# Notes

**Abstract**

* Old view: sensorimotor adaptation is purely error-based process
* New view: sensorimotor adaptation is interplay of error-based and other learning processes
* How to elucidate contributions of each learning process
* Savings – people show faster performance gains when the same learning task is repeated
* Conclusion: error-based learning alone cannot account for savings. Savings reflects an improvement in action selection rather than motor execution

**Introduction**

* Error-based learning: learning driven by the difference in predicted and actual sensory information
  + Reduce error until adapted motor command = intended sensory output
* Models responding only to error cannot account for savings
* Physiological understanding of savings: latent facilitation of synaptic potentiation
* 3 different error-based classes to explain:
  + 1. Multiple error-based adaptation mechanisms operate in parallel, but at different rates
  + 2. People learn to switch between different internal models. One for baseline performance and one for perturbation performance
  + 3. Learning process is modified by context. Perturbation is reintroduced and either recruitment of additional error-based process or change gain on learning rate based on direction and magnitude of past errors
* In contrast, pattern of behavior for visuomotor savings doesn’t follow these error-based classes, but may better explained by changing action selection
* Want to distinguish how performance gains are being achieved (faster adaptation of internal model, recall a strategy, or combination?)
* Hypothesis: Savings arises from an action selection process rather than error-based adaptation
  + Participants will recall an aiming strategy that was used to facilitate performance
  + Allow for improvement in performance without “true adaptation” (i.e. recalibration of sensorimotor mapping)

**Materials and Methods**

* Make reaches on a table with a similar tv/mirror set up as KINARM
* Six-axis magnetic position sensory attached to index finger
* Reach to targets 10 cm away
* No vision of the arm
* Vision of the hand as a white cursor until hit target distance, leave for (2 or 0.5) s, return via ring diameter decreasing
* Must move <300ms
* Experiment 1
  + Asses the effect of perturbation size on savings
    - 15, 30, 45, and 60˚
  + 80 baseline, 80 perturbation, 160 washout, 80 perturbation
* Experiment 2
  + Does savings observed with large perturbations result from faster adaptation of internal model or from changes to action selection?
  + 3 groups
    - 45˚ rotation for 2 targets
    - 30˚ rotation for 4 targets
    - 45˚ rotation for 4 targets
  + 2 target group protocol
    - 80 baseline, 80 perturbation, 100 washout, 80 perturbation, 60 washout
  + 4 target group protocol (adjusted to accommodate for more targets, but same # of reaches overall)
    - 40 baseline, 100 perturbation, 120 washout, 100 perturbation, 40 washout
  + To evaluate aiming strategy:
    - Turn off perturbation, tell participant it is off and to reach directly for target, turn back on and finish experiment
    - 2 target:
      * After 7th trial of rotation 2, pause + turn off + instruct for 2 trials (each target)
    - 4 target
      * After 12th trial of rotation 2, pause + turn off + instruct for 4 trials (each target)
    - \*\* If savings is via recalibration of sensory map, error will show in these trials even though they are explicitly told to reach directly to target and can do so in the baseline trials. If savings is via action selection, errors shouldn’t show in these catch trials because action selection is explicitly controlled
* Experiment 3
  + Elucidate the contribution of aiming strategy in visuomotor adaptation task
  + Aim report technique with ring of numbers
    - Ring appear and reports start after 21st trial of baseline
  + 15 or 45˚ rotation
  + 4 targets
  + 40 baseline, 100 perturbation, 120 washout, 100 perturbation, \*remove numbers + instructed to aim direction to visual location of target\*, 40 washout
* Experiment 4
  + Is compensatory aiming controlled via arbitrary cue or is action selection dependent on size of perturbation ?
  + Rotation blocks included both rotation and no-rotation trials
  + !! Cursor and return ring in red for rotation trials, cursor and return ring white for non-rotation trials
  + Participants told: When cursors is red, something weird will happen, just keep trying to reach towards the target
  + 15 or 45˚ rotation
  + Protocol
    - 80 baseline, 80 perturbation (70 red rotation, 10 randomly interspersed non-rotation), 100 washout, 80 perturbation (same random order as rotation 1), 60 washout
* Experiment 5
  + How participants respond to a novel perturbation, comparing conditions where aiming strategy is operative versus non-operative
  + 15 or 45˚ rotation
    - 45˚ use aiming strategy
  + Protocol
    - 80 baseline, 80 CCW, 160 washout, 80 30˚ CW
      * \* 30˚ CW is different in both direction and magnitude as compared to both 15 or 45˚ CCW
* Data analysis
  + Movement duration = finger exit staring region and pass 10 cm threshold
  + Position data cubic spline interpolation to 150 points
  + Cartesian 🡪 polar
    - Why? To make into angles
  + Differentiated to find speed independent of hand angle
  + Peak speed
    - Smooth radial speed with 75-window loess function and taking maximum value
  + Hand angle, relative to target angle, at point of peak speed was primary dependent measure
    - Why at peak speed? Why not at 10 cm distance?
  + Experiment 3
    - Verbal aiming report (explicit strategy) and implicit adaptation
  + In order to compare 2 and 4 target conditions, create a standardized savings metric
    - Create a savings difference score (average of 3 reaches to target)
      * 2 targets – 6 total reaches (data points)
      * 4 targets – 12 total reaches (data points)
    - Difference score = 3 trials in rotation 2 – mean hand angle on 10 null trials that precede associated rotation block
      * Basically rotation 2 trials – end of washout
  + Learning rate determined via fitting an exponential function of form
    - a – b \* e^x\*c
      * a = asymptotic performance parameter (mean of last 5 trials )
      * b = difference between mean of last 5 trials and first trial
      * free parameter – learning rate constant

**Results**

* Experiment 1
  + Everyone learned perturbation and compensated by end of rotation block 1
  + Compare rate of adaptation for two rotation blocks
    - If savings present, higher rate in adaptation 2 than 1
    - Mixed-factor ANOVA w/ rotation size and block %%
      * Within subject effect of block
      * Significant block x rotation size interaction
      * Bonferroni correction %%
        + Faster learning rate in second rotation for 45 and 60 groups, but not 15 and 30
        + One tail t-test v two tailed t-test %%
      * This result held true when difference scores calculated
        + First 6 trials of rotation 2 – first 6 trials of rotation 1
  + Purely error-based adaptation models would predict that savings would occur no matter the perturbation size
  + Hypothesize that the difference is in the explicit strategy and not the implicit adaptation
  + 45 and 60 groups had faster learning rates (i.e. indicating more savings) because there was a prominent use of an aiming strategy due to the size of the perturbations
* Experiment 2
  + Directions used to terminate use of aiming strategy being used
  + Initial trials of rotation 2 allow probe into savings
  + Probe trials allow to see what is contributing to that savings
    - If it’s adaptation (implicit), the reaches/hand angle should remain relatively constant
    - If it’s action selection, hand angle should change
  + 2 target condition
    - Faster relearning with 45˚ rotation (i.e. savings achieved)
    - When perturbation turned off, large drop in heading angle
    - Observation is consistent with the idea that savings is related to a process under volitional control
    - Small 4˚ shift held constant, probably the amount of implicit adaptation
  + 4 target condition
    - (45˚ group)
      * Showed savings in rotation 2
    - (30˚ group)
      * Didn’t show reliable savings in rotation 2
        + Other groups have shown that this perturbation should be enough to elicit a strategy (and thus savings)
    - Both groups showed significant decline in hand angle following verbal command
      * Decline larger for 45 (relatively or overall?)
    - Both groups showed small amounts of implicit adaption
    - Amount of adaptation from strategy > amount of adaptation from implicit adaptation
  + Savings observed early in a second rotation can be attributed to aiming behavior that is under volitional control. Small amounts of implicit adaption suggest strategy and implicit adaptation occur in parallel.
* Experiment 3
  + Report aiming
  + Exclude trials in which aiming was more than 2 times perturbation size OR discrepancy between aim and reach was > 45˚
    - ~3% of 45˚ and ~2% of 15˚
    - Mostly from 3 bad subjects
  + 45˚ group showed savings, but 15˚ group did not
  + 45˚ group showed reliable aiming location for rotation 2 compared to rotation 1
  + 15˚ group did not show consistent reporting between rotation 2 and 1
  + Estimate implicit adaptation
    - Subtract participants reported aim by hand angle
      * Reported aim = explicit
      * Hand angle = implicit + explicit
    - Then calculated savings
      * Neither group showed savings in estimate of implicit adaptation
  + Significant difference in aiming and overall performance between 45 and 15 groups
  + Conclusion: savings in visuomotor adaption is associated with how participants change their aiming strategy when re-encountering a perturbation and not associated with faster modification or recall of an internal model
    - Larger performance changes observed with large perturbation is primarily due to changes in explicit aiming
* Experiment 4
  + If participants are employing an aiming strategy, they should be able to use the color cue to determine whether or not to use the strategy
  + 15 and 45˚ groups
  + Expect savings on first trial of rotation 2, if people can be cued to use the strategy
    - 45, but not 15
  + 45 – clear separation of hand angle for cued and uncued
  + 15 – considerable overlap of hand angle for cued and uncued
  + Mixed ANOVA – Rotation Size X Block X Trial Type
    - Main effects of rotation size and block
    - Three-way block X rotation size X trial type interaction was reliable
      * Driven by simple effects of block and trial type in 45 group, but not 15
  + Difference for 45 group, but not for the 15 group
  + First trial of rotation 2
    - 15 group did not show
    - 45 group did have significant show
    - Two groups were different from each other
      * Not from online correction – individual reach trajectories were straight
* Experiment 5
  + How aiming plan generalizes to a novel perturbation
    - Use 15 as a baseline performance and 45 as real deal
  + Both groups showed good learning in first rotation along with return to baseline before rotation2
  + 15 showed standard adaptation curve
  + 45
    - Second trial of rotation2, 9/10 participants moved in direction that amplified visual error
      * Testing at the extremity to see if it was like last perturbation (i.e. CCW)
    - Trial 2: Redeploy strategy that was successful in last rotation block
    - Trial 3: abandon strategy and uptake new strategy
    - Showed faster learning compared to 15 group
  + Those initially trained with 45˚ rotation were sensitized to invoke and adjust an aiming strategy upon encountering the novel rotation

**Discussion**

* Savings reflects recall in the action selection domain, with participants invoking an aiming strategy when a perturbation was reintroduced
* Error-based adaptation does not appear to make any contribution to savings in visuomotor adaptation
* Savings as action selection
  + Experiments 4 and 5 showed that a strategy can be recalled without re-exposure to the errors that drove its development
    - 4 – color cue
    - 5 – error of opposite sign (CCW 🡪 CW)
  + In a traditional sense, large error can become a cue for the recall of aiming strategy
  + Huang model – savings arises from the memory of hand positions associated with successful performance during earlier presentations of perturbation
    - Experiment 5 – 45 group reach in direction of past success
      * In trial 2 didn’t they?
      * Doesn’t this agree with the model, not go against it?
    - Savings isn’t equal among all perturbation sizes
    - Savings is only seen when preparation time is enough
* The role of perturbation size
  + Didn’t observe with 15˚ perturbation because aiming does not occur with perturbation this small
    - Wrong, previous experiments show that people aim at a range of perturbation sizes
  + “We surmise that use of an aiming strategy alone is not responsible for savings. Rather, savings may depend on a substantial change in aiming strategy between the beginning and end of the first rotation, the absolute angular magnitude of the aiming strategy, or the relative proportion of aiming and implicit adaptation.”
    - Savings depends on the difference between aiming strategy at beginning and end of rotation1
  + Why didn’t 30˚ group show savings?
    - Could be many reasons
  + Big claim of the paper is that savings is associated with action selection rather than error-based adaptation, and not dependent on the idea that there is an absolute point at which aiming/savings operates
* Relationship to error-based models of savings
  + Smith two state
    - Doesn’t account for:
      * Rotation size
  + Berniker and Kording
    - Two process model for large and small errors
      * Doesn’t account for cue rather than re-exposure
  + Favor a model with multiple processes
  + Herzfeld model
    - Savings comes about because the system is sensitized to familiar errors
      * Fails to predict
        + Dependent on rotational magnitude
        + Volitional nature of aiming
        + No need to re-experience error to exhibit savings
* Awareness and aiming
  + Assuming aiming strategies are generally accessible to awareness even when not directly probed
    - If people are choosing/refining aiming strategies, they must be aware of their reaches, perturbation, and some error
  + Expect that some parts of action selection are not explicit (or don’t need to be)
  + Do not consider awareness to be the defining distinction between adaptation and action selection in the context of savings
  + Motor learning is a result of a variety of learning processes that allow a flexible behavior in multiple environments
    - Within session savings for a visuomotor adaptation task is accounted for by action selection

# Comments

* Experimental apparatus
  + No arm support
    - Feel friction on table?
* Brush up on polar coordinates
* Learn how/why fit exponential function
* Learn ANOVA
  + Mixed-factor
  + Bonferonni correction
  + One tail v two-tail t-tests
* -
* Why did they do this study?
  + Purely error-based models of learning do not fully account for some phenomenon associated with learning, like savings
  + Is saving a result of an increased ability to rapidly adapt internal models or is it an improvement of action selection?
* What’s their interpretation of the results?
  + Savings is a result of an improvement to select appropriate actions
* Do I agree with their interpretation?
  + Yes
  + Why?
    - The subjects ability to “turn on and off” their rotated reaches as seen in the cue experiment and aiming strategy experiment (without number ring)
      * Can’t switch back and forth between two internal models, but can easily switch back and forth between two strategies
* How do the experiments fit together to answer the broader question?
  + Broader question: Is savings a result of an improvement in action selection or an improvement in the ability to adapt internal models
  + If savings is the result of an improvement in action selection, then when subjects are adapted to a visuomotor adaptation (experiment 1), then they should be able to easily and quickly switch between actions (normal visuomotor map and adapted visuomotor map). For example, after they are fully adapted, making reaches that correspond to an adapted visuomotor map, then when they are explicitly told that now the perturbation is off and cursor = exact hand position, they should be able to reach directly to targets (Experiment 2). Also, if subjects are fully adapted and asked to explicitly report where they are reaching, their aiming angle should be most of what contributes to the reach (Experiment 3 [need to be refined]). Also, if it is an explicit act of action selection, a simple cue should be able make participants chose the correct action (Experiment 4). Also, if participants are adapted to one strategy, then if they are given a new perturbation, they should be able to create a new strategy fairly quickly (Experiment 5).
  + –
  + Experiment 1: make sure correct perturbation sizes are being used for the upcoming experiments
    - Test if savings is not dependent on perturbation size (like in the error-based models)
  + Experiment 2: if savings is from recall of a strategy, then participants should be able to make accurate reaches when they know if perturbation is on or off
  + Experiment 3: if savings is from recall of a strategy, then it should be explicit and thus they should be able to explicitly call out (accurately) where they are reaching to
  + Experiment 4: similar to experiment 2, except this time, it is not a verbal cue, but a visual cue
  + Experiment 5: how participants respond to a novel perturbation. If savings is from recall of a strategy, then participant should be able to switch/create a new strategy quickly
* -
* Key take-aways
  + Savings is a result of an improvement in action selection and not quicker recall/adaptation of an internal model
* Are the statistical analyses appropriate for the question asked?
  + Yes
* What is the big picture idea?
  + Adaptation, and the associated phenomenon such as savings, cannot be explained by one singular learning process, but can be explained by multiple learning processes working in union with one another.

# Questions

* Finding peak speed
* Why use angle at peak and not just angle at 10 cm?
  + Is it likely that these two events occur at the same time?
  + Needed to make reach <300 ms (i.e. probably reach true peak after reach done)
* Know about fitting exponential functions?
* How much know about statistics that come out of the ANOVA
  + Paired t test, t(9)
  + F values
* Discrepancy between experiment 5 and Huang model (savings as action selection)
* How well should I know the other error-based models of savings?