Human sensorimotor learning: adaptation, skill, and beyond

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Sensorimotor Learning

“Improvement, through practice, in the performance of sensory-guided motor behavior”

Error-based paradigms

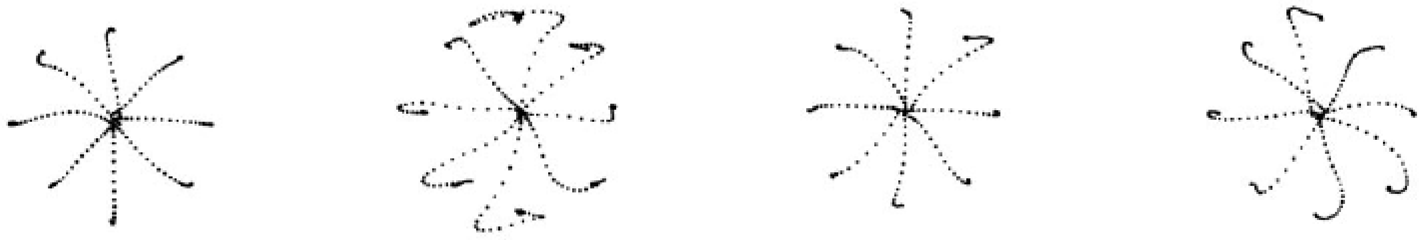
- Adaptation* (model-based)
- Use-dependent (model-free)
- Success-based (model-free)
- Structural

Optimization and skill

Implicit and explicit processes

Adaptation

Incremental reduction in sensory prediction of errors caused by a perturbation (force, visual) through trial-by-trial modification of a forward model (motor-to-sensory mapping)

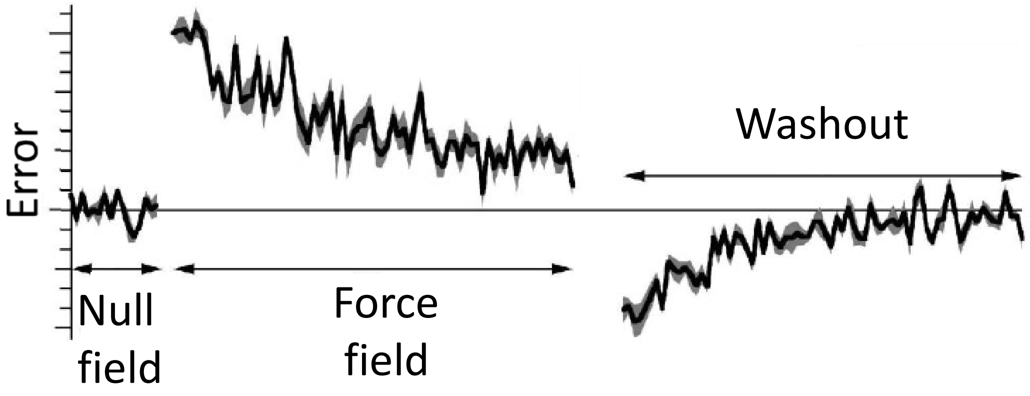


Null field

Force field (early)

Force field (late)

Null field (washout)



Adaptation – Learning Rates

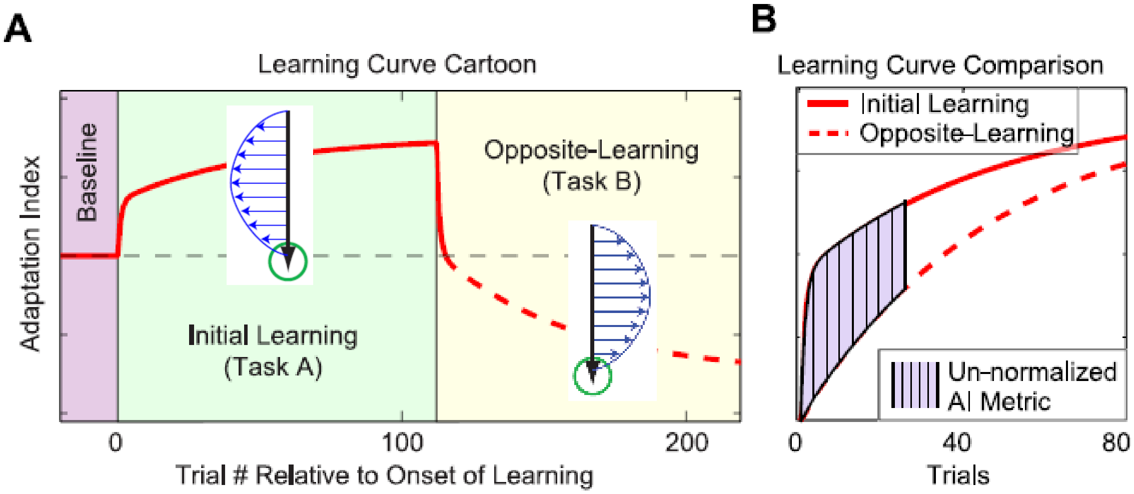
LTI two-rate state-space model:

$\mathbf{x_1(\mathit{n}+1) = A_f\, x_1(\mathit{n}) + B_f\, e(\mathit{n})}$ fast system

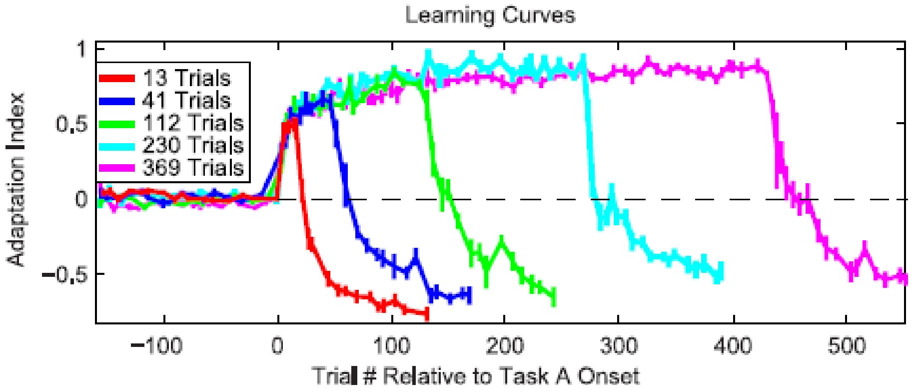
$\mathbf{x_2(\mathit{n}+1) = A_s\, x_2(\mathit{n}) + B_s\, e(\mathit{n})}$ slow system

$B_f > B_s$	learning rate
$A_s > A_f$	retention factor
$x = x_1 + x_2$	internal states contribute to net motor output

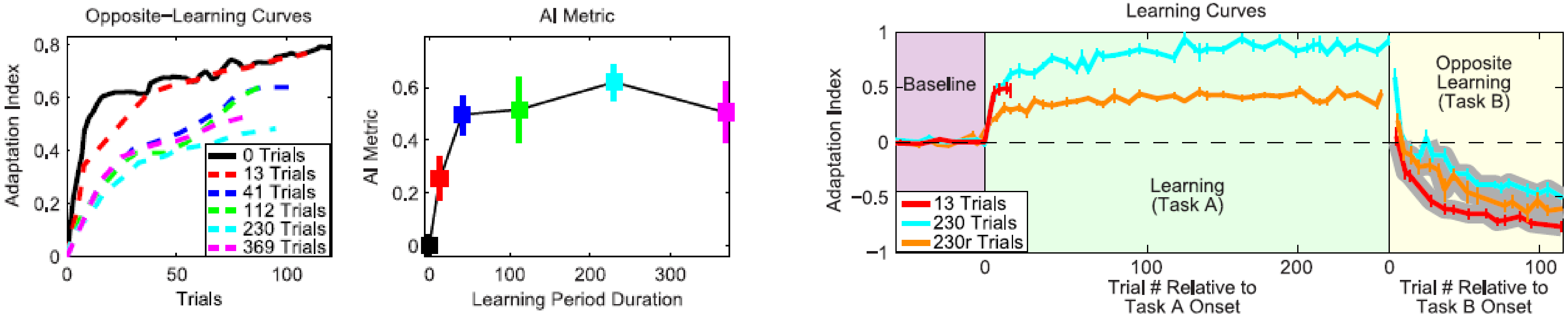
The amount of anterograde interference can be explained by this model (Sing and Smith, 2010).



Different durations of learning of Task A

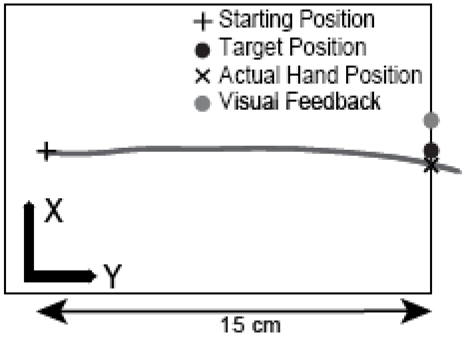


The amount of anterograde interference (AI) to the learning of Task B was determined by both 1) duration of Task A (reaches asymptote), and 2) final level of adaptation to Task A.

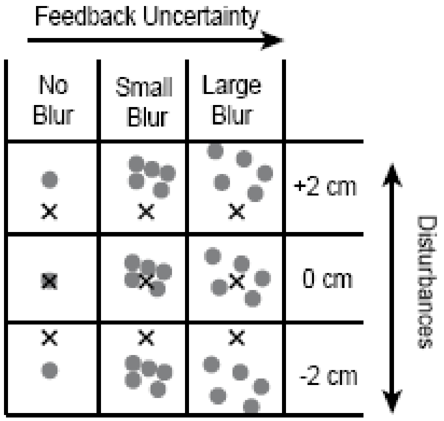


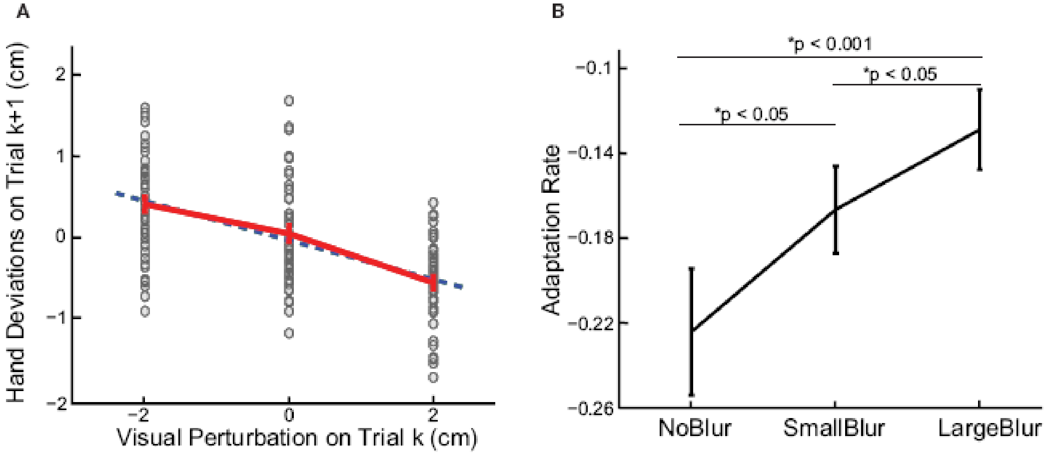
Net adaptation is weighted more towards the slow system as adaptation proceeds.

Trial-by-trial learning rates can be explained within the framework of Bayesian estimation (Wei and Kording, 2010).

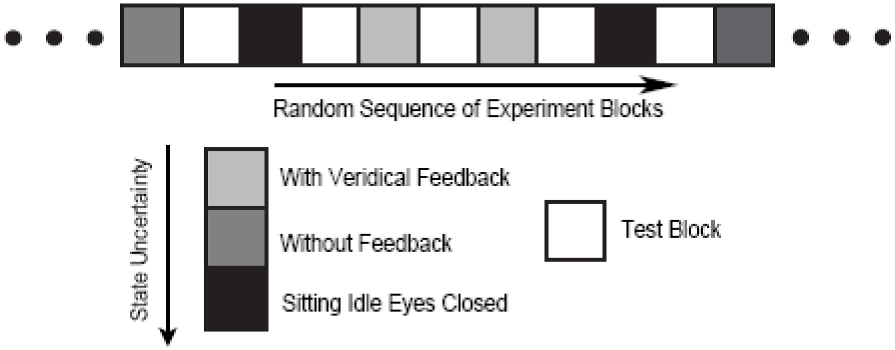


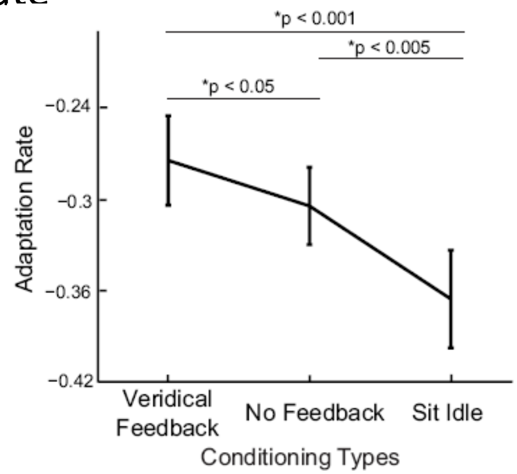
Greater feedback uncertainty → reduced learning rate





Greater state estimation uncertainty → increased learning rate

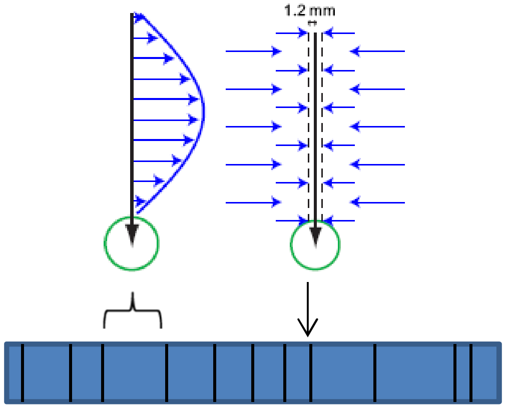


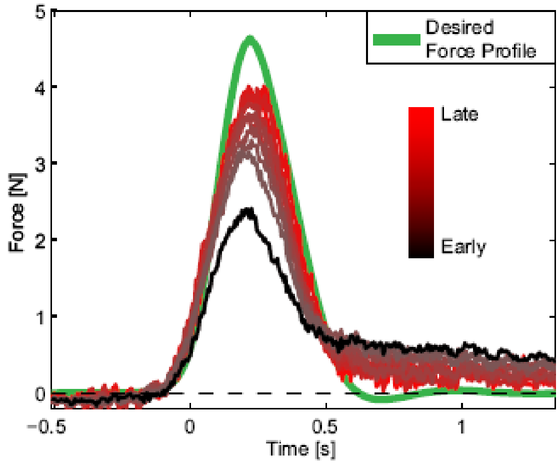


Adaptation – Neural representation of mappings

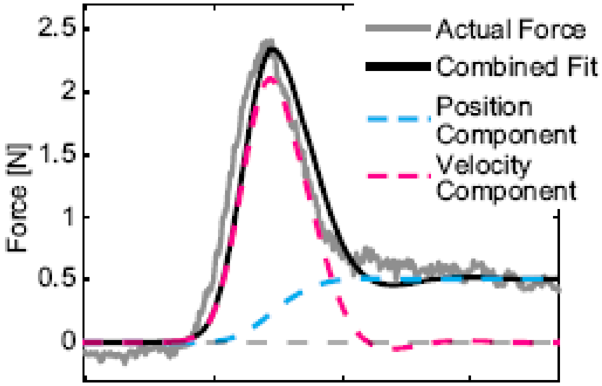
During learning, position- and velocity-correlated <u>motor primitives</u> best tuned to a particular perturbation are selected (Sing et al., 2009).

Learn velocity- (or position-) dependent force field. Error-clamp trials measure adaptation.

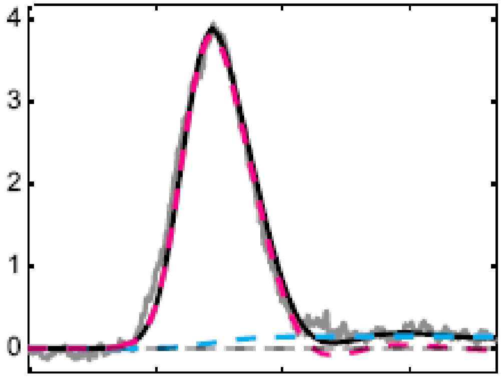




Early learning: position and velocity components

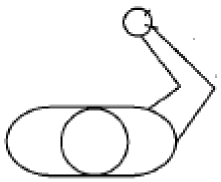


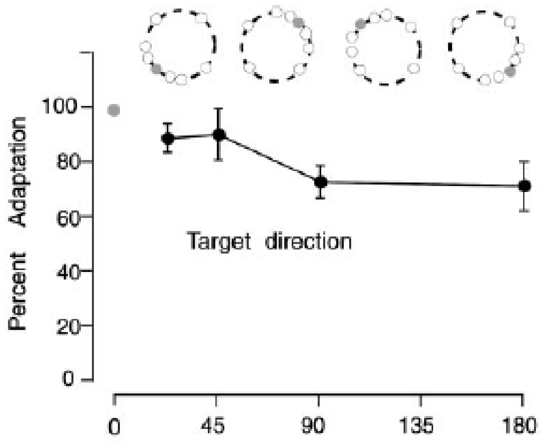
Late learning: velocity component

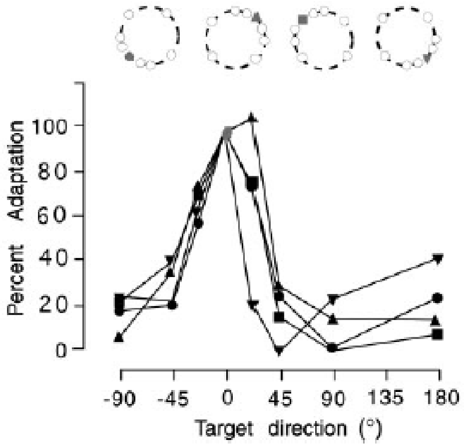


Generalization – how learning transfers to an untrained condition (provides insight about stored representation/learned mapping)

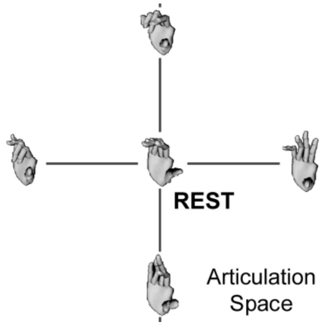
Gain (1.5:1) generalizes widely, unlike visuomotor rotation (30^o) → distinct processing of gain and directional errors (Krakauer et al., 2000)

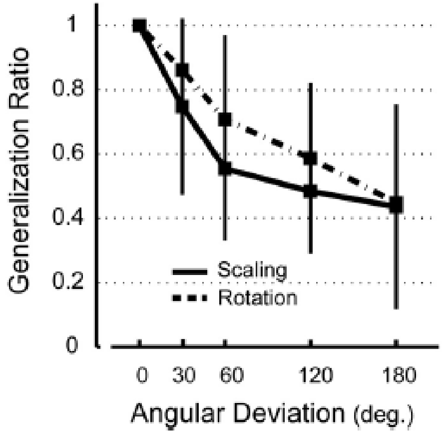






When the task space is more complex (subjects have no prior experience), generalization is narrow (limited by neural tuning width) (Liu et al., 2010).

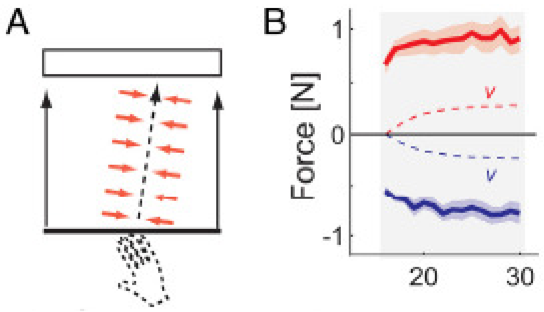




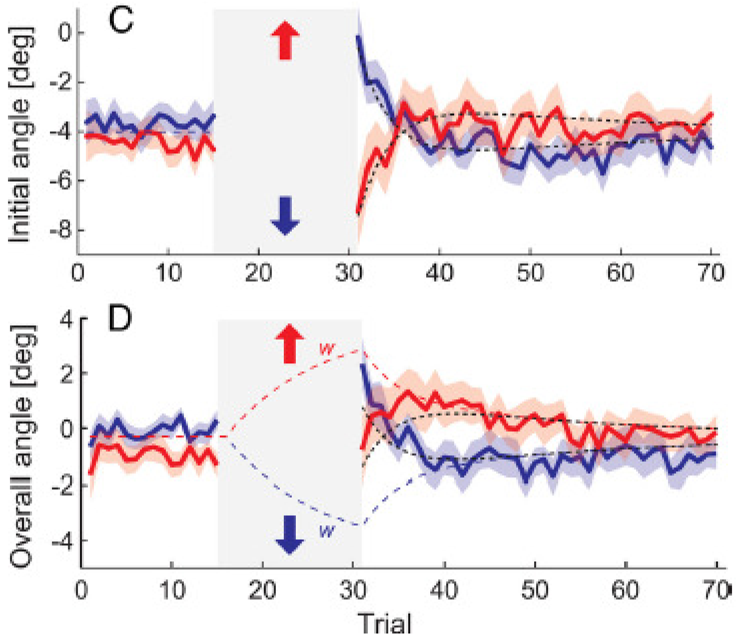
Use-dependent plasticity

Repetition of a particular movement causes future movements to be biased towards in that direction.

Can occur simultaneously with adaptation, even in the opposite direction (Diedrichsen et al., 2010).



Tilted trajectory (±8°) imposed by force channel in task-irrelevant direction

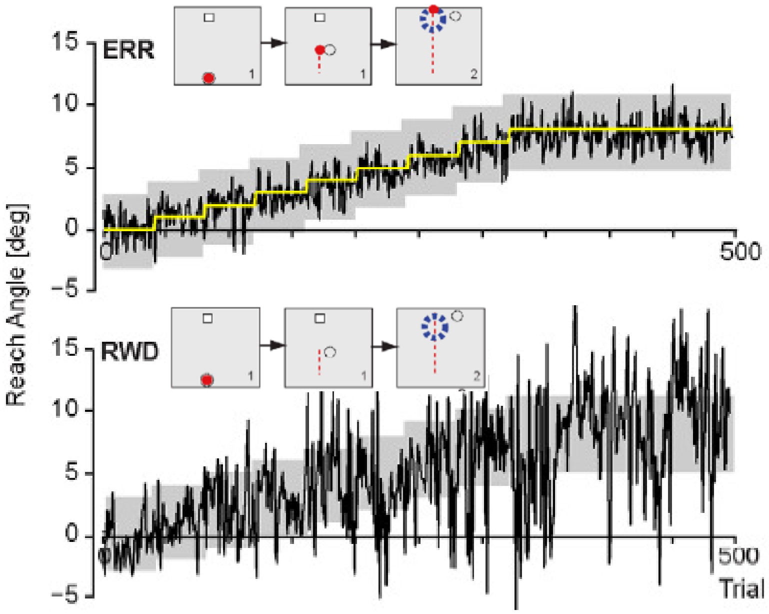


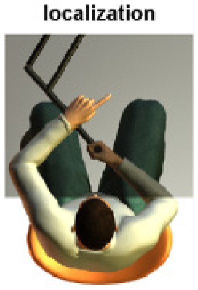
After initial after-effect washes out (adaptation), there is a change in baseline (use-dependent)

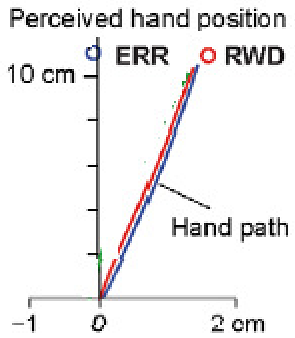
Success-based learning

Consequence of movement	Form of prediction error	What is altered by learning from error
Sensory (vision, proprioception)	Vector	Forward model (sensory consequence predicted from motor commands)
Reward (dopamine release)	Scalar	Value function (value of sensory states that result from those motor commands)

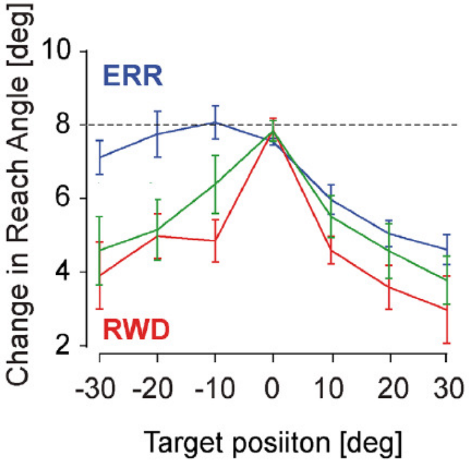
Both groups modify motor commands





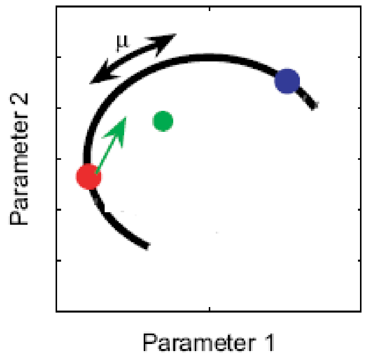


Differences in sensory remapping and generalization



Structural learning

"Learning-to-learn": Learning the general structure of the perturbation (e.g., visuomotor rotation) allows an increase in learning rate (reduce dimensionality of exploration space) (Braun et al., 2009).



Exposure phase

Rot-Learner: Random rotations between ±90° (every 8 trials)

Control: No rotation

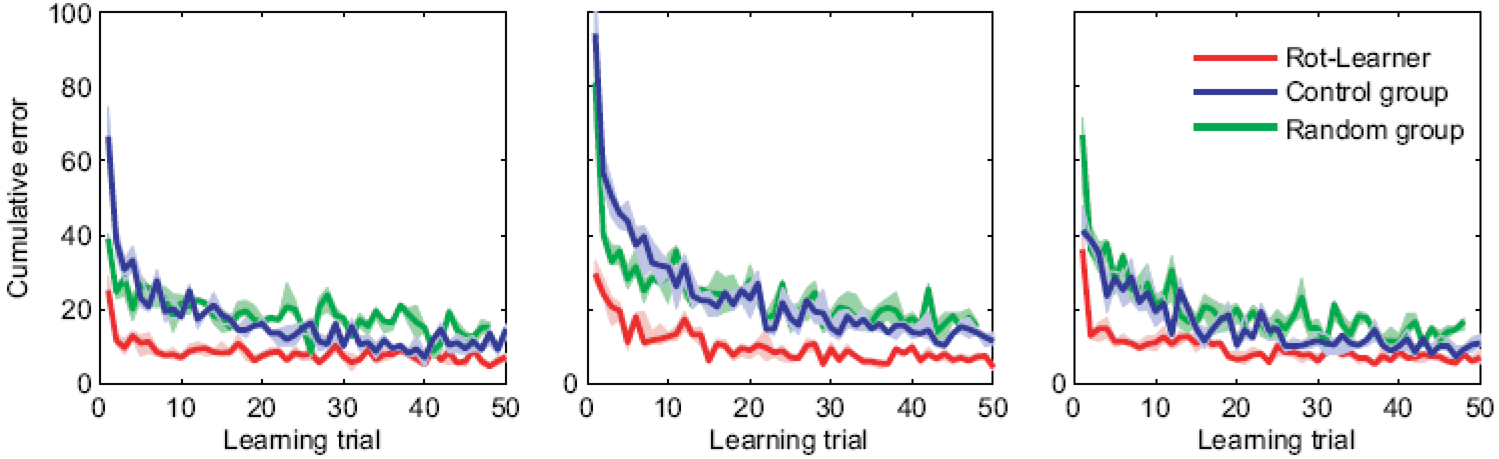
Random: Rotations near ±60°, shearing, scaling (every 8 trials)

Test phase

+60° rotation
Facilitation

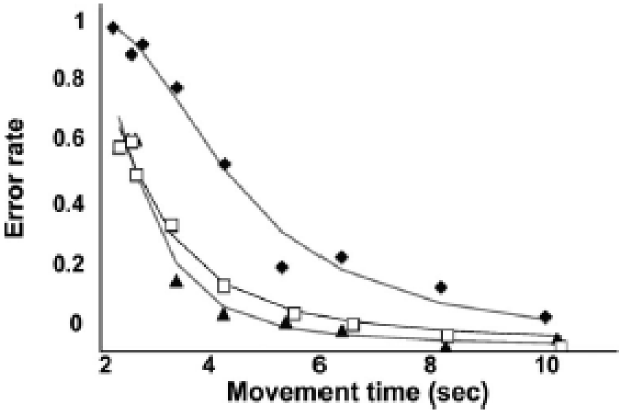
-60° rotation
Interference reduction

+60° rotation
Re-learning facilitation



Optimization and skill

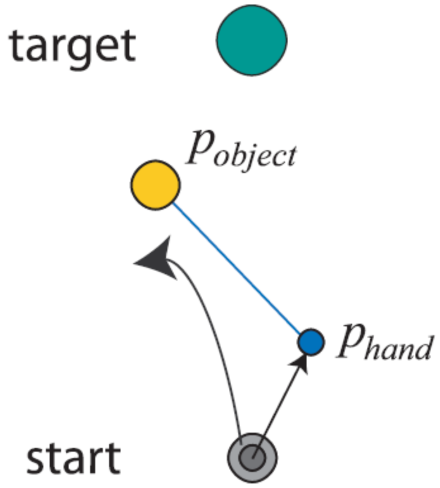
- Unlike adaptation: perturbation, then return to baseline
- Consequences of motor skill learning:
  - Shift in speed-accuracy function
  - Reduction in variability
- Possible reasons for better performance
  - Better state estimation (forward models, sensory feedback processing)
  - Better motor execution (improved SNR)
  - Convergence on optimal control policy



Reis et al., 2008

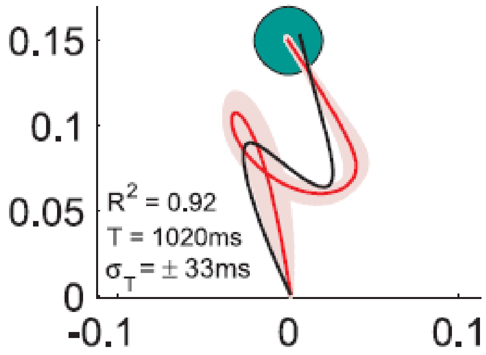
Subjects learn to control a complex object with internal degrees of freedom (improve SAF) by adopting movements predicted by OFC (Nagengast et al., 2009).

Complex mass-spring-damper system (off-diagonal terms)



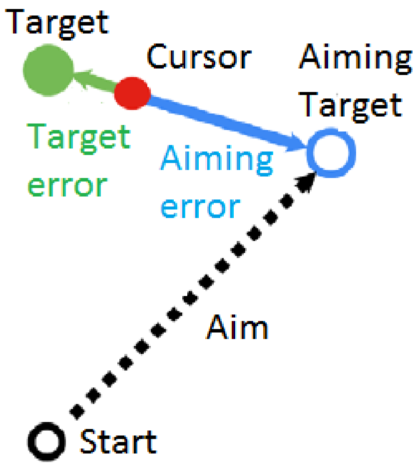
OFC: Find control sequence to minimize cost function. Predicts subjects' hand paths.

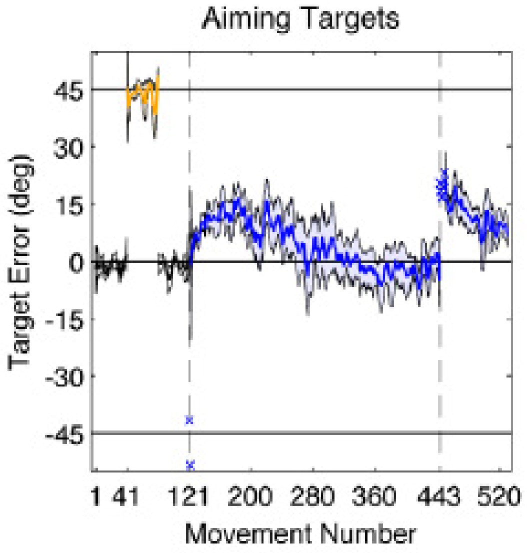
$$J = w_o\left(\|p^*(T) - p_o(T)\|^2 + w_v\|\dot{p}_o(T)\|^2\right) + w_h\left(\|p^*(T) - p_h(T)\|^2 + w_v\|\dot{p}_h(T)\|^2\right) + w_e\int_0^T \|u(t)\|^2 dt.$$



Implicit and explicit processes - Adaptation

- Competition when implicit (based on prediction error) and explicit (based on target error) processes conflict





- Fast process and working memory may compete for resources

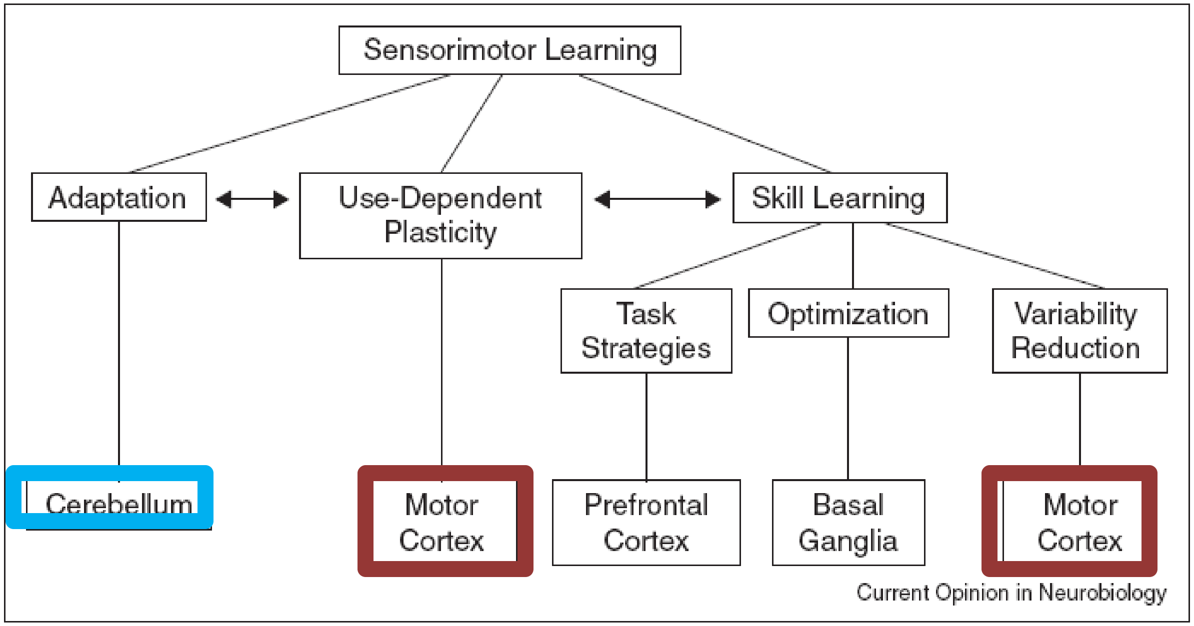
Implicit and explicit processes – Skilled sequential movements

Explicit cognitive processes may further improve overlearned skills

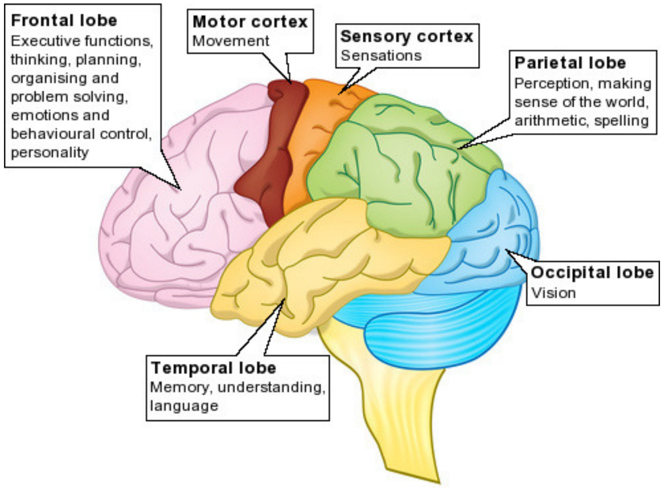
- Spatial accuracy better for well-practiced reaches when target order known
- In skilled typists, sequence execution improved when typing a recently seen word versus a new word

Brain structures involved

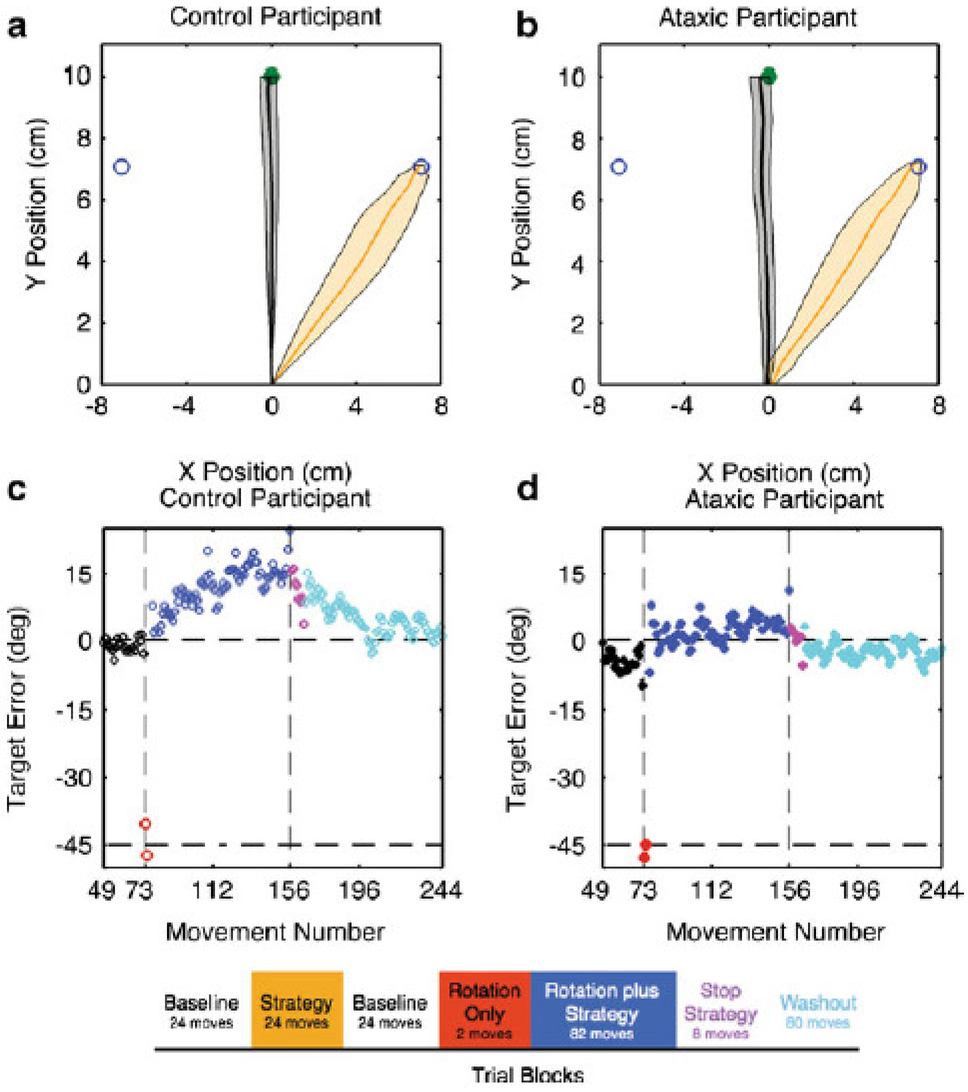
- Neurological patients and brain stimulation
- Cerebellum:
  - Cerebellar atrophy impairs adaptation
  - Enhancement of cerebellar activity via tDCS improves rate of adaptation
- Motor Cortex:
  - Representations of finger postures elicited by TMS are specialized for trained persons



Current Opinion in Neurobiology



Taylor JA, Klemfuss NM, Ivry RB. **An explicit strategy prevails when the cerebellum fails to compute movement errors**.
Cerebellum 2010, 9:814-586.



Baseline and Strategy
←shooting movements (only
endpoint feedback)

- Larger drift for controls
- Larger aftereffect (due to implicit adaptation) for controls (w/ and w/o visual FB)