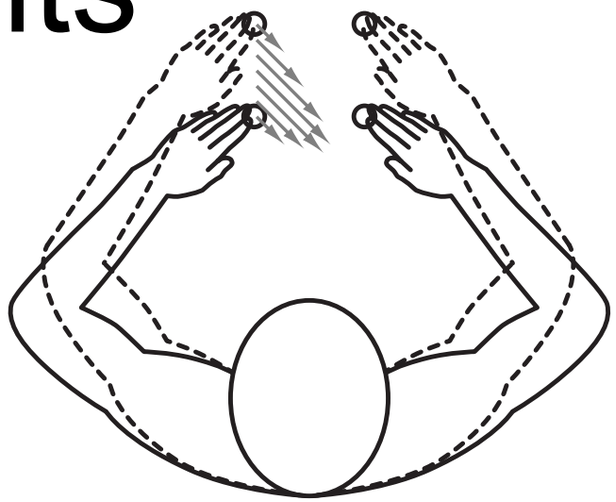
Uni- learning



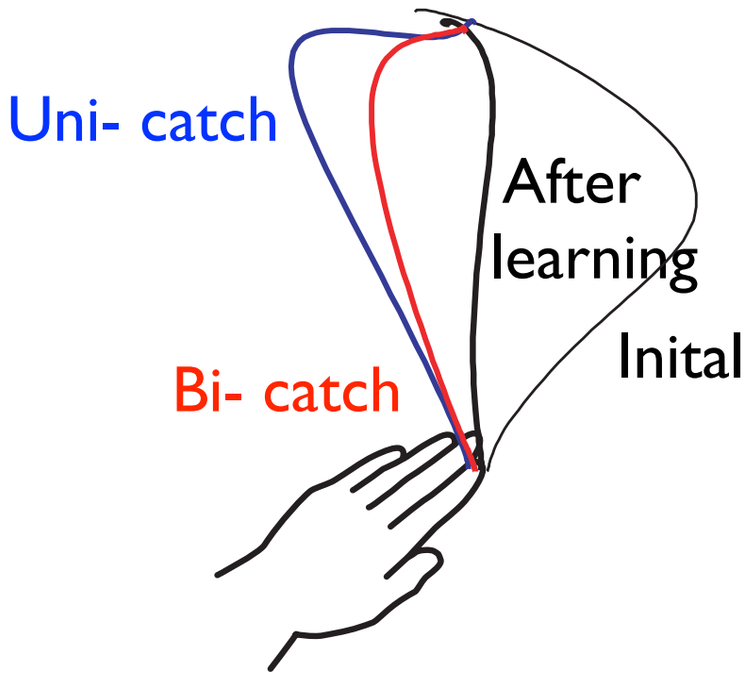
Uni- catch trial

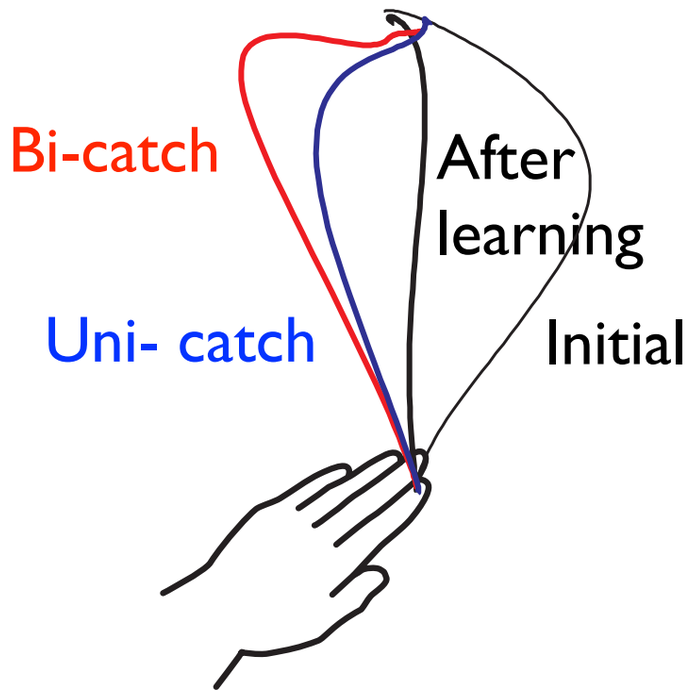


Bi- catch trial

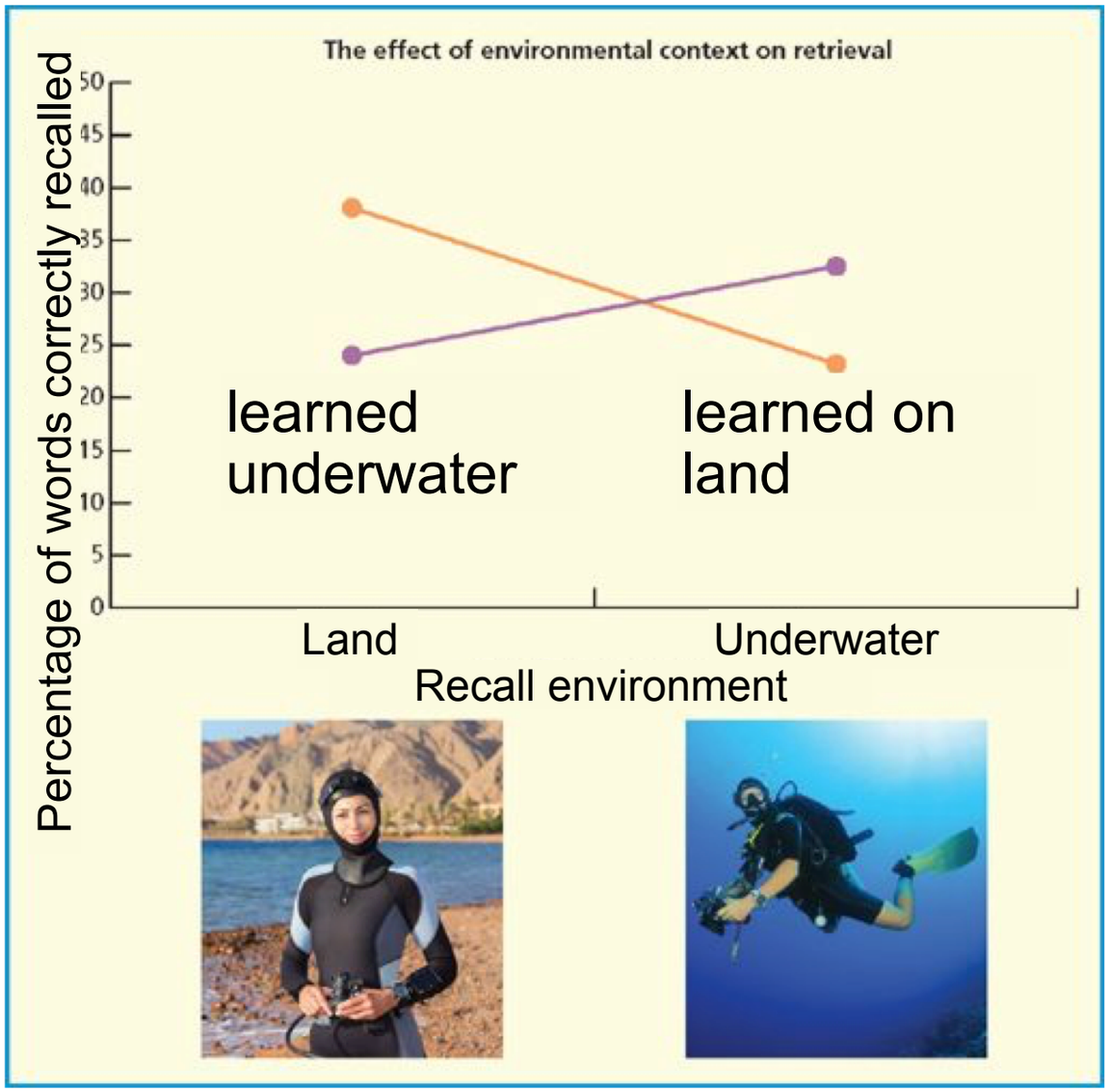


Bi- learning

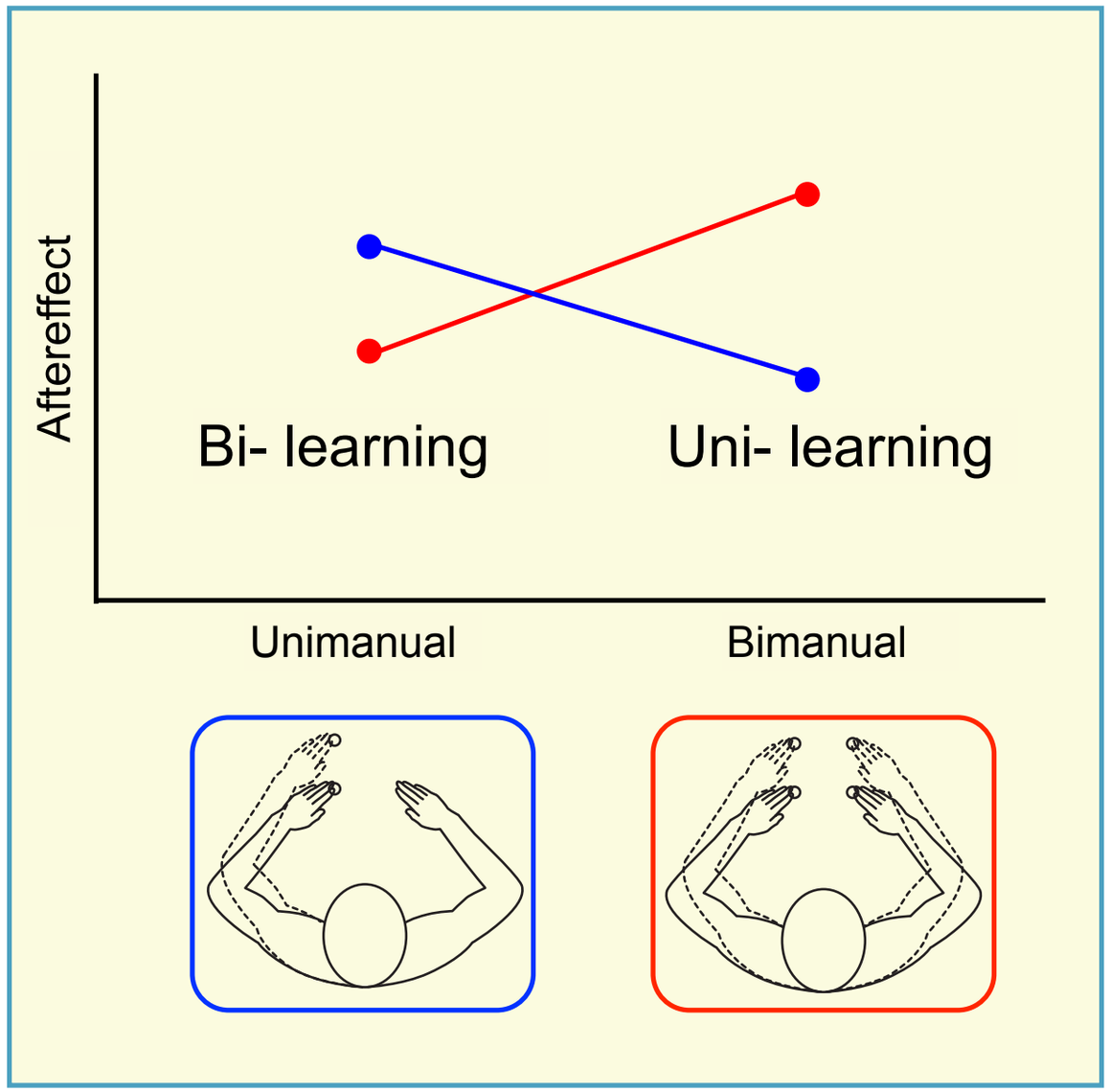




Motor memory is context-dependent

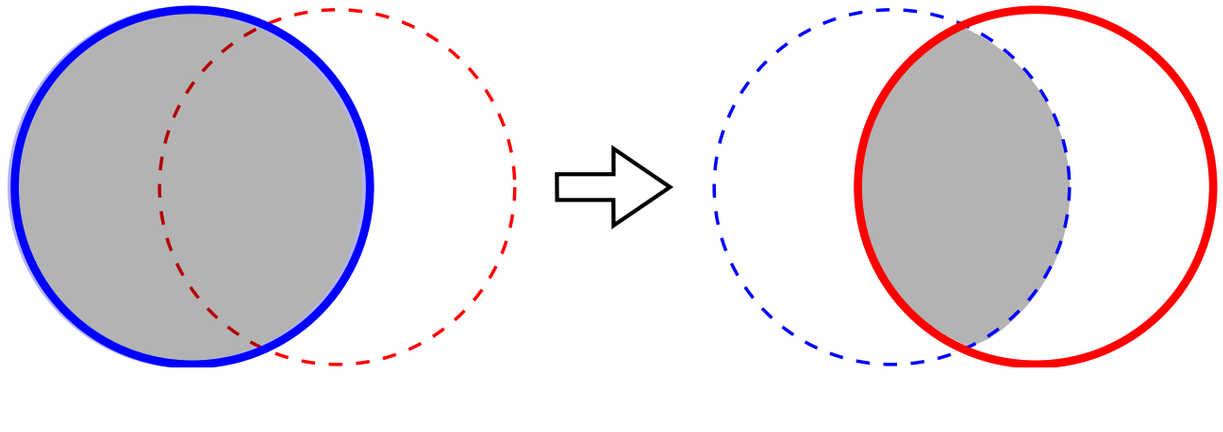


Godden & Baddeley, British Journal of Psychology, 1975

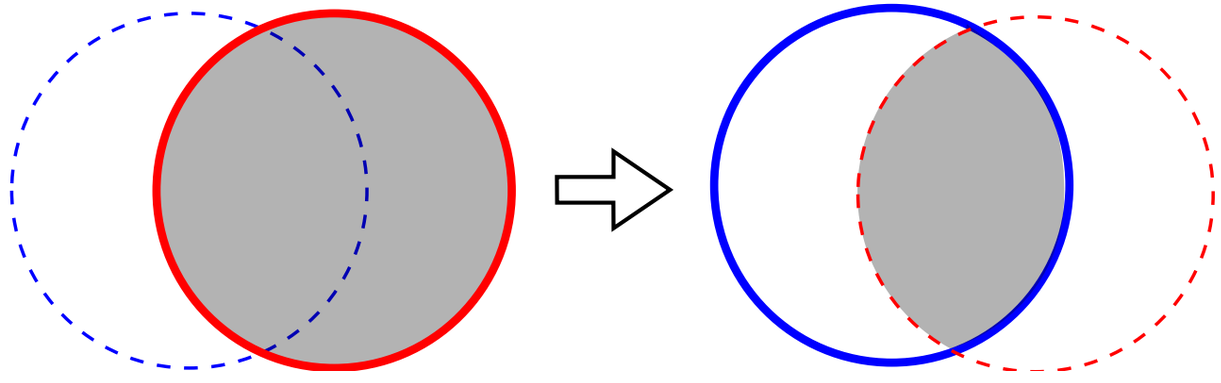


Nozaki et al., Nature Neuroscience, 2006

Partially overlapping motor memories

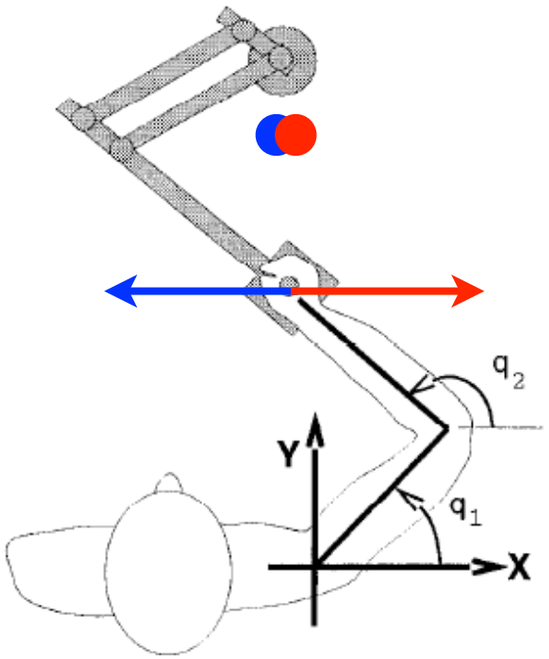


After uni- learning Transfer to bi- mov

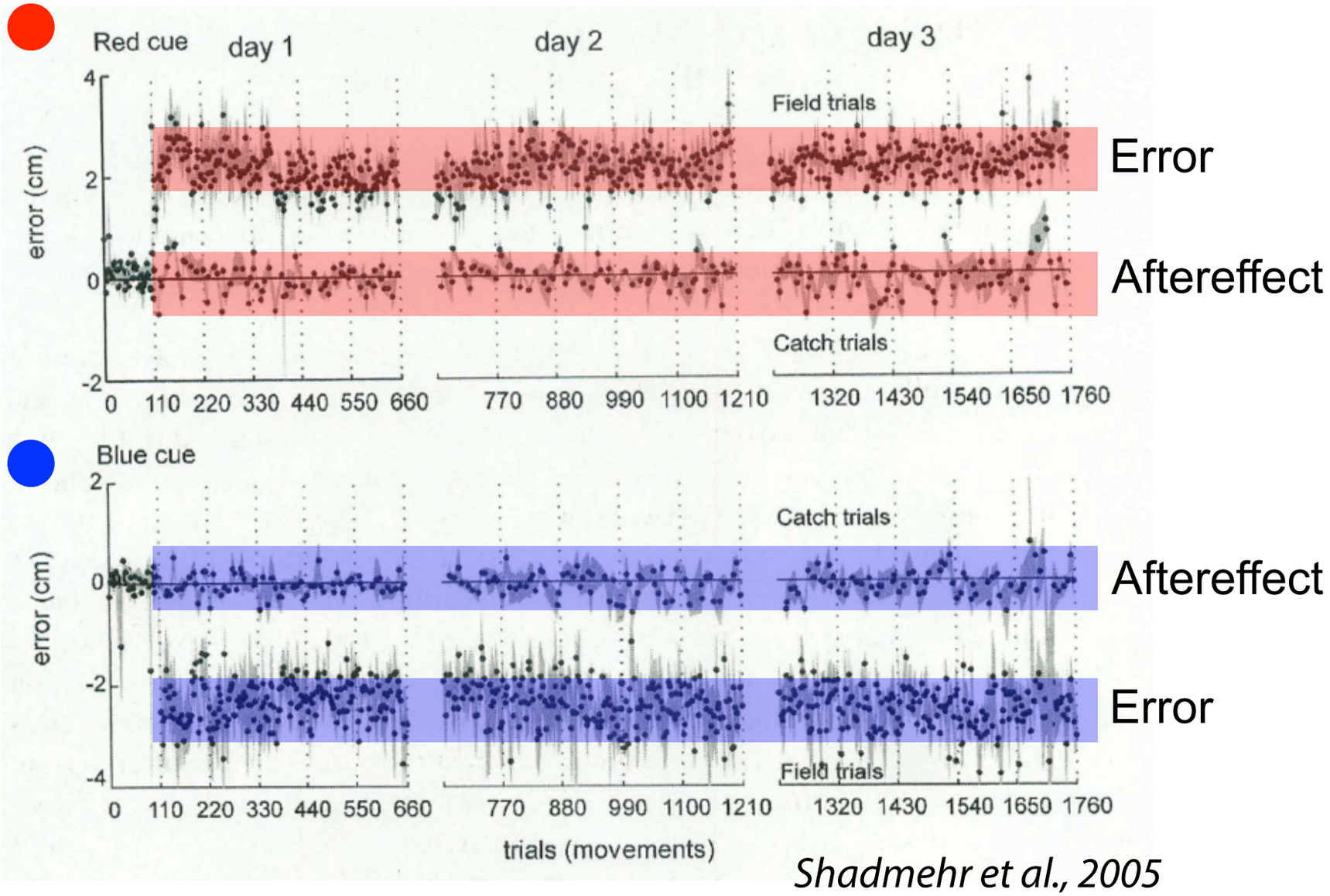


After bi- learning Transfer to uni- mov

Difficulty in adapting to opposing force fields

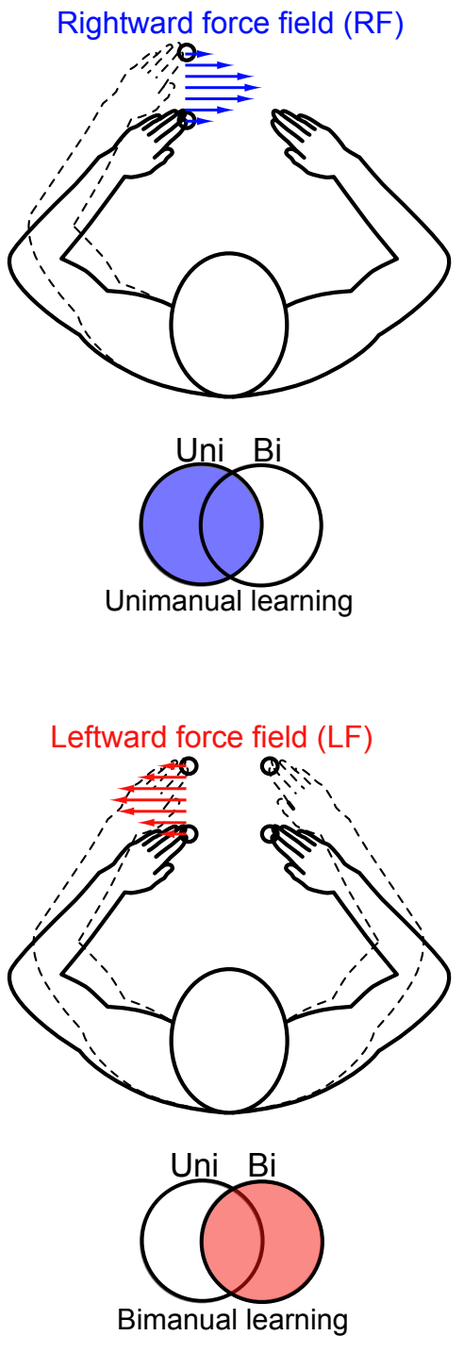


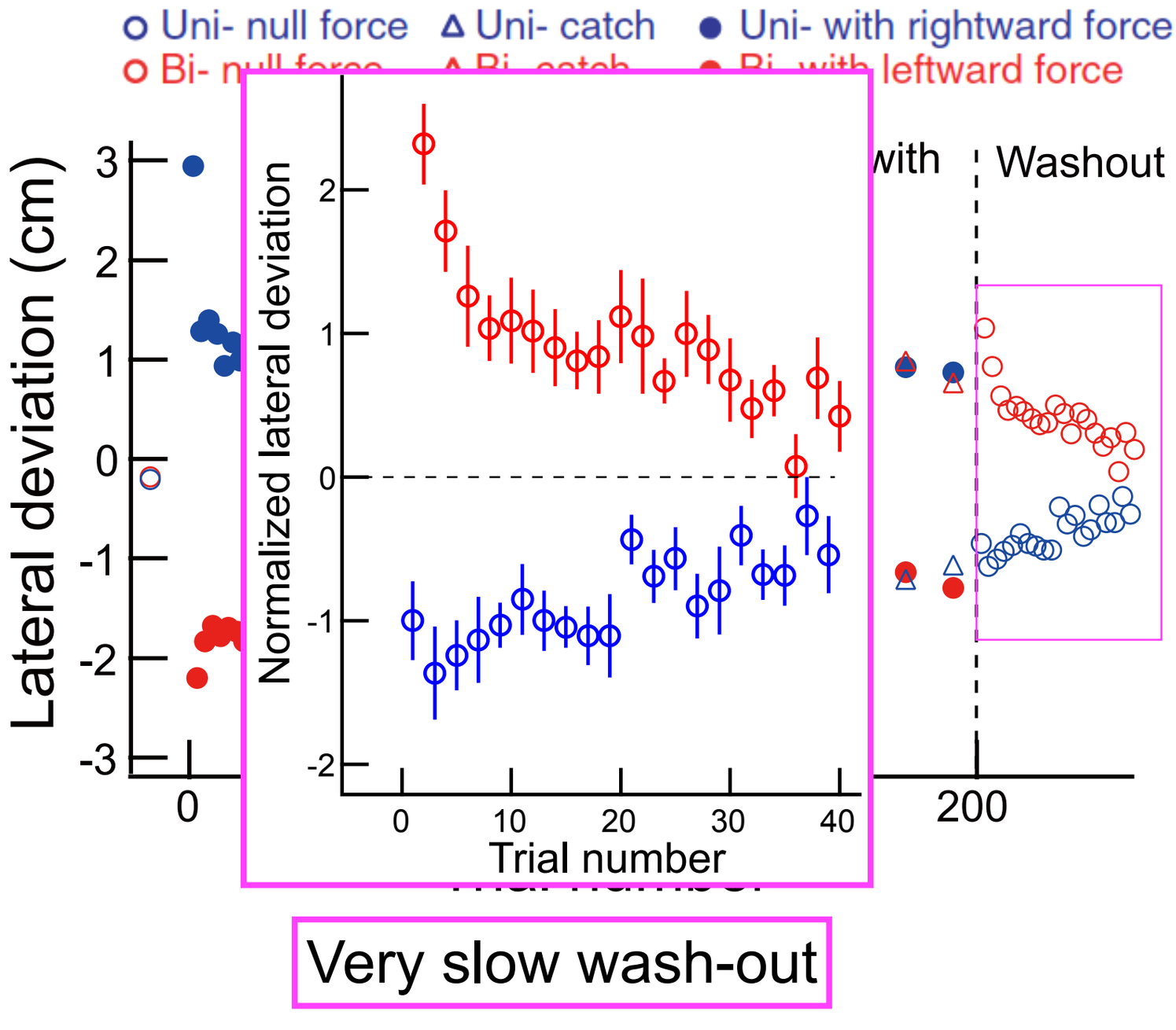
FF directions were changed according to the target color.



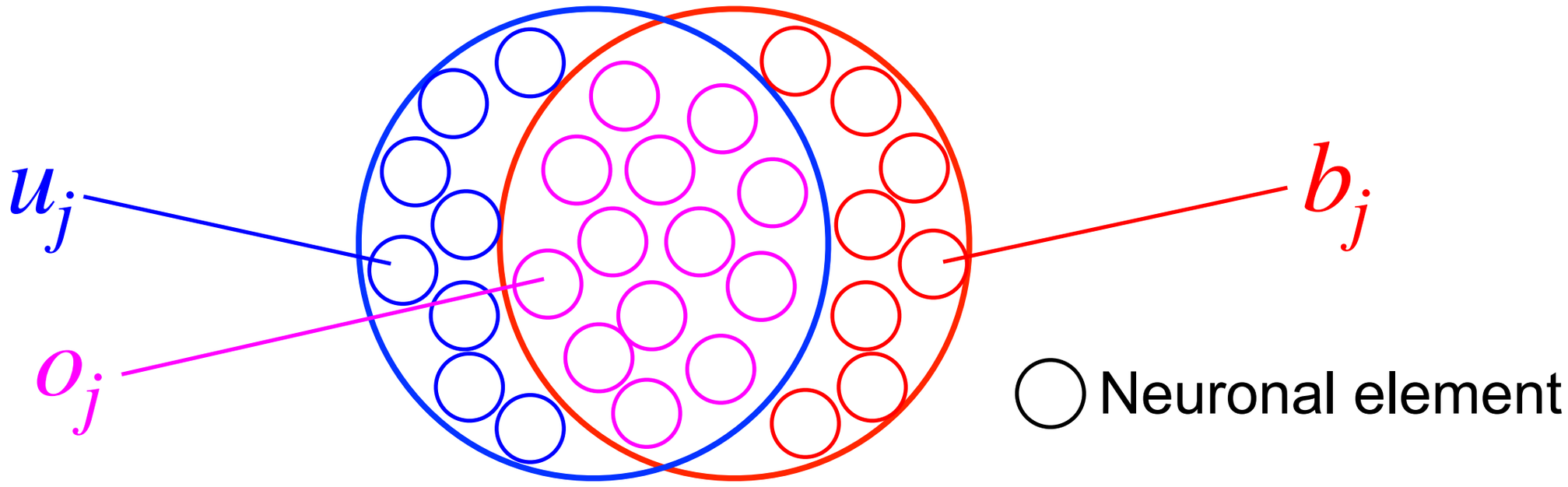
Shadmehr et al., 2005

Adaptation to opposing force field with and without the opposite arm





State-space model



After the i-th uni- learning

$$e(i) = f - \left\{ \sum_{j=1}^{N_u} u_j(i) + \sum_{j=1}^{N_o} o_j \right\}$$

Perturbation

Motor command

$$u_j(i+1) = \alpha u_j(i) + ke(i)$$

$$o_j(i+1) = \alpha o_j(i) + ke(i)$$

$$b_j(i+1) = \alpha b_j(i)$$

After the i-th bi- learning

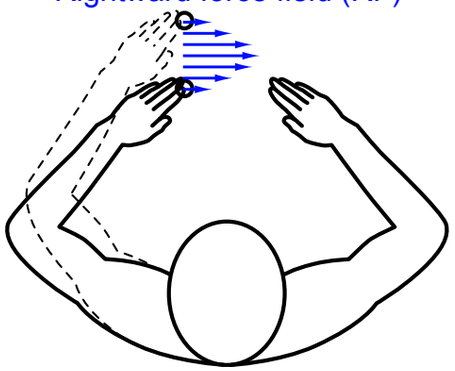
$$e(i) = f - \left\{ \sum_{j=1}^{N_b} b_j(i) + \sum_{j=1}^{N_o} o_j(i) \right\}$$

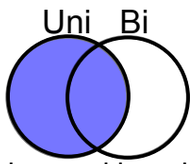
$$u_j(i+1) = \alpha u_j(i)$$

$$o_j(i+1) = \alpha o_j(i) + ke(i)$$

$$b_j(i+1) = \alpha b_j(i) + ke(i)$$

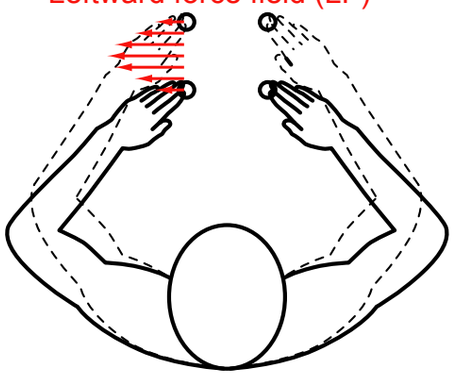
Rightward force field (RF)

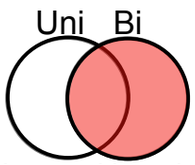




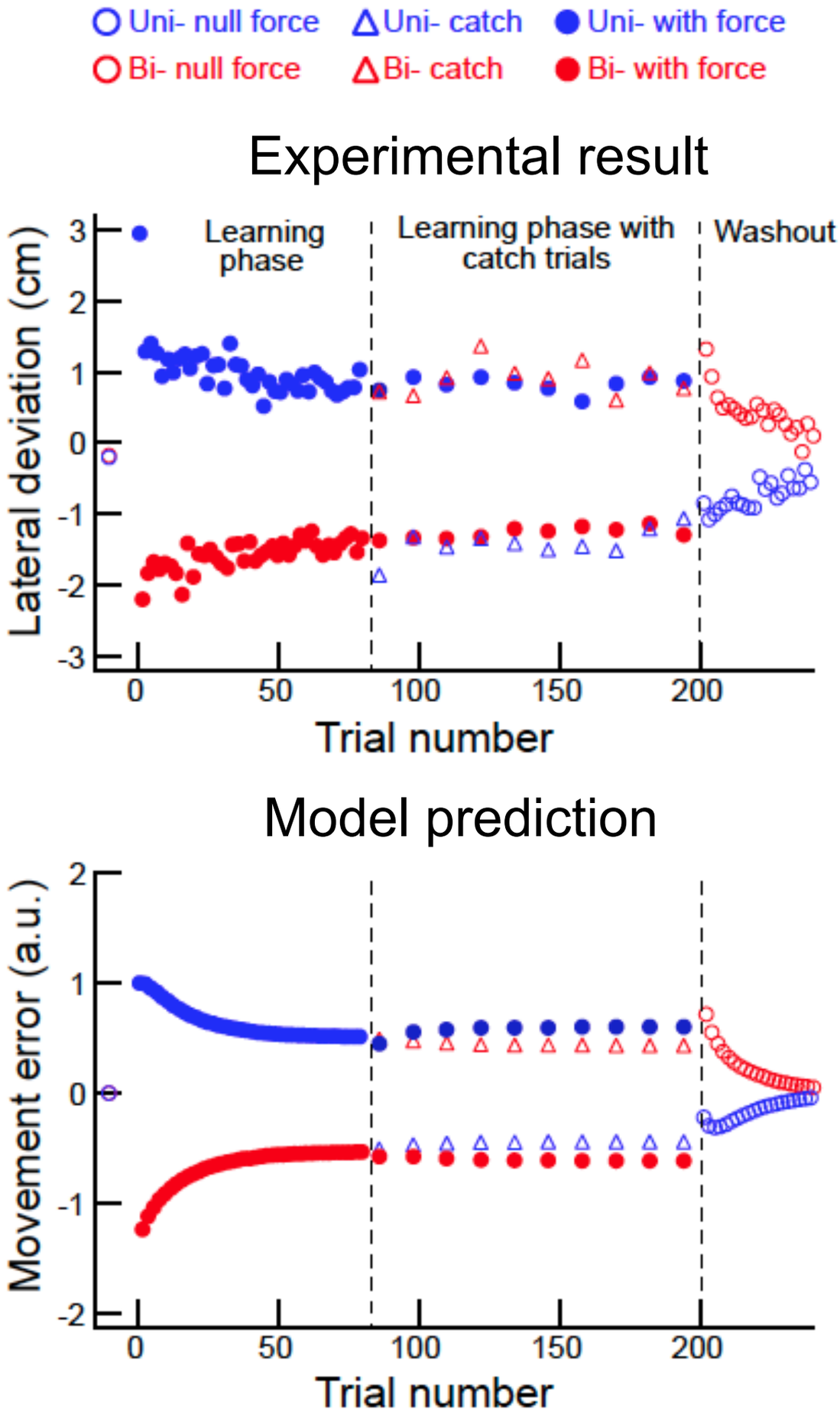
Unimanual learning

Leftward force field (LF)



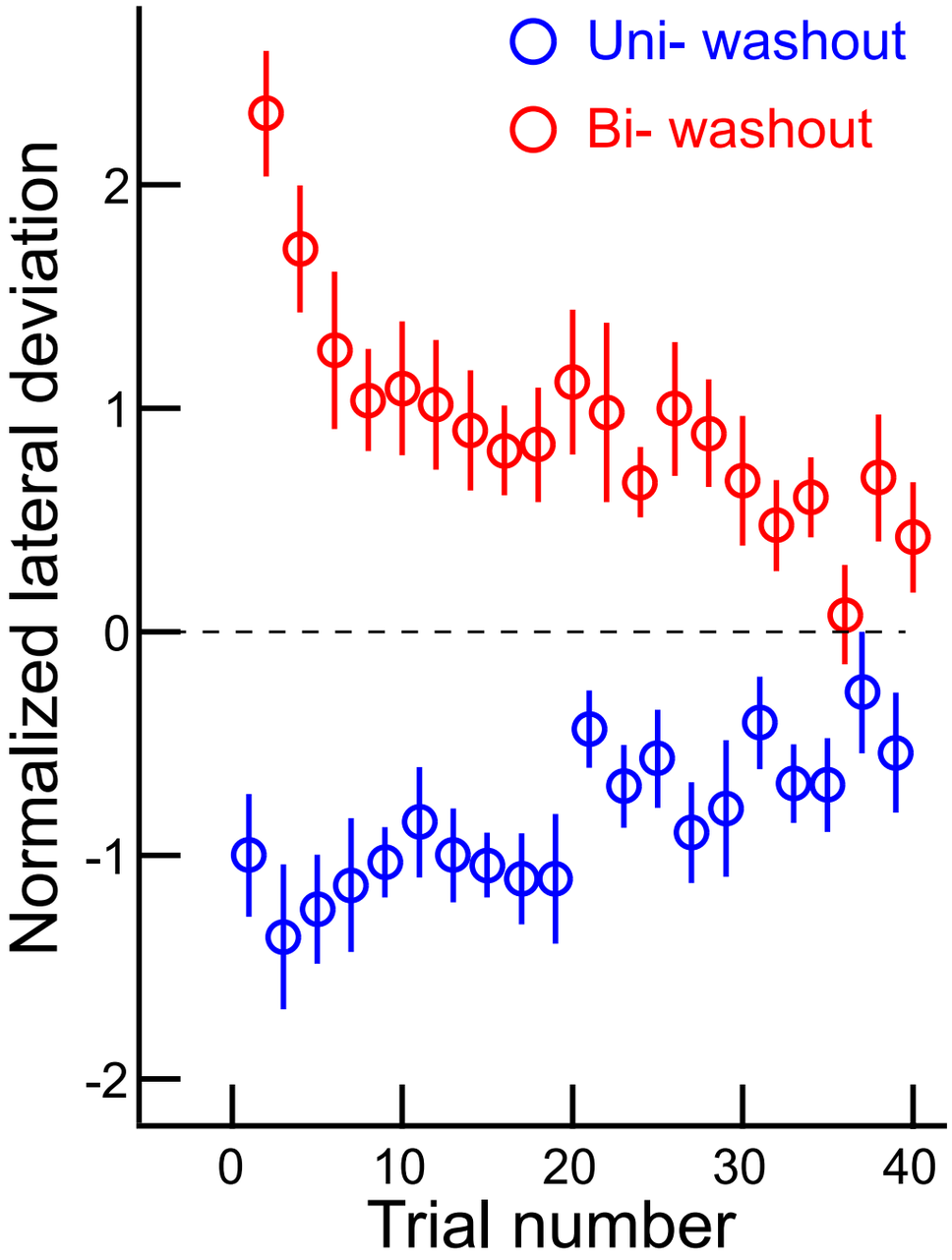


Bimanual learning

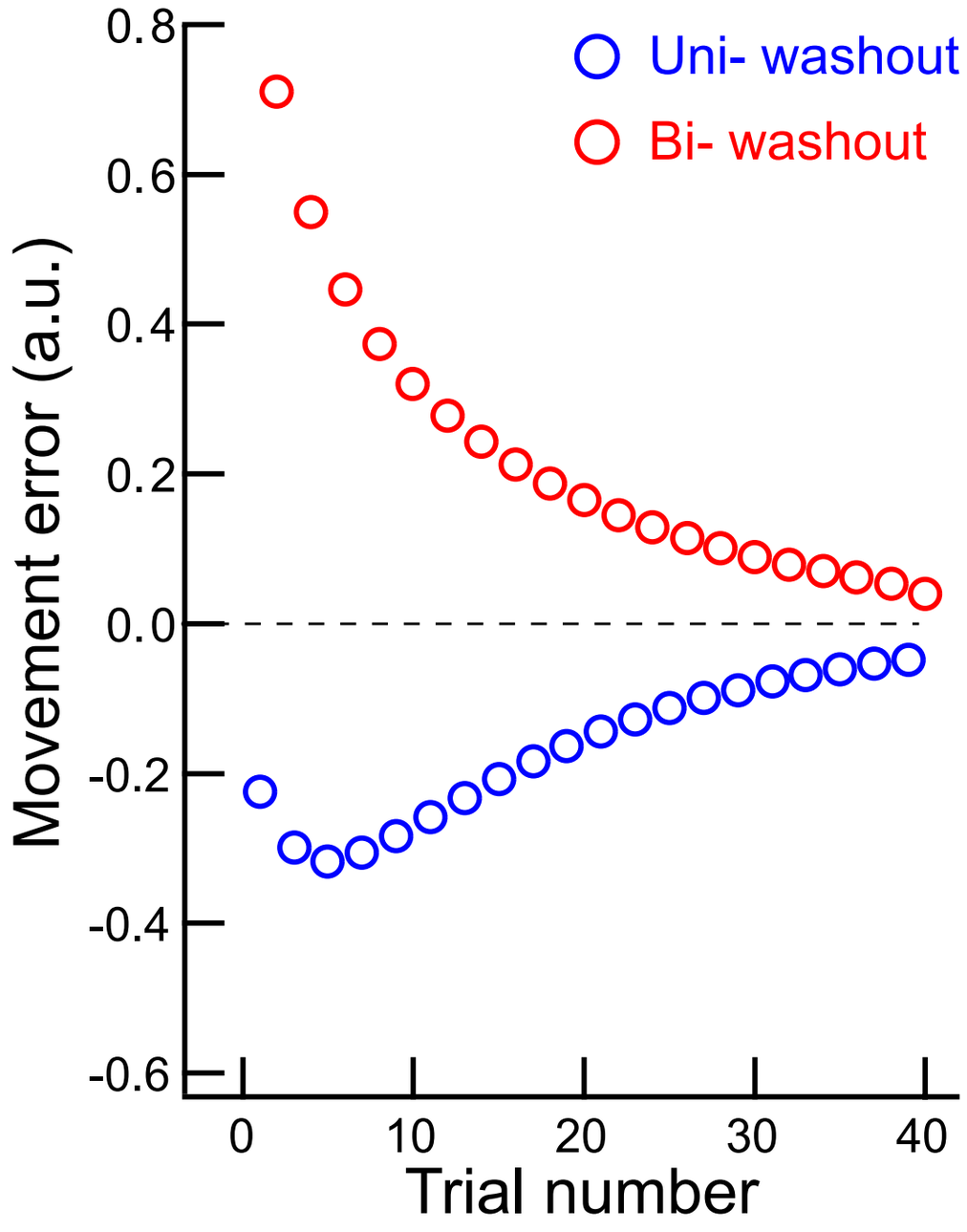


The model reproduces very slow washout

Experiment



Model prediction



The number of elements matters

Motor command $X(i) = \sum_{j=1}^{N} x_j(i)$

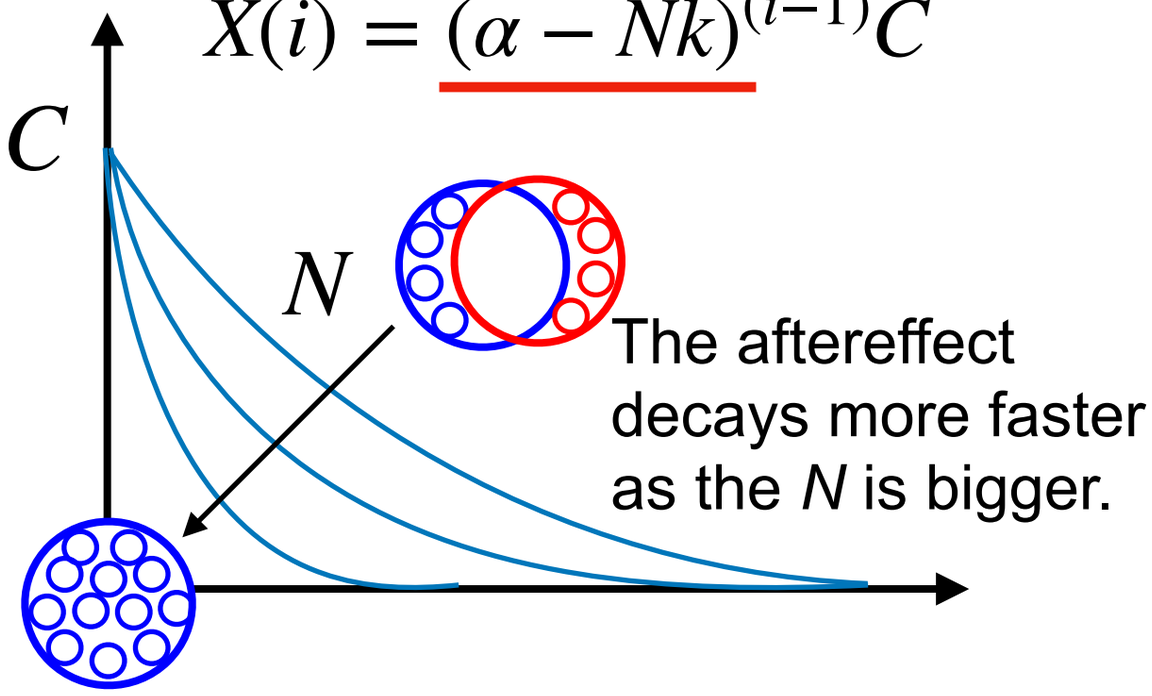
Error $e(i) = f - \sum_{j=1}^{N} x_j(i)$

Update $x_j(i+1) = \alpha x_j(i) + ke(i)$

$$\rightarrow X(i+1) = (\alpha - Nk)X(i) + Nkf$$

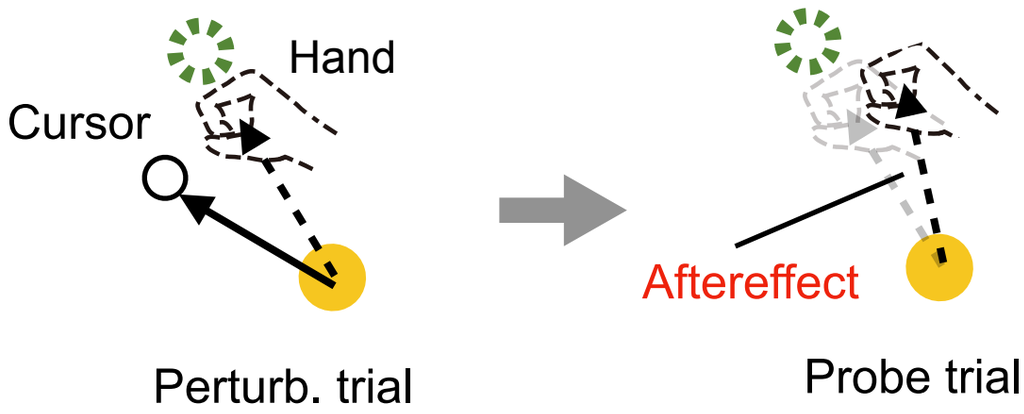
Washout

$$X(i) = (\alpha - Nk)^{(i-1)}C$$



Single trial adaptation

$$X(i) = 0 \longrightarrow X(i+1) = Nkf$$



Aftereffect induced by the error is proportional to the *N*.

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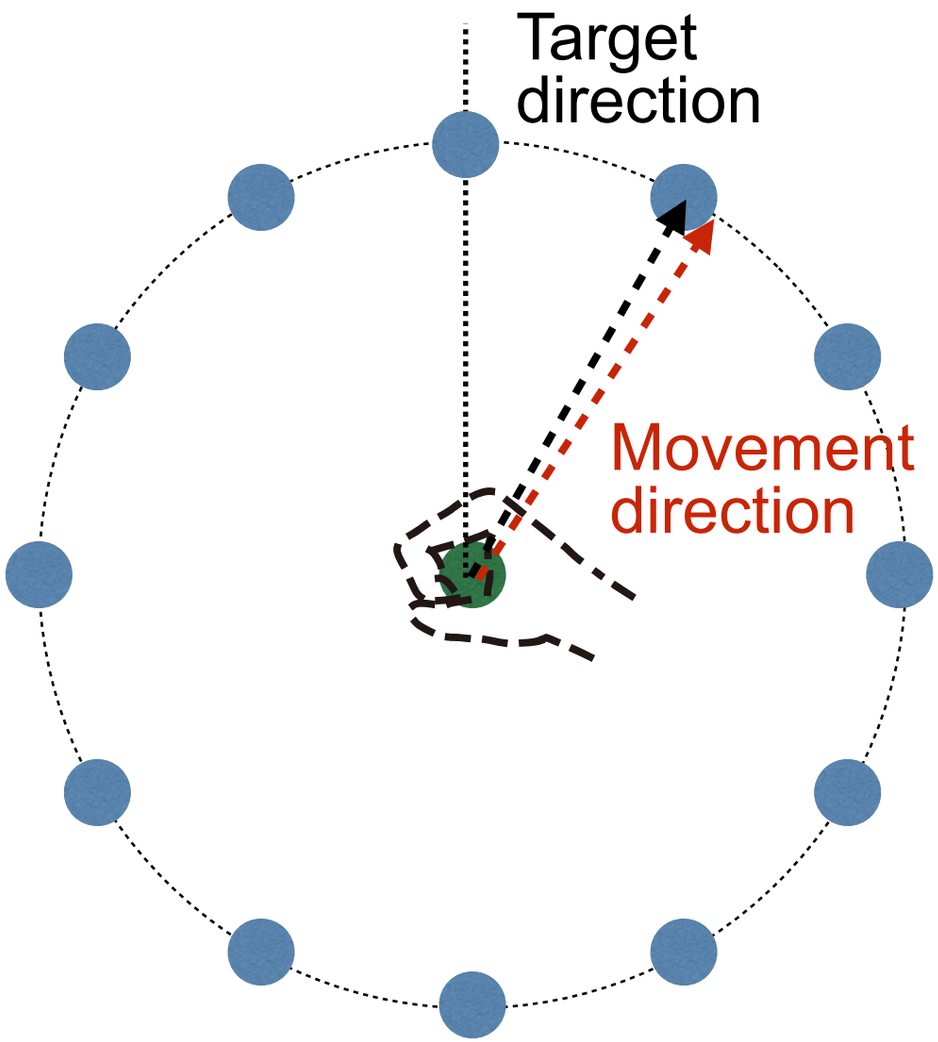
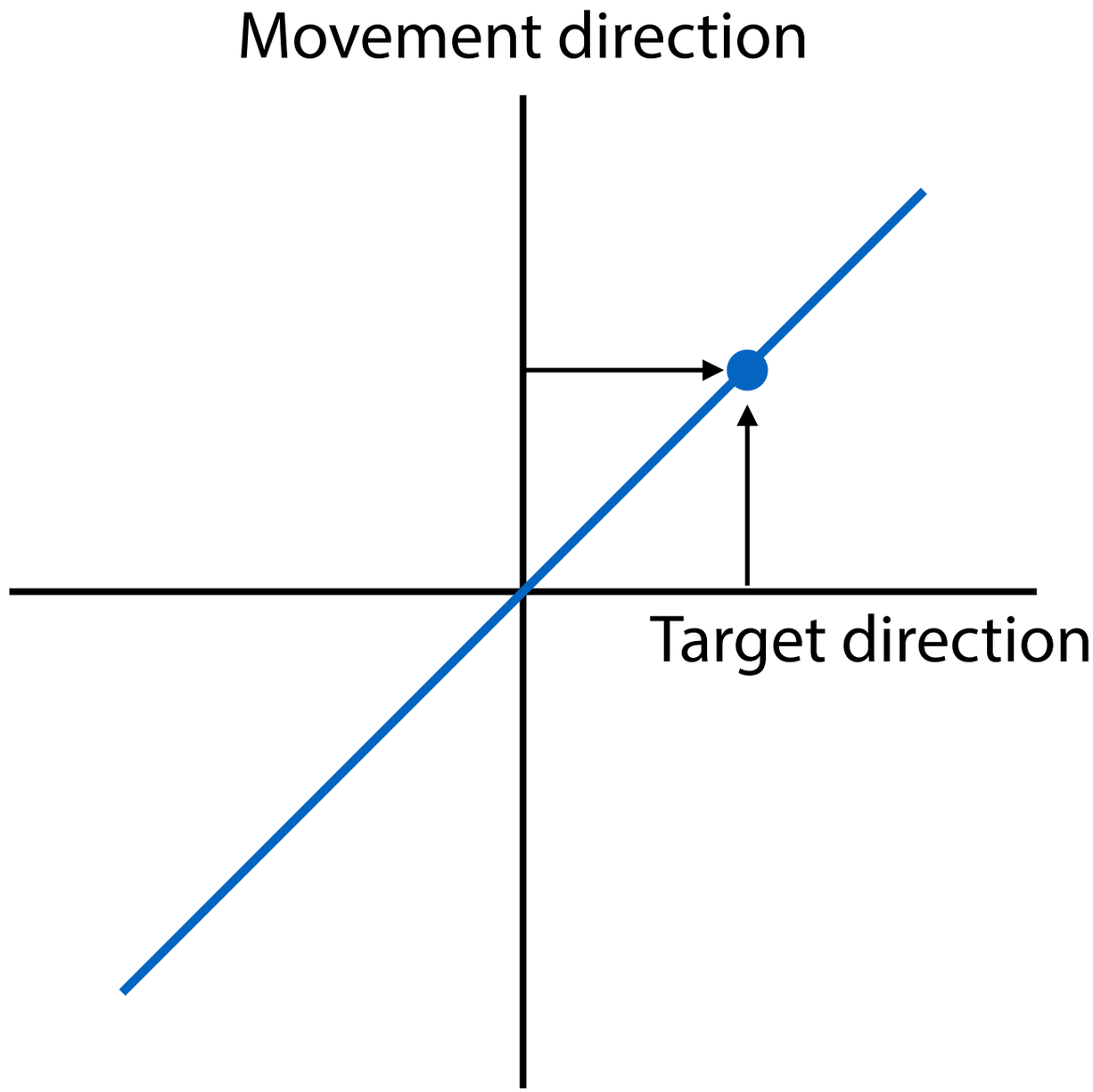
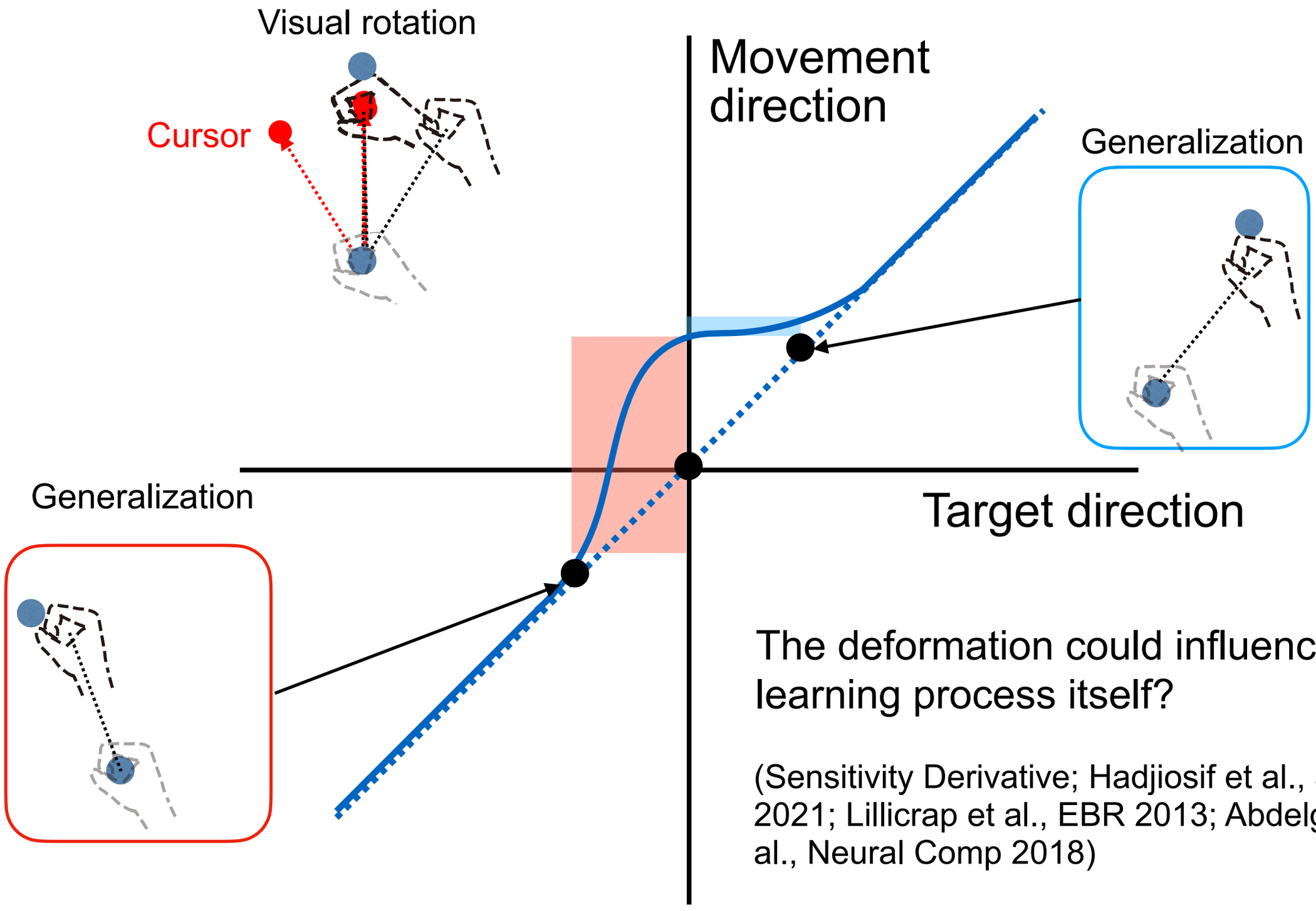
Visuomotor map





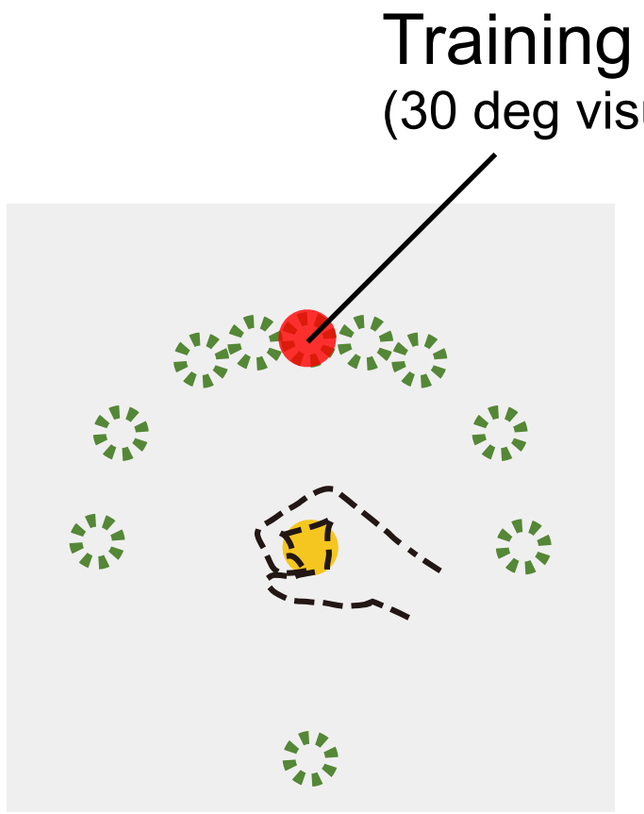
Deformation of visuomotor map

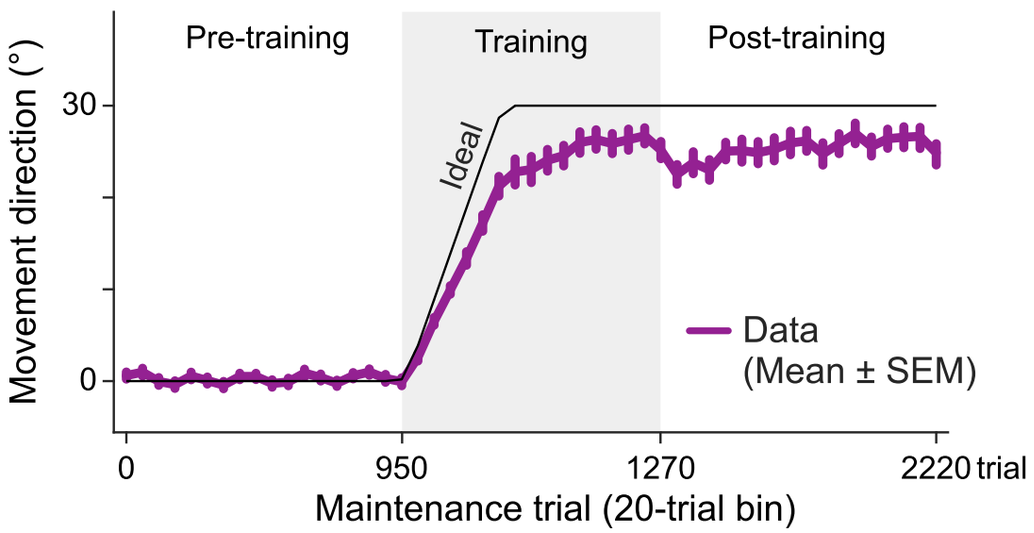


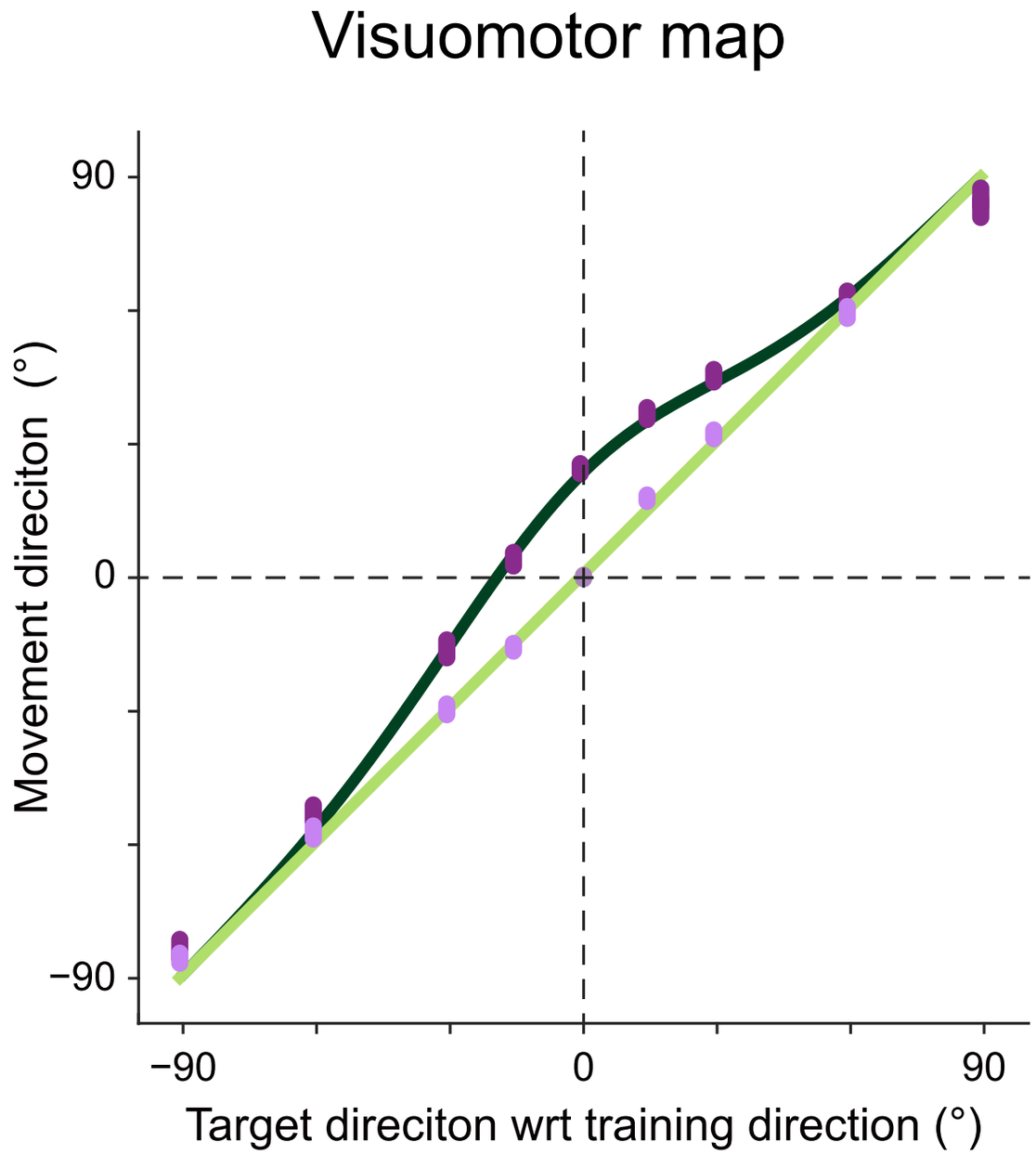
The deformation could influence the motor learning process itself?

(Sensitivity Derivative; Hadjiosif et al., JNS 2021; Lillicrap et al., EBR 2013; Abdelghani et al., Neural Comp 2018)

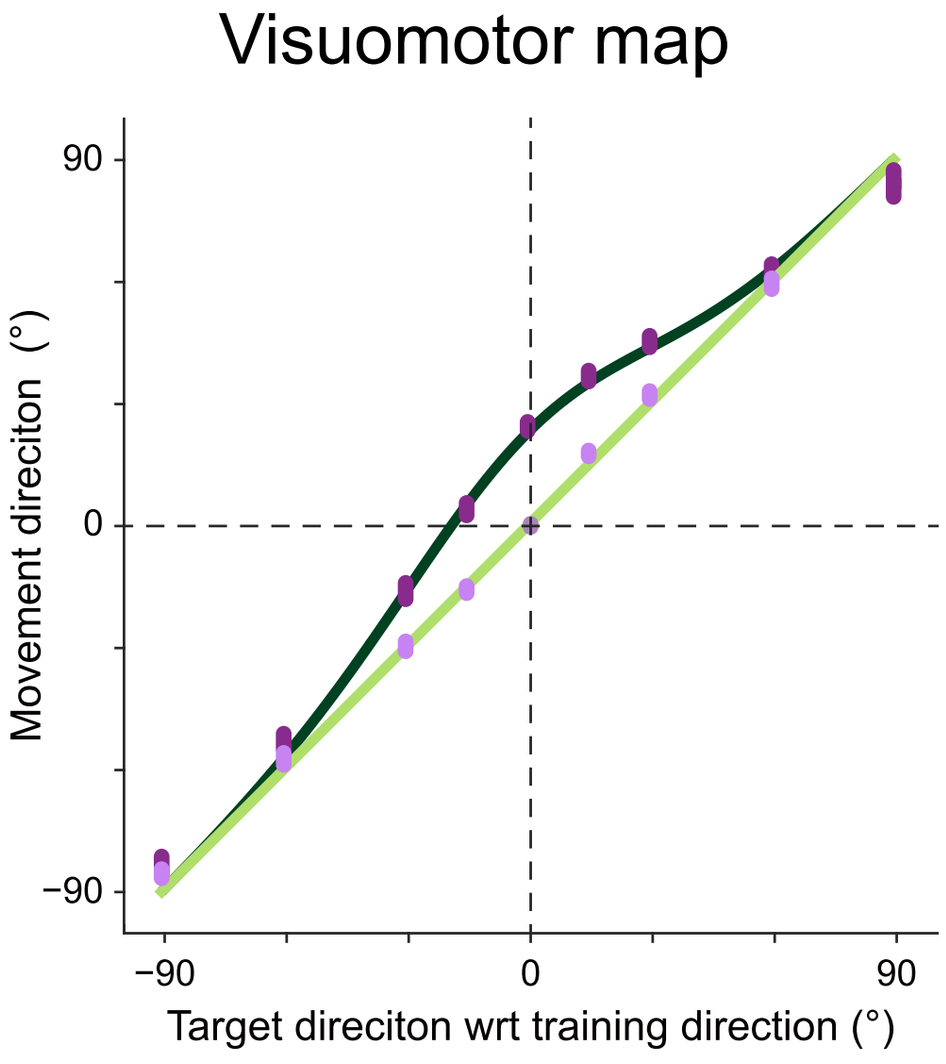
Deformation of Visuomotor map

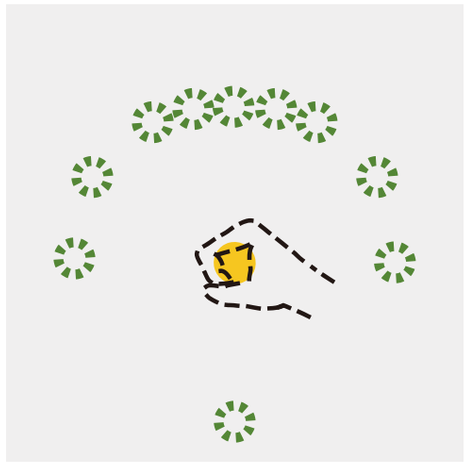




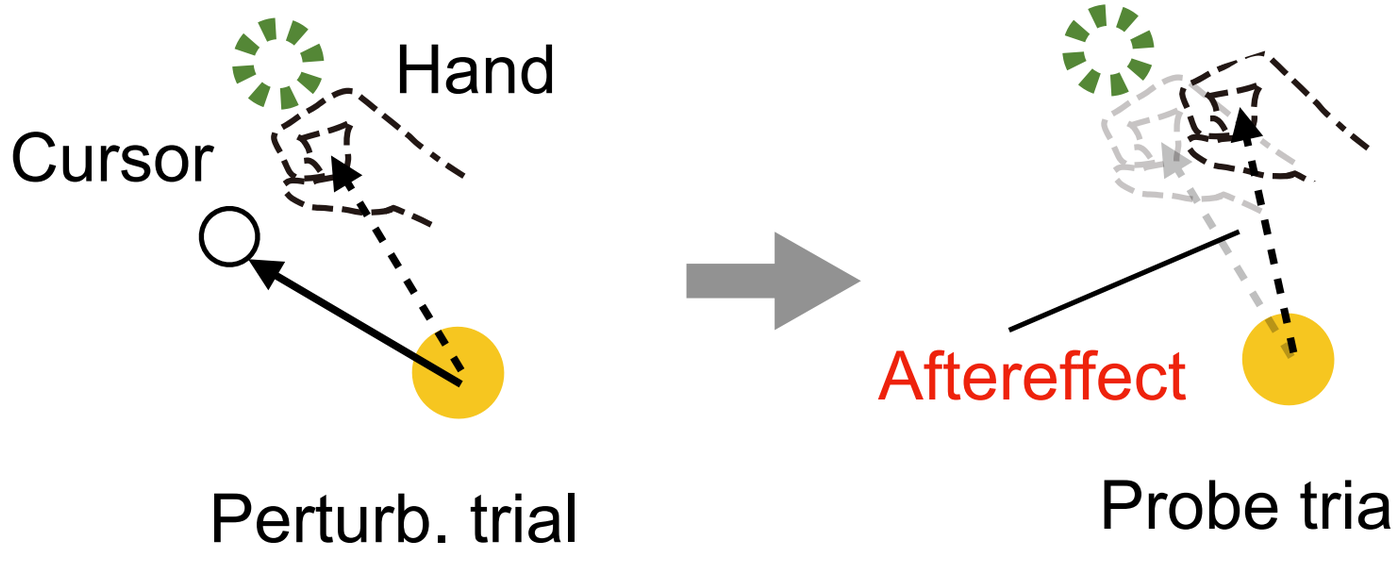


Quantifying movement correction to a visual error perturbation



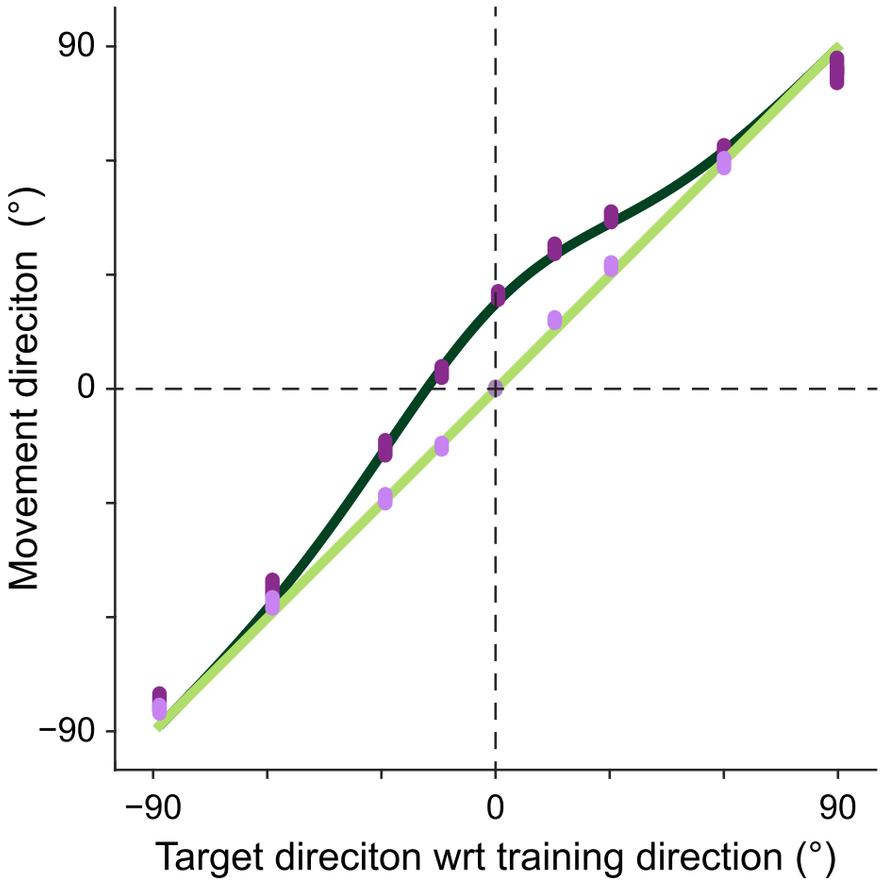


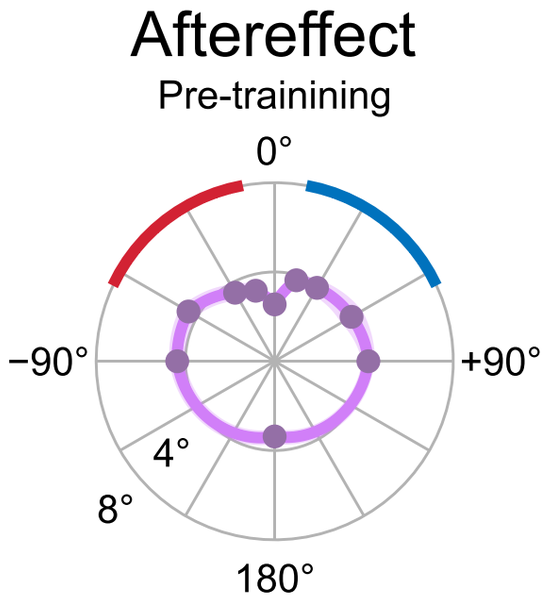
Test target

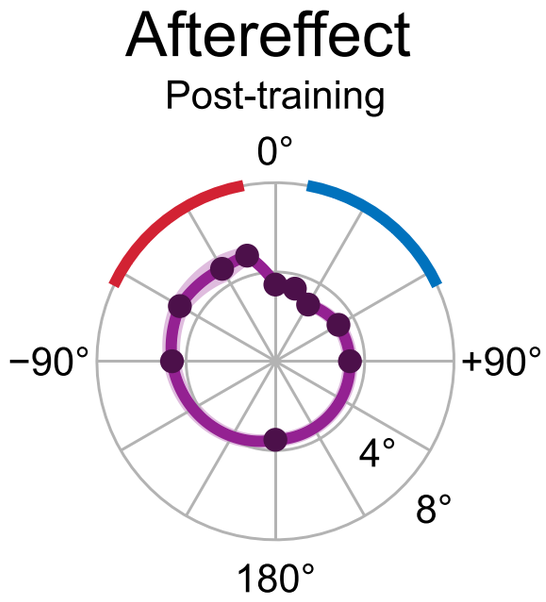


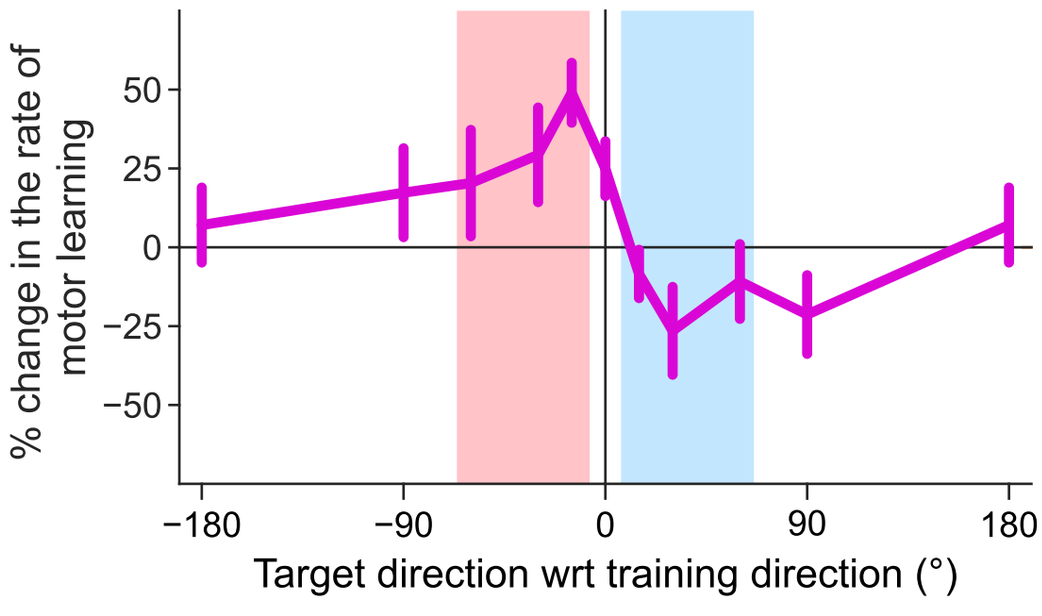
Single trial adaptation

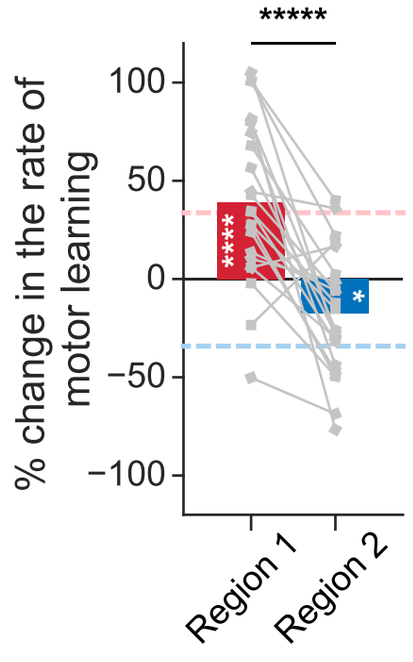
Deformation of VM map influences the movement correction sensitivity





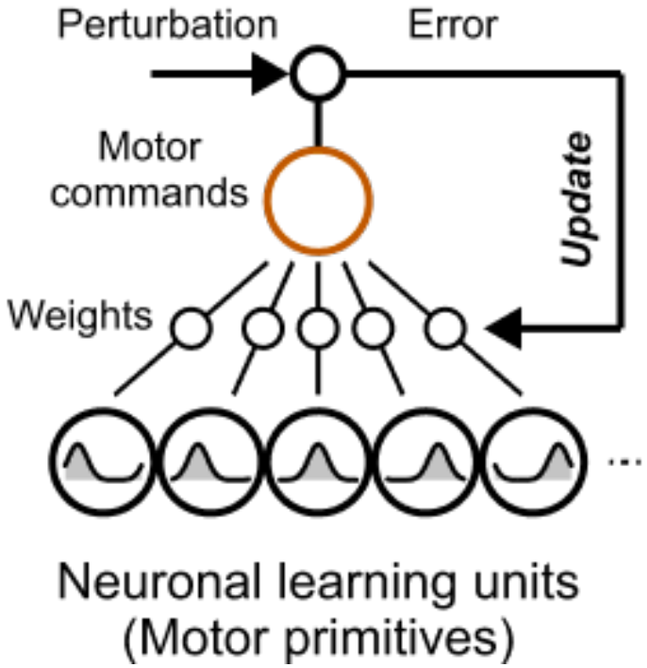






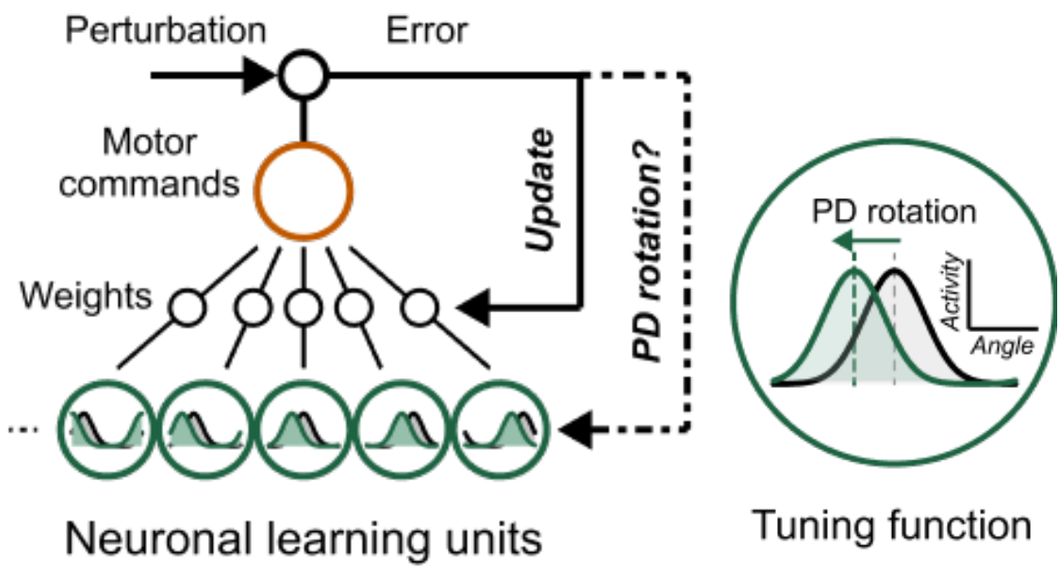
State space models

Conventional model



Theoretically, this model cannot explain our experimental results.

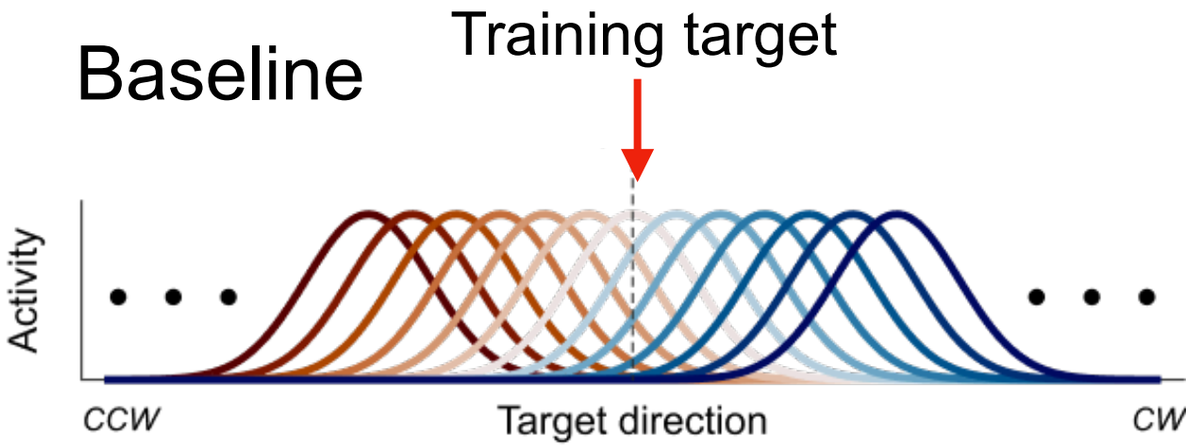
New model with PD rotation



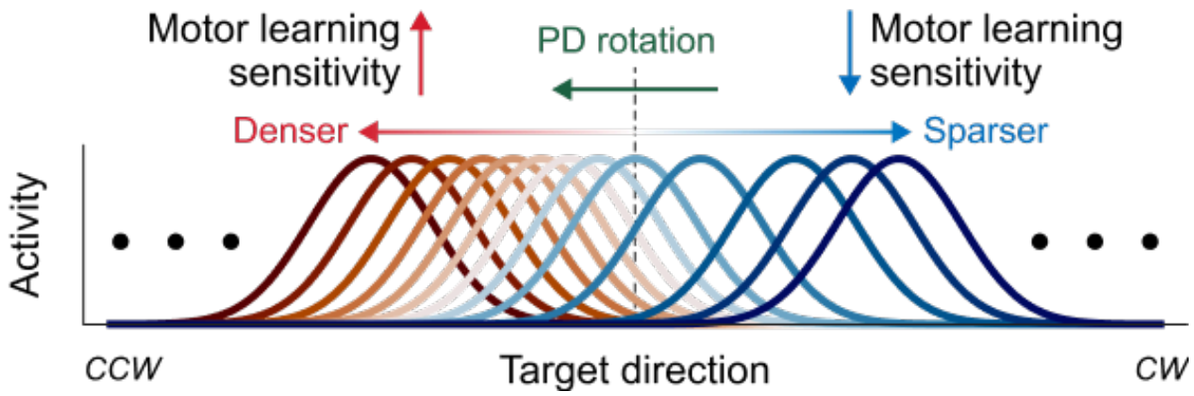
Li et al., Neuron 2001

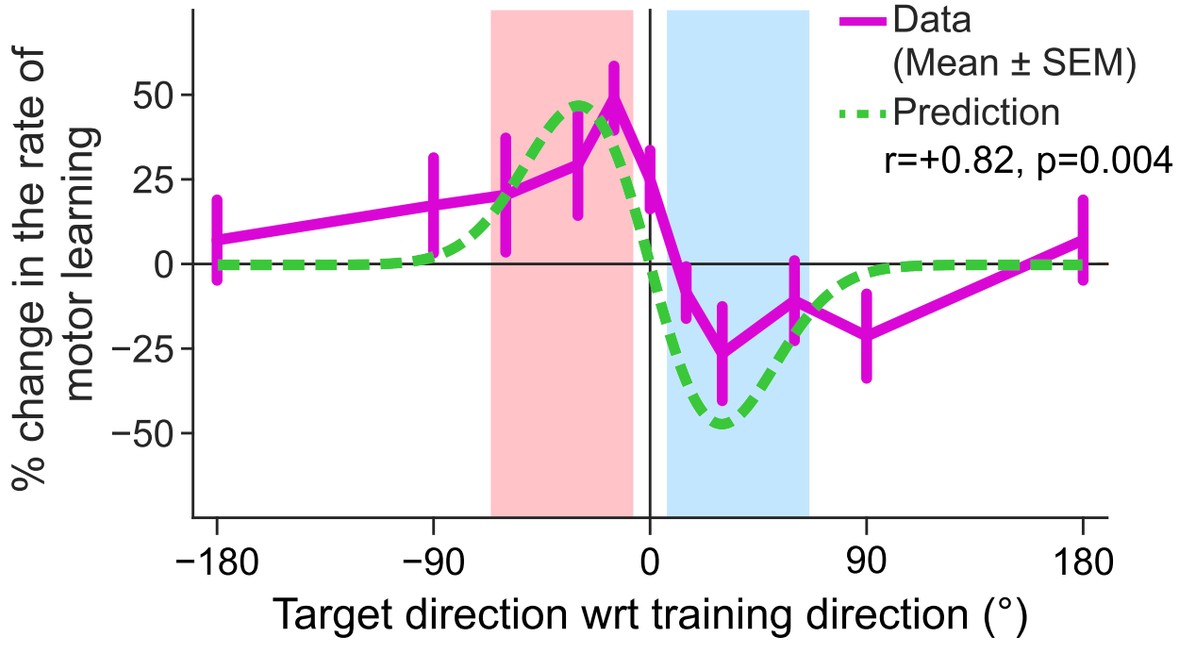
This new model takes into account the rotations of the PDs of the neural learning units.

The number of elements matters

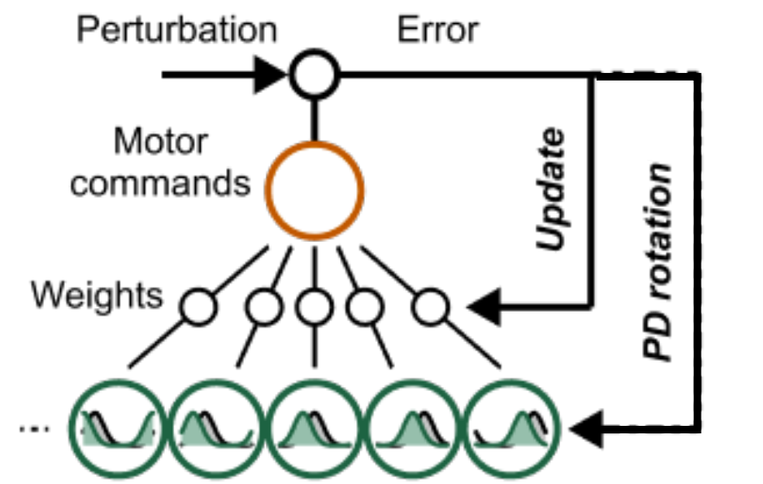


After adaptation to VM rotation

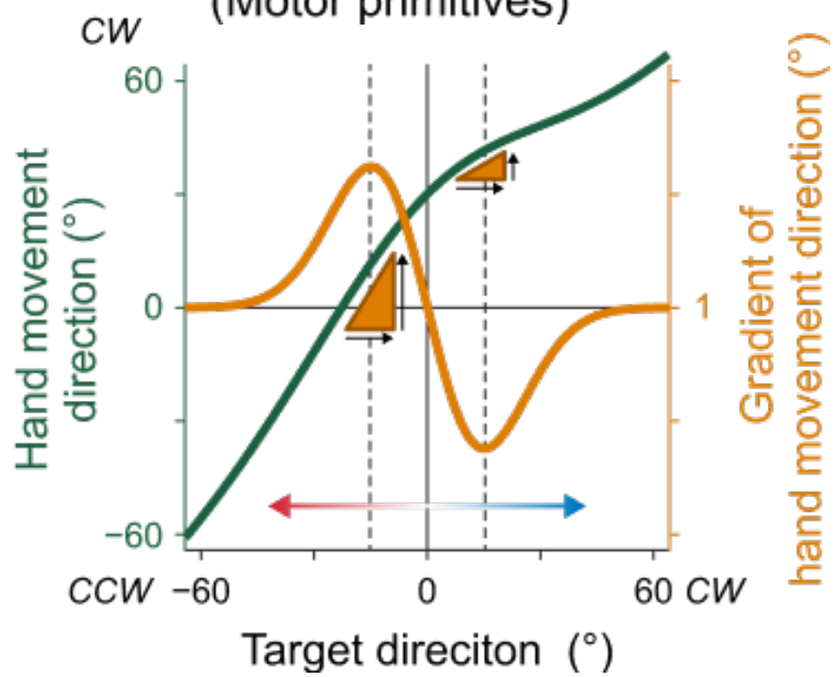


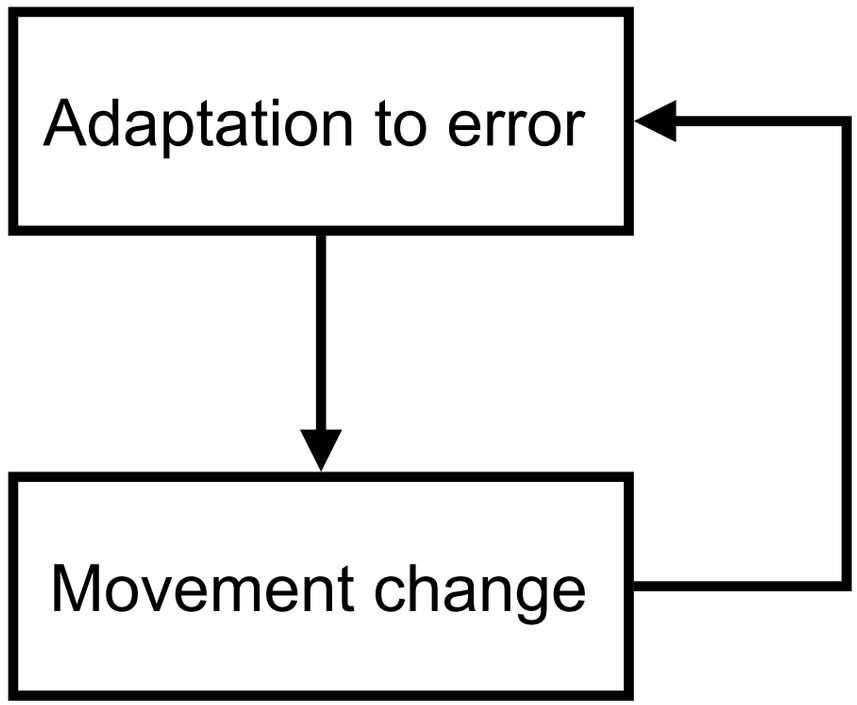


Learn to learn



Neuronal learning units
(Motor primitives)





The PD rotation provides a mechanism whereby the motor system can simultaneously learn how to move and learn how to learn

Contents

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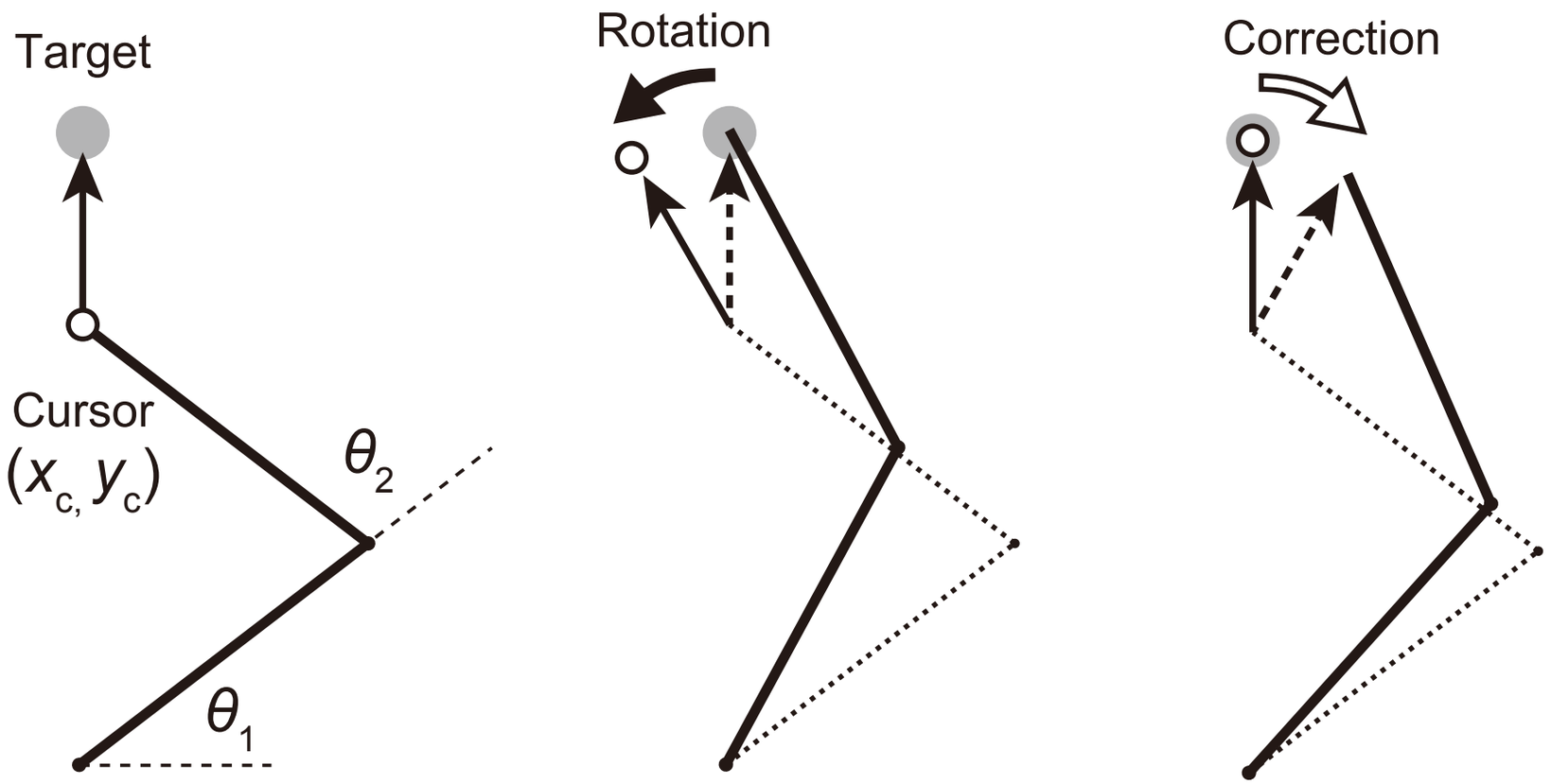
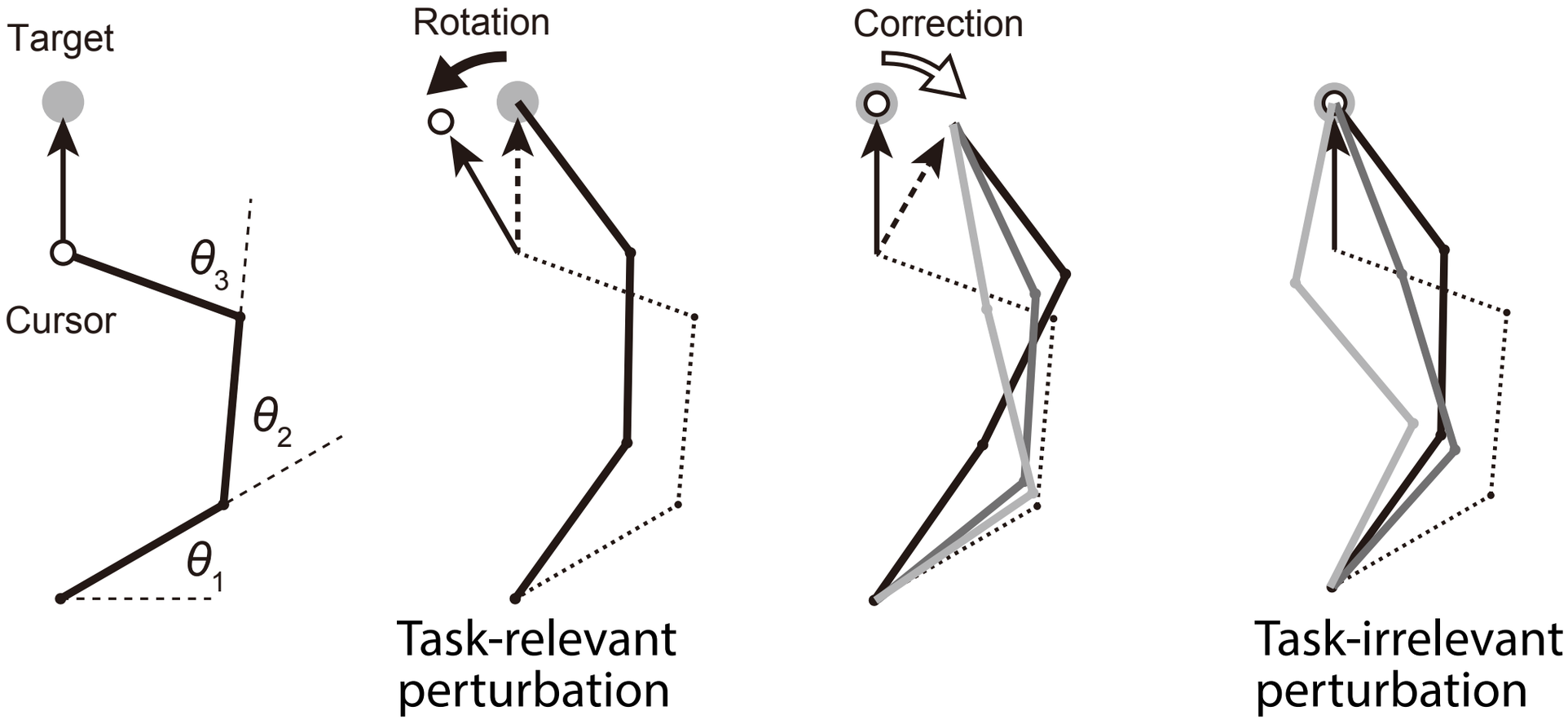
Movement correction for a simple reaching movement



- There is no redundancy in planar reaching movements that primarily involve the shoulder and elbow joints.
- The kinematics of movement and movement corrections are uniquely determined.

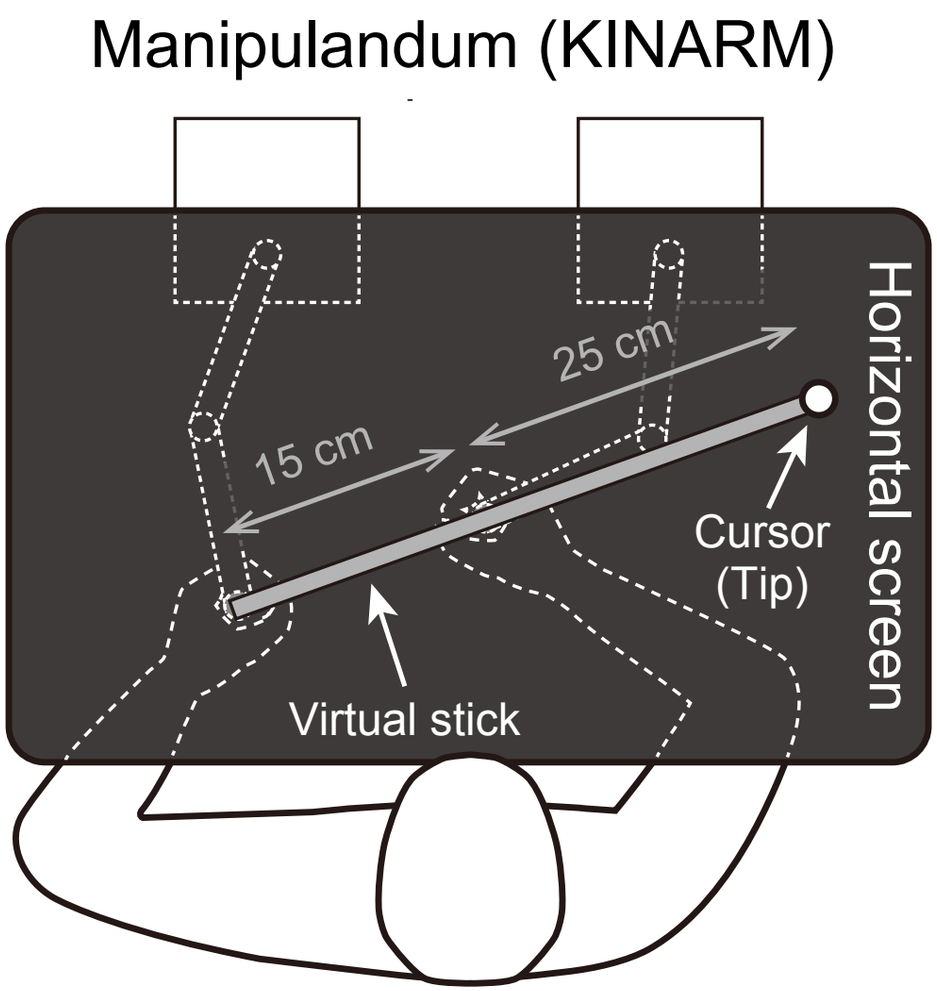
Movement correction for a redundant system

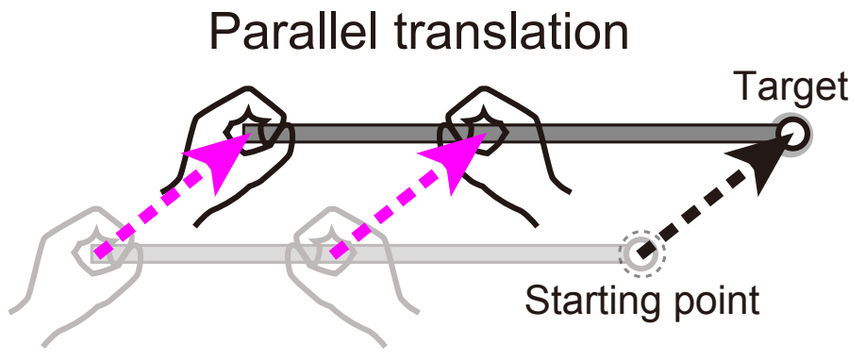


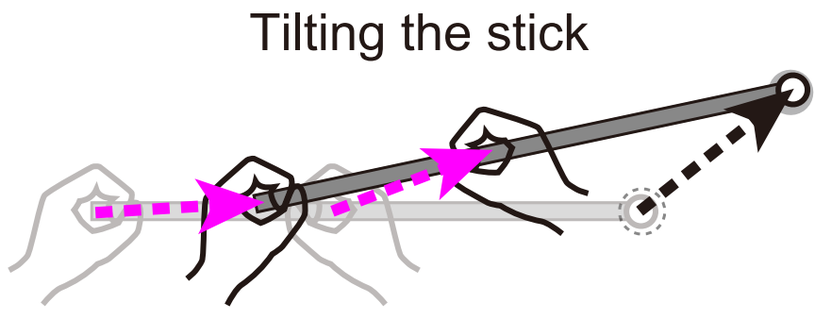
- How does the motor system coordinate the pattern of movement to correct for the perturbation to the end effector?

- Does the motor system correct the movement pattern even if the perturbation does not influence the performance?

Bimanual stick-manipulation task







This reaching task is redundant: The stick tilting angle is not uniquely determined.

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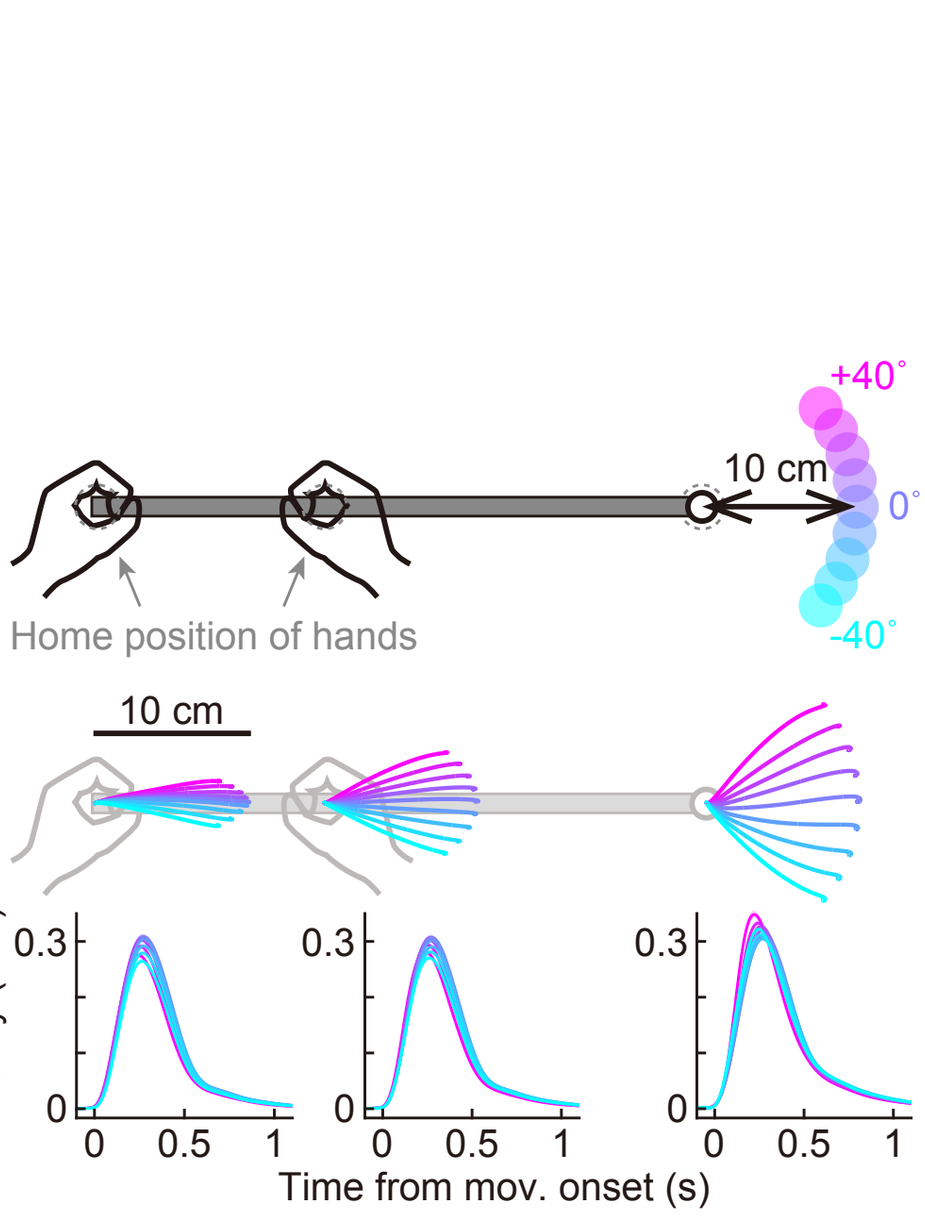
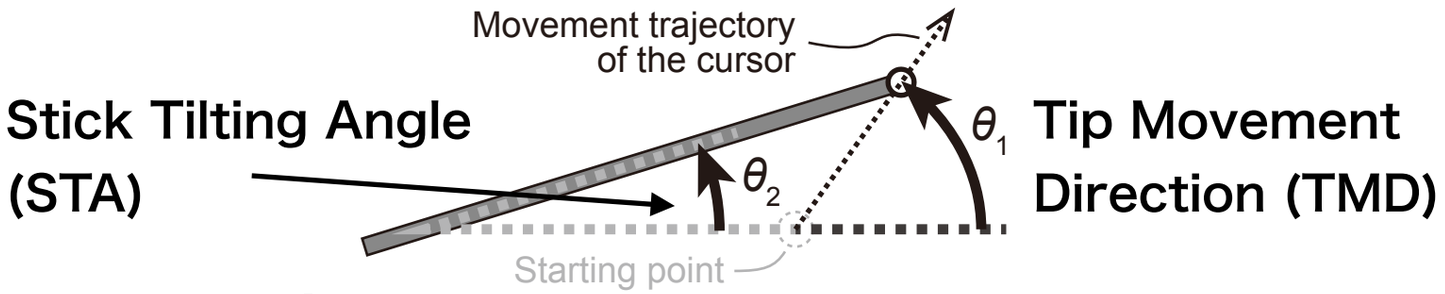
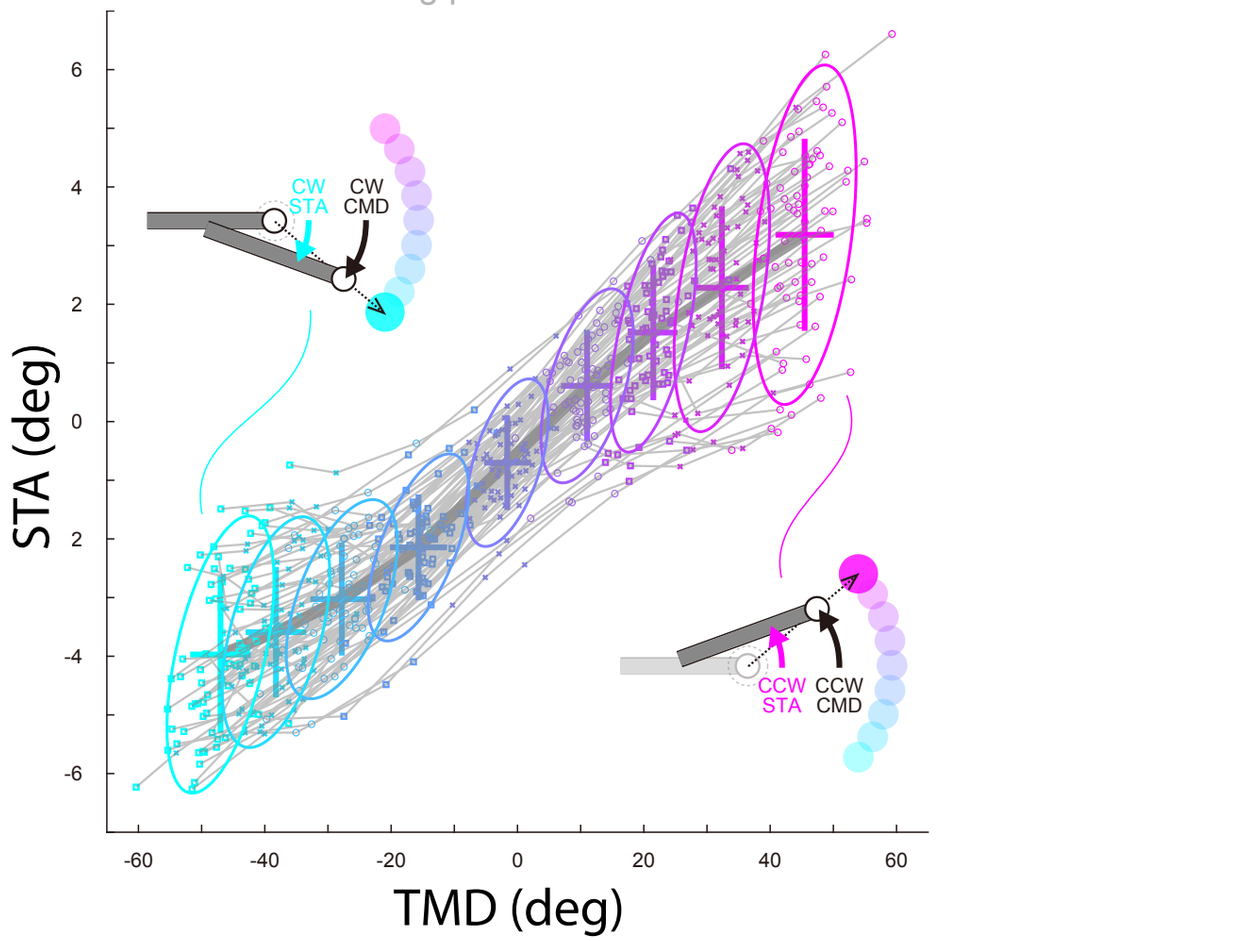
Movement pattern

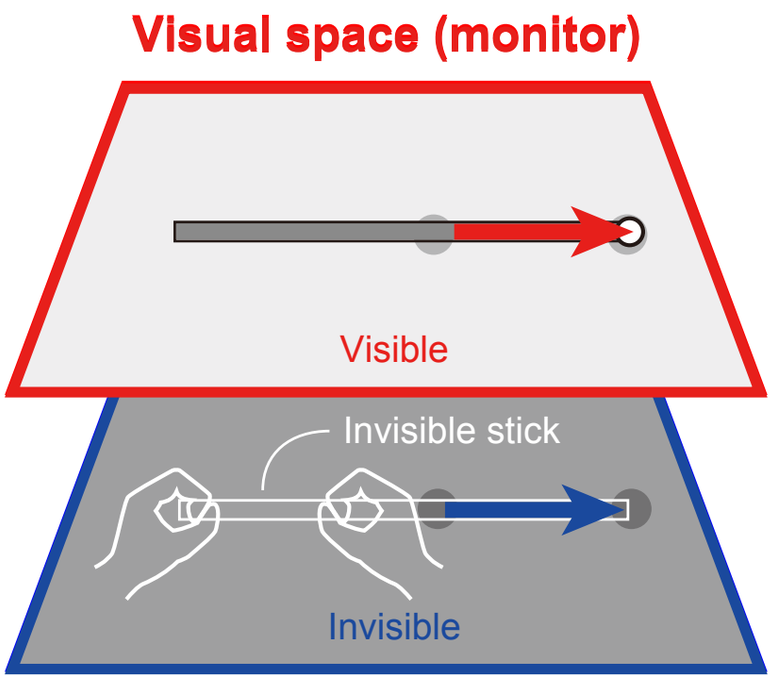




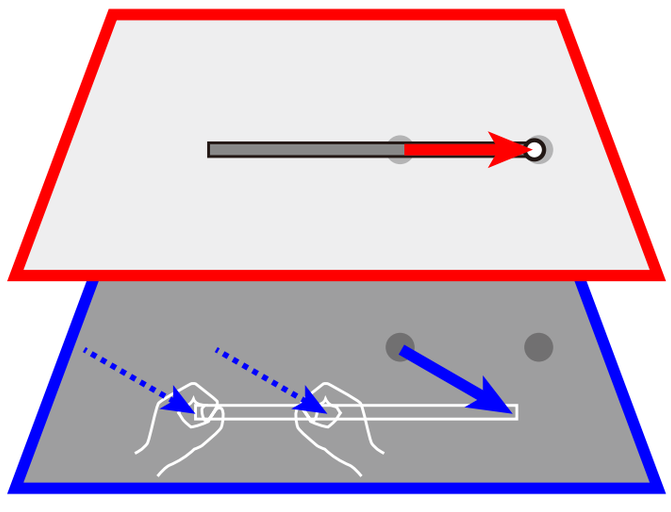


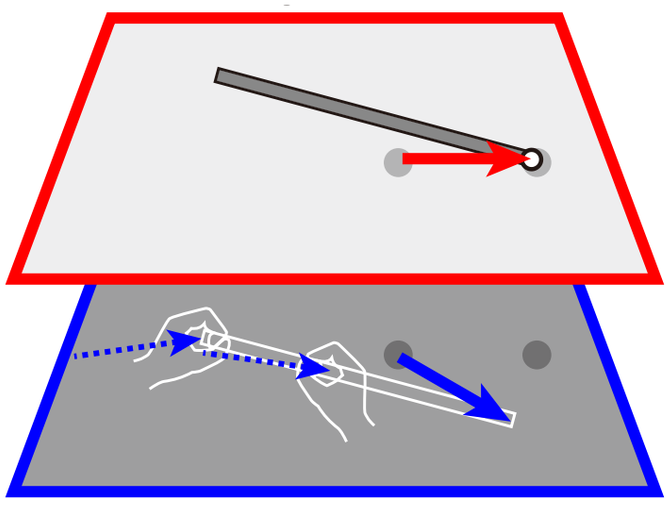
Almost all participants performed this reaching task with the tip of the stick by tilting the stick.

Exp 1: Adaptation to tip-movement rotation

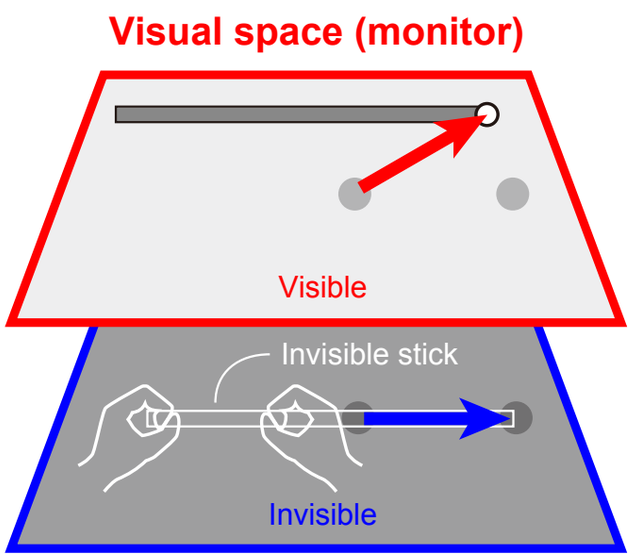


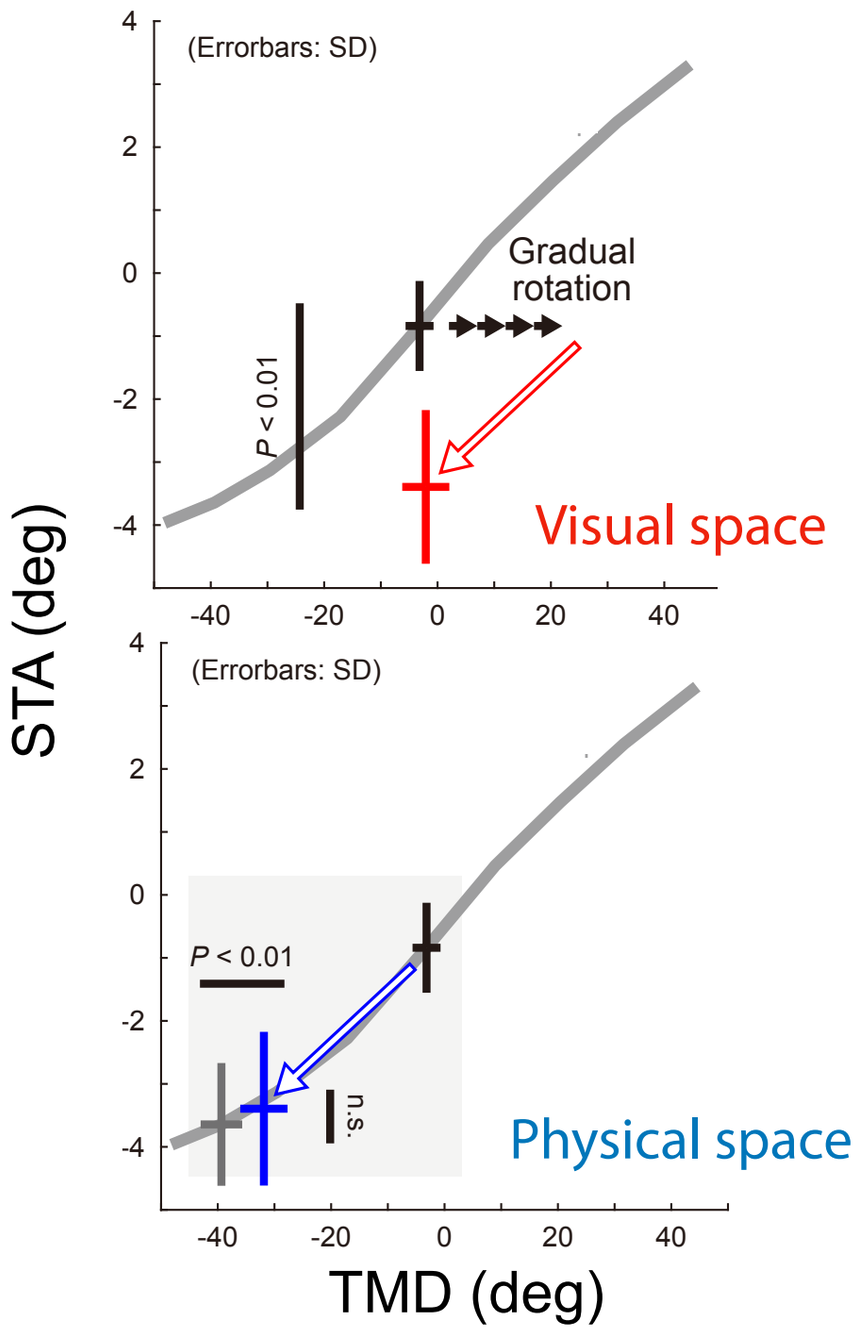
The tip rotation was gradually increased with trials (1 deg/ trial). Participants were not aware of the rotation.

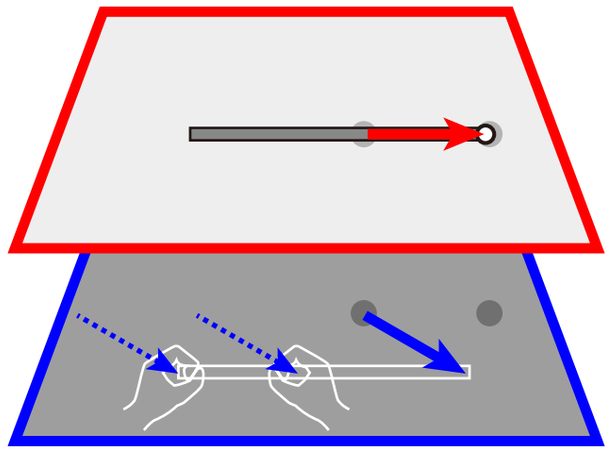


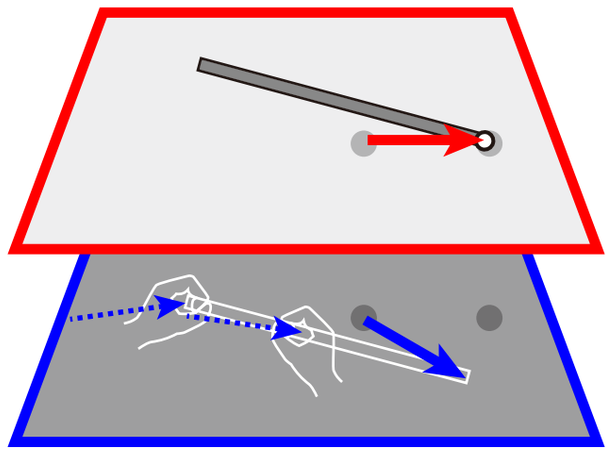


Exp 1: Adaptation to tip-movement rotation



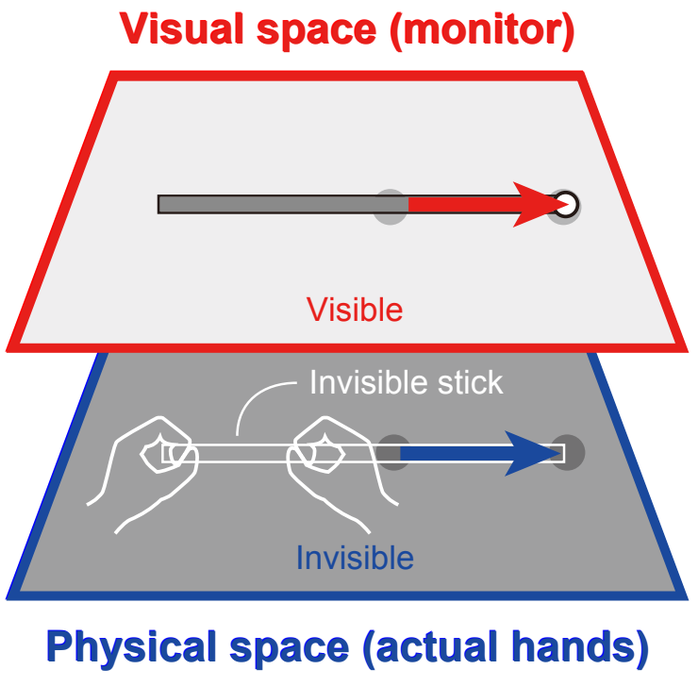






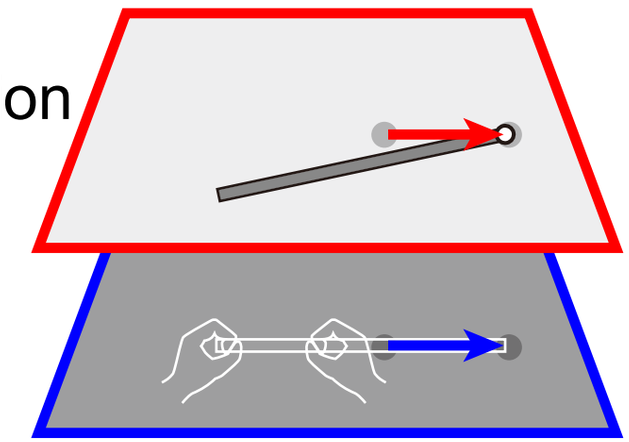
The motor system implicitly changes the direction of the tip movement by tilting the stick as if it were aiming in that direction.

Exp 2: Adaptation to stick rotation

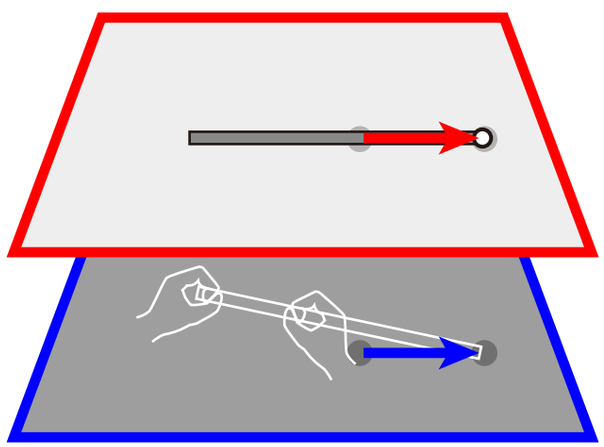


Stick was rotated by 6 deg around the tip. Participants were not aware of the stick rotation.

Minimal intervention principle

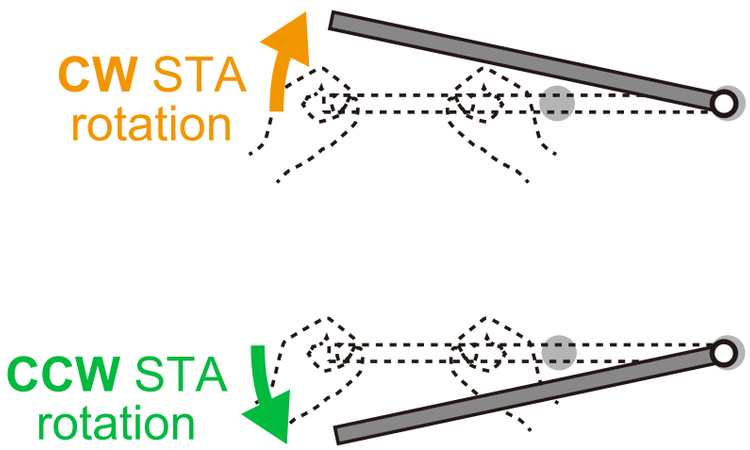


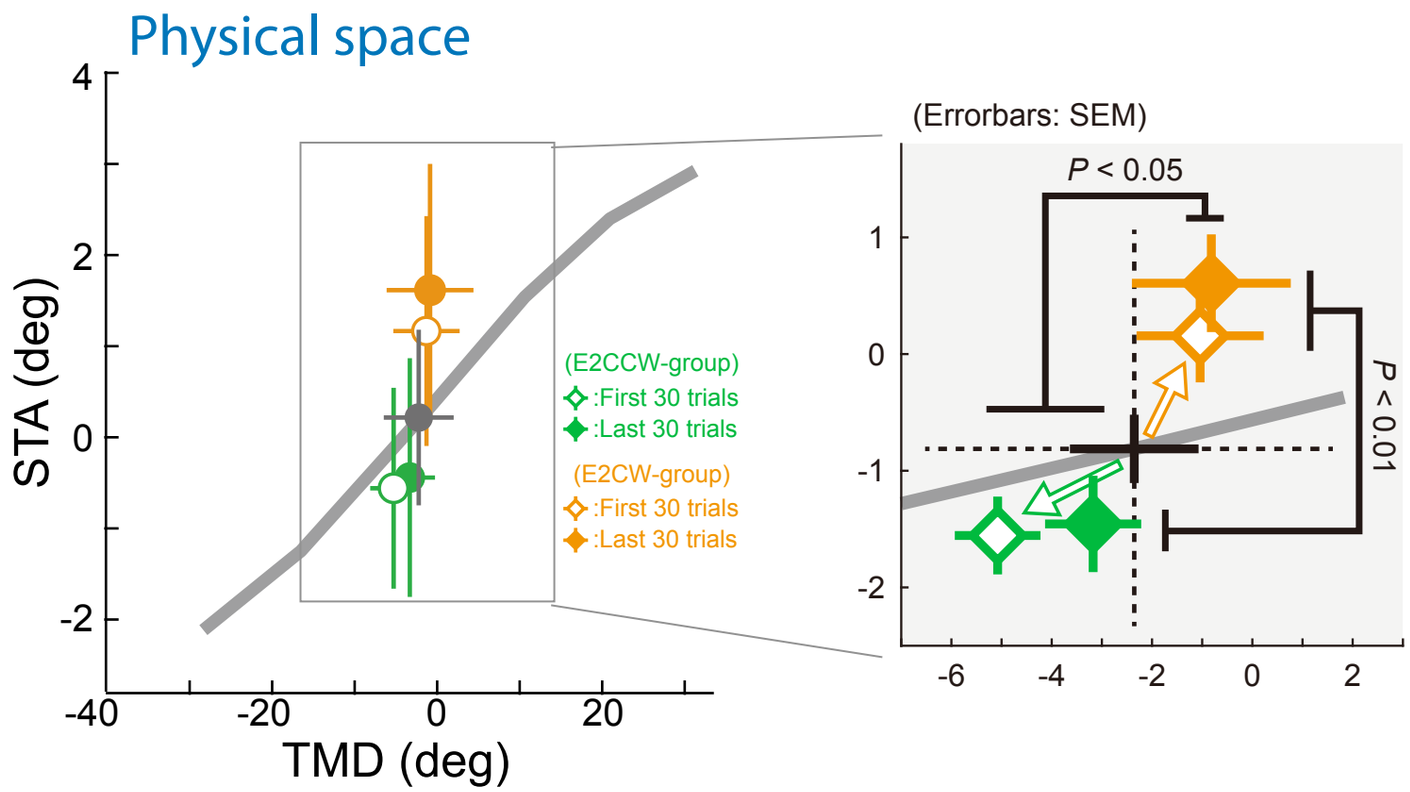
Ignore the rotation

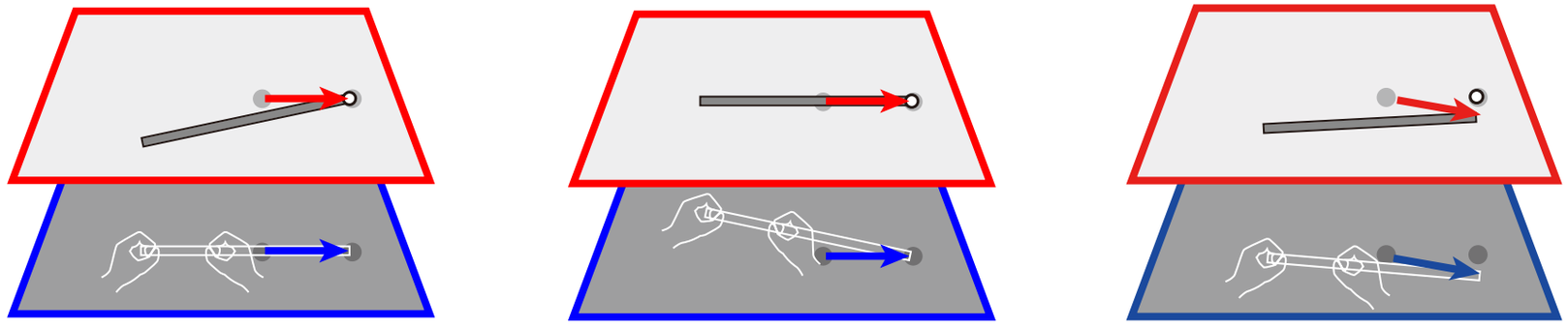


Correct the stick angle

Exp 2: Adaptation to stick rotation



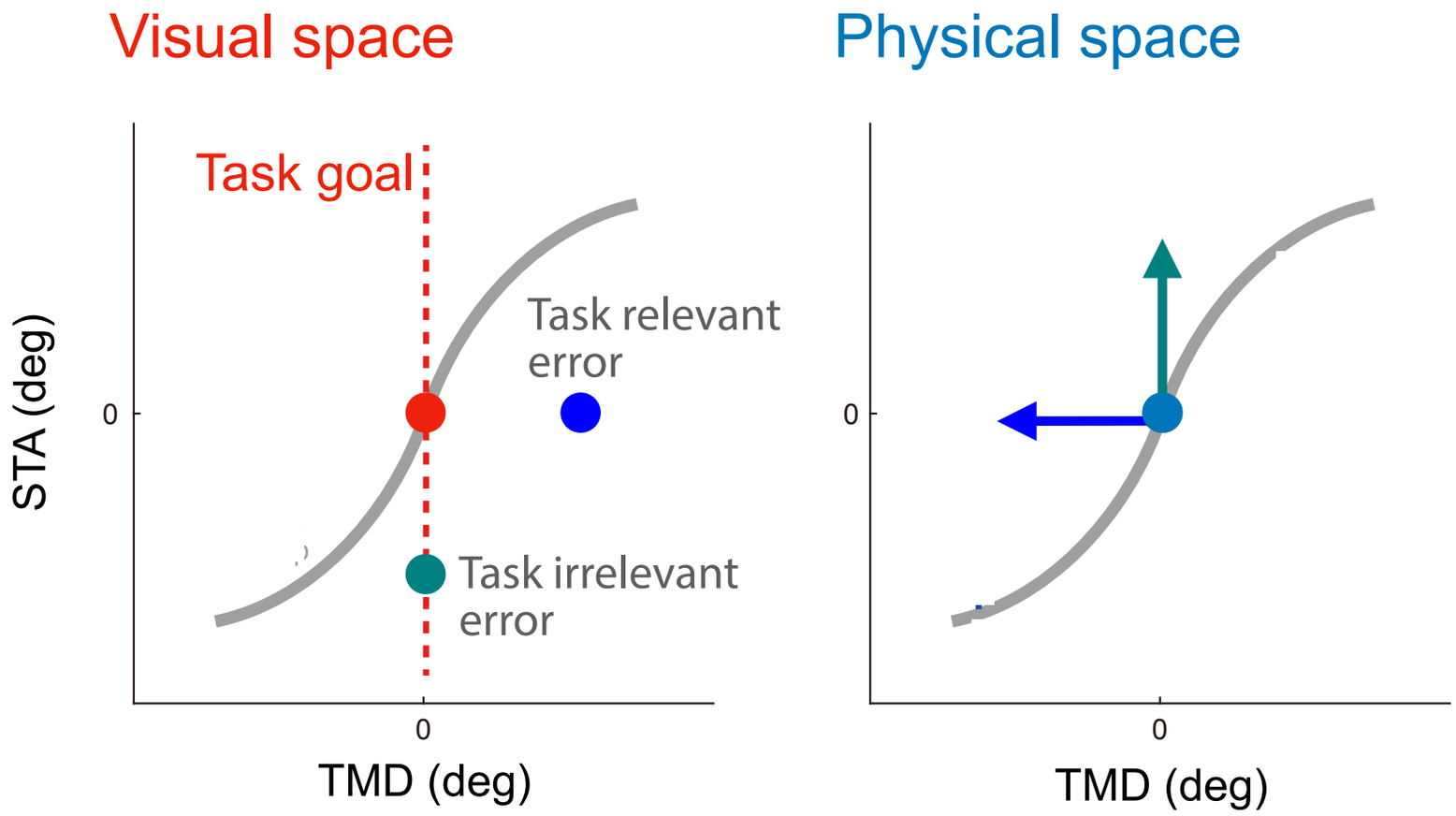




Stick rotation was partially corrected, although the correction was not necessary.

The unnecessary correction resulted in the task error.

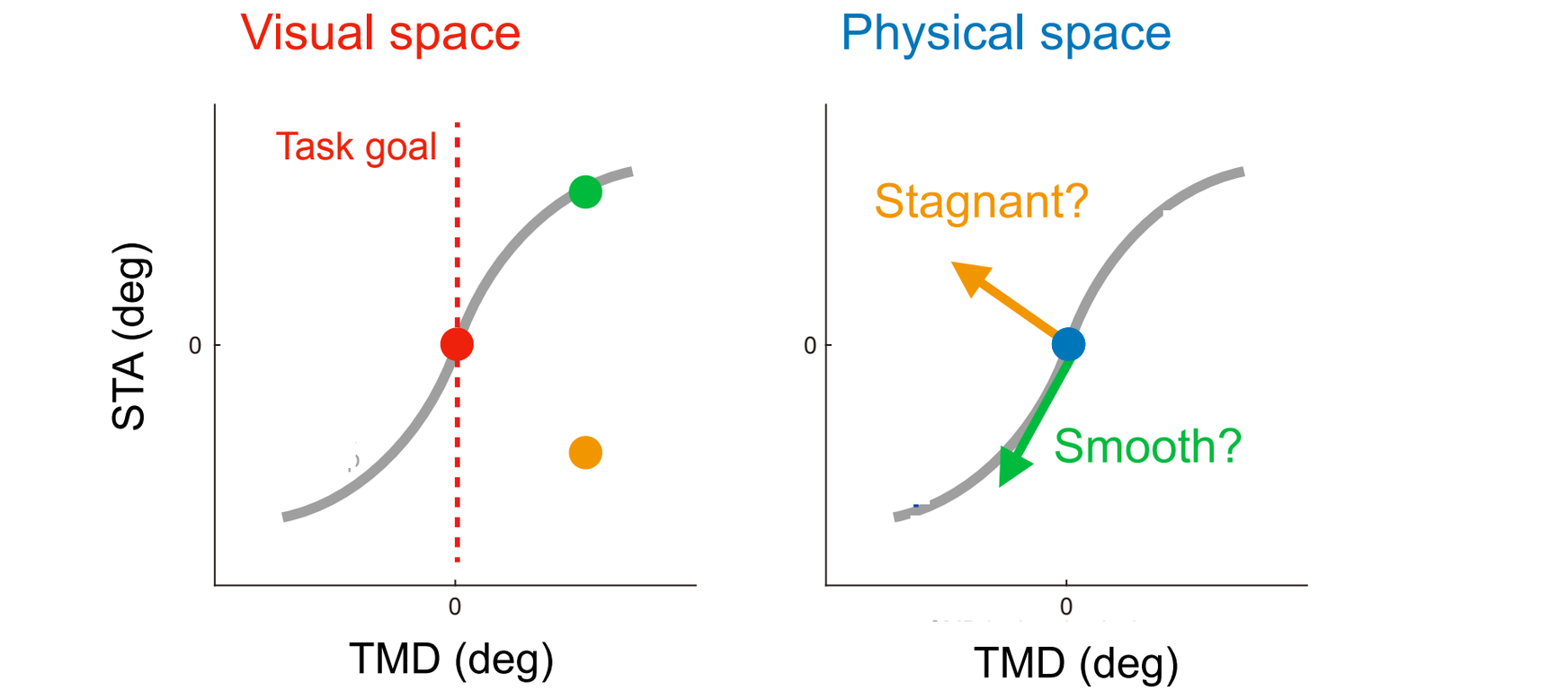
Movement correction patterns in redundant systems

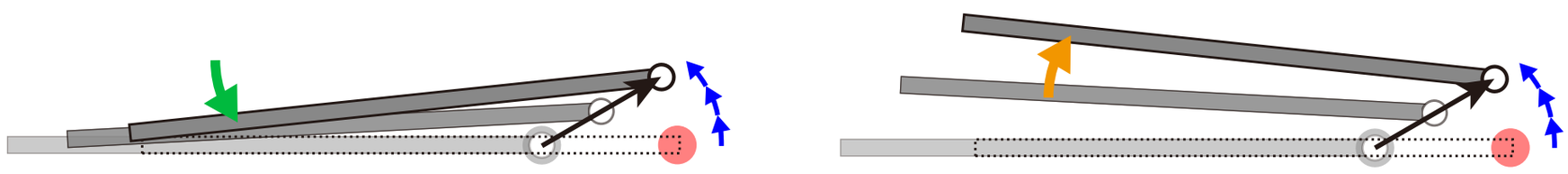


The motor system attempts to correct visual errors whether they are task-relevant or task-irrelevant.

The physical correction patterns are constrained by the inherent relationship (i.e., TMD-STA relationship).

Exp 3: Adaptation to simultaneous application of tip rotation and stick rotation

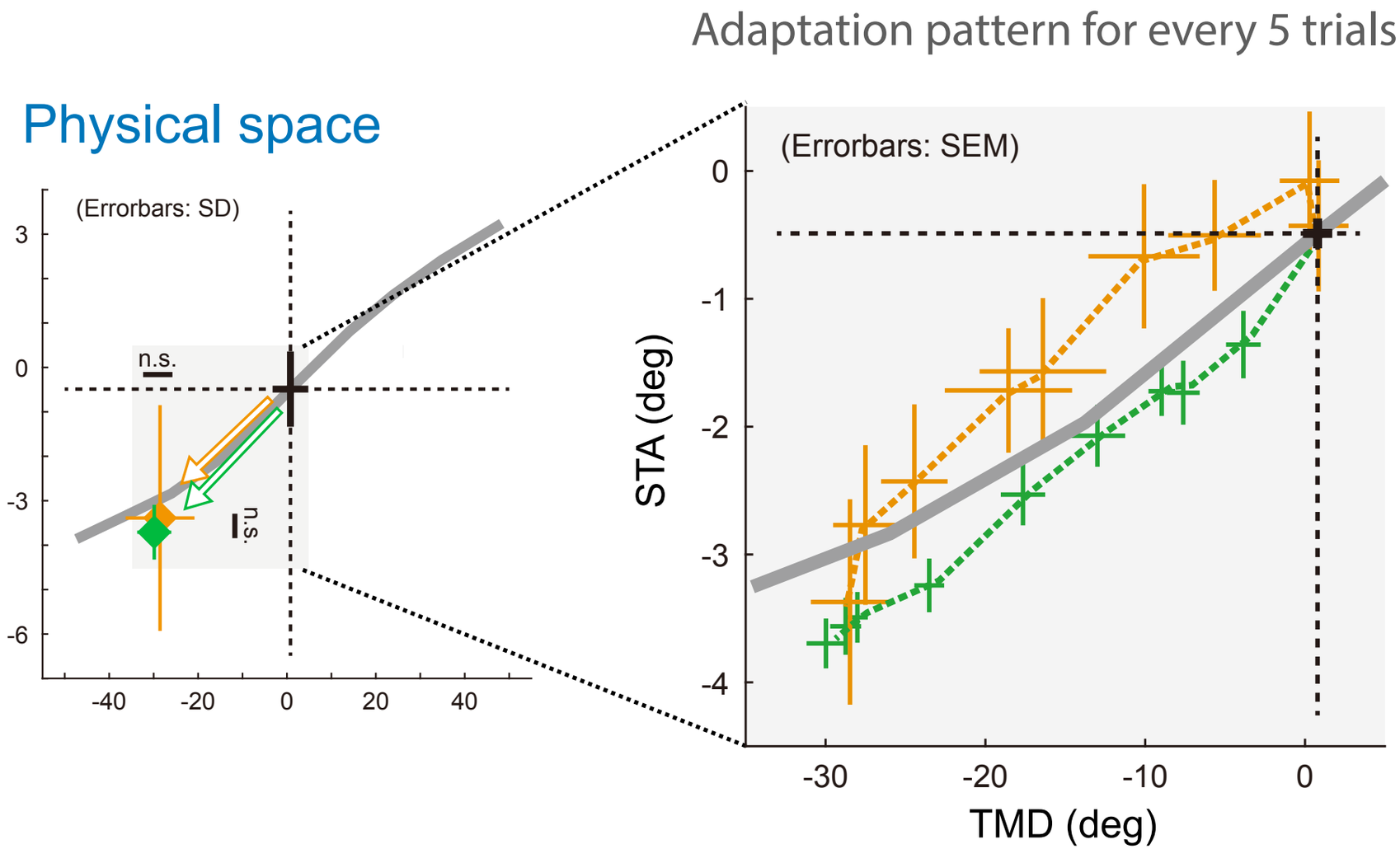




CCW group

CW group

Exp 3: Adaptation to simultaneous application of tip rotation and stick rotation



The adaptation was more delayed for E3CW group.

The task-irrelevant error information significantly influences how the task-relevant error is compensated.

References

Context dependency

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Nozaki & Scott, Exp Brain Res 2009
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Meta learning

Hayashi et al., eNeuro 2016
Hayashi et al., bioRxiv “Shifts in neural tuning systematically alter sensorimotor learning ability”

Redundancy

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Acknowledgment

Takuji Hayashi PhD (UTokyo)
Toshiki Kobayashi PhD (OIST, UTokyo)
Prof Maurice Smith (Harvard)
Prof Ken Takiyama (Tokyo UAT)
Prof Stephen Scott (Queens)
Prof Issac Kurtzer (NY Tech)

Asako Munakata
Yasuko Shinya
Kanae Abe
Megumi Annen
Jun Naito

UTokyo

UTSSI
東京大学スポーツ先端科学連携研究機構

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