# Notes

**Abstract**

* Correction of a perturbation to visually guided reaching is implicitly corrected in 2 ways:
  + Immediately after perturbation via feedback control (online correction)
  + In next movement by adjusting feedforward motor commands (offline correction or motor adaptation)
* What is the relationship between feedback and feedforward control?
* This paper shows both implicit online and offline movement correction utilizes the same visuomotor map for feedforward movement control that transforms the spatial location of visual objects into appropriate motor commands
* Procedure
  + Distort visuomotor map via opposite visual rotation
    - Either more or less sensitive to movement direction
  + Exam how distorted visuomotor map influenced online movement correction
    - Magnitude of online movement correction altered according to shape of visuomotor map
  + Exam offline movement correction (i.e. aftereffect in a trial by trial basis)
* Results highlight importance of visuomotor map as a foundation for implicit motor control mechanisms and relationship between feedforward, feedback, and motor adaptation

**Introduction**

* Feedforward control tells us what we should do, feedback control tells us what to do if we are perturbed during the movement (i.e. the feedforward control isn’t exactly what it was thought to be)
* Feedback control happens during the movement (online correction) and in how the next movement is altered (offline correction)
* Feedback control isn’t voluntary (i.e. conscious)
  + Online correction occurs <150 ms after perturbation
  + Next reach is inevitably in opposite direction (aftereffect)
* Hypothesize: Visuomotor map for voluntary movement control could influence the implicit online and offline movement correction
  + Exam how movement correction is altered when visuomotor map is altered
  + If the visuomotor map is distorted
    - Reaching movements should be more/less sensitive to differences in target’s direction
      * If both (online and offline) movement correction refer to the visuomotor map, then both (online and offline) movement corrections should increase/decrease following distortion
      * If both (online and offline) movement corrections **don’t** refer to the visuomotor map, then both (online and offline) movement corrections should remain the same (even after the visuomotor map is distorted)
* If online and offline movement correction rely on visuomotor mapping, then if that visuomotor map is distorted so that reaches to 3 different locations are all achieved via 1 reach direction, then when the target is perturbed, both the online movement correction should be reduced (not fully reach to the moved target) and the offline movement correction should be reduced (not a full opposite direction aftereffect). On the other hand, if the visuomotor map is distorted so that reaches to 2 locations are achieved via increased angular excursion, then when the target is perturbed, both the online movement correction should be increased (reach further than the moved target) and the offline movement correction should be augmented (larger than expected aftereffect).

**Materials and Methods**

Participants

* 54 right handed

General task settings

* Reaching movement with right arm in horizontal plane w/ KINARM endpoint
* No vision of arm
* “Move cursor from starting circle toward the target circle”
  + Too fast or too slow (600 – 750 mm/s Experiment 1) (380 – 450 mm/s Experiment 2 [ample time for online correction])
* Move cursor to start circle (green), 1s hold, target (green) appear, 1-1.5 s target 15 cm away (magenta [ i.e. go signal]) reach
* Robot bring back to start

Procedure for distortion of visuomotor map

* Visuomotor map – relationship between target direction and actual hand movement direction
  + Normally, there is a near perfect linear relationship between the two
    - Two directions should be identical (we can reach anywhere with precision)
* Inward adaptation group
  + Target at either 30˚ or -30˚
  + Visual rotation around the starting position
  + Amount of visual rotation increased gradually from 0 to 30˚ at a rate of 0.5˚ / trial
  + Implicit adaptation made movement direction of the handle closer even when participants aimed at the two different targets
* Outward adaptation group
  + Target at either 30˚ or -30˚
  + Visual rotation around the starting position
  + Amount of visual rotation increased gradually from 0 to 30˚ at a rate of 0.5˚ / trial
  + Implicit adaptation made movement direction of the handle further even when participants aimed at the two different targets
  + If participant noticed a difference, their data was discarded

Experiment 1

* Confirm visuomotor map was actually distorted
  + 6 participants in each group (inward and outward adaptation [2 groups]) reach to targets (0, +-7.5, +-15, +-30, +-45, and +-60) without visual feedback before and after intervention
* Before intervention
  + Reach towards each target and cursor is invisible immediately after color of target changed
* After intervention
  + Reach alternatively to +/-30˚ targets with probe trials
    - Probe trials – reaches to one of the 11 targets
    - Cursor invisible immediately after color of target changed
* After adapting inward/outward, expected that movement direction would become less sensitive/more sensitive to target location
* -
* Procedure
  + 66 reaches (6/location), no perturbation, no visual feedback of cursor
  + Intervention (adaption): 122 reaches to +-30 (0.5˚/trial)
  + Post intervention
    - Probe trials: 66 reaches (6/location), no perturbation, no visual feedback of cursor
  + Reach to +- 30˚ with rotation
    - Probe trials: cursor invisible immediately after color change

Experiment 2

* 16 participants
  + Inward or outward adaptation
* Investigate how the intervention influenced online movement correction via a target jump
* Movement to central (0˚) target was unchanged after intervention
* Used 0˚ target as probe trials
  + Start reaching towards 0
  + Jump to +-30, +-15, +-7.5, or 0 after force to handle exceeded 1 N
  + Cursor disappear simultaneously so no more adaptation occurred
* Pre and post intervention
  + 100 reaches towards +-30 target in alternative fashion
  + 100 trials to 0 interleaved
    - 30 with visual feedback
    - 70 without visual feedback (target jump)
* Protocol
  + 200 reaches
    - 100 to +- 30 (no perturbation + veridical vision?)
    - 100 to 0
      * 30 with visual feedback
      * 70 without visual feedback (target jump) (to any of the 11)
  + Intervention (adaption): 122 reaches to +-30 (0.5˚/trial)
  + 200 reaches
    - 100 to +- 30 (no perturbation + veridical vision?)
    - 100 to 0
      * 30 with visual feedback
      * 70 without visual feedback (target jump) (to any of the 11)

Experiment 3

* How intervention influenced offline movement correction
* N = 22 per inward and outward groups
* Movement to 0 as probe trials
* Rotations of +-30 or 0 applied when reaching to central target
* In next trial, reach to same central target, measured the corrected movement direction (i.e. after effect)
* Asked participants to aim at central target as accurately as possible and not use an explicit strategy
* In perturbation trials, asked participants to not correct during the movement so online corrections did not influence offline corrections
* Before and after intervention
  + 120 reaches to each location +-30 in alternative fashion
  + One pair of one visual rotation and one probe trial was randomly interleaved (10 pairs for 0, +- 30˚)
* Protocol
  + 120 reaches to +/- 30˚ targets in alternating order
    - Movement to 0 as probe trials
      * Rotate either 0, -30, or 30
      * Next trial, reach to 0 again + measure aftereffect
      * 10 pairs of these
    - 300 total reaches
  + Intervention (adaption): 122 reaches to +-30 (0.5˚/trial)
  + 120 reaches to +/- 30˚ targets in alternating order
    - Movement to 0 as probe trials
      * Rotate either 0, -30, or 30
      * Next trial, reach to 0 again + measure aftereffect
      * 10 pairs of these
    - 300 total reaches

Data analysis

* Butterworth filter at 10 Hz %%
* Movement direction calculated as angle of line connection starting position and handle position at peak velocity relative to the forward direction
* Rightward movement = +; leftward movement = -
* Movement direction = angle connection starting position with final hand position
  + Linear relationship between target and movement direction
  + Calculate slope of regression line for each participant as index
  + Compare slope between period (before and after intervention) and group (inward v outward) by a two way repeated-measure ANOVA %%
* Online movement correction
  + Analyzed lateral component of force exerted on handle 170-200 ms after target jump
    - Force output depended on amount of target jump
  + Force output for each target jump = slope of regression line \* size of target jump (??)
  + Force output compared between target jump size, groups, and periods via 3 way repeated measures ANOVA
    - Force output calculation contains size of jump, so of course they will be correlated
* Considered influence of other factors besides change of visuomotor map
  + Changes in kinematics of movement to central target caused by visuomotor map distortion intervention
  + Peak velocity of handle + lateral deviation of handle at peak velocity when cursor visible
  + Whether intervention caused changes in cursor’s deviation from targets
    - Greater deviation from targets = more opportunity to correct online (which would strengthen feedback response)
      * Measure lateral deviation of the cursor from a straight line connecting start and target position
        + For trials in which cursor was visible
      * Root mean-squared calculation %%
    - Compare via two-way repeated-measures ANOVA
* Offline movement correction (aftereffect)
  + Aftereffect = movement direction 120 ms after movement onset
    - Data from experiment 1 showed that online correction start ~130 ms after onset
      * Remove influence of online movement correct (??)
  + Compared between periods (pre and post) and groups (inward and outward) via two-way repeated-measures ANOVA
  + Compared movement error experiences for the trial in which visual rotation was applied in order to confirm participants experienced the same amount of movement error
* Online movement corrections are capable of influencing offline movement corrections made in subsequent probe trials, make sure no online corrections in experiment 3
  + How online corrections for visual rotation trials were different between groups and periods
  + Experiment 3, analyzed cursor direction 500 ms after onset from central target direction and force output for movement correction averaged from 170 – 200 ms after onset (during perturbation trials of experiment 3?)
    - Two-way repeated-measures ANOVA

**Results**

* Artificial distortion of the visuomotor map (Experiment 1)
  + Inward adaptation – movement direction became closer to the straight-ahead position as adaptation occurred
    - Participants unaware of visual rotation
  + Outward adaptation – movement direction further from straight ahead position as adaptation occurred
  + Before and after adaptation
    - Measure visuomotor map by reaching to various positions without visual feedback
    - Before – reach directly to target (“... movement directions were almost identical to target directions.”)
    - After
      * Inward adaptation – lowered sensitivity to changes in target direction
      * Outward adaptation – higher sensitivity to changes in target direction
      * Both groups sensitivity towards 0 was unchanged
* Gain alteration of online correction (Experiment 2)
  + How online movement corrections were influenced by distortion of the visuomotor map
  + Compare online movement corrections induced by target jumps between trials before and after distortion of the visuomotor map
  + “The degree of correction seemed to decrease or increase depending on the type of distortion each group received.”
    - Quantify amount of online movement correction
      * Determine angle of handle position relative to starting position at 1000 ms after target jump (i.e. final position)
    - Linear relationship between target jump angle and hand direction at 1000 ms (final position angle) (?????)
      * Calculate slope of regression line as an index to quantify degree of online movement correction
  + Two-way repeated-measures ANOVA revealed
    - Significant interaction between period (before and after) and group (inward and outward)
    - Main effect of period significant for both inward and outward
  + “Specifically, distortion of the visuomotor map resulted in diminished online corrections in the inward adaptation group and exaggerated online corrections in the outward adaptation groups.”
  + How early movement correction started
    - Examine lateral force exerted on handle during online movement correction
      * Force output for movement correction appeared to emerge ~ 130 ms after target jump
    - Averaged force output between 170 -200 ms after target jump to examine how distortion of visuomotor map influenced force output for rapid online movement correction and grouped by target jump size
    - Three-way repeated-measures ANOVA
      * No second order interaction
      * First order interaction between period and group
        + Two types of visuomotor map distortions differentially altered the force output for a movement correction
      * Simple main effect of period in both inward and outward
    - Rapid component of lateral force for online movement correction was decreased (inward) and increased (outward)
    - Corrected force outputs during this time appeared to increase as size of target jump became smaller
      * Opposite of what was expected
      * Possibly because online correction was nonlinearly modulated by the size of the target jump
        + Doesn’t this contradict earlier assumptions/calculations
  + Whether changes in the online movement correction could be explained by factors other than distortion of the visuomotor map itself
    - Two-way repeated-measures ANOVA (peak velocity)
      * No significant main effect for group or period
      * No significant interaction between them
    - Two-way repeated-measures ANOVA (deviation in path of lateral hand at peak)
      * Significant interaction between period and group (inward/outward)
      * Significant simple main effect of period only for the outward group
        + Difference is small and effect not seem in inward group
  + Whether cursor movement deviated from the straight path to the target more or less in different groups and periods (root mean squared values of lateral deviation) %%
    - Two-way repeated-measures ANOVA
      * Significant interaction between group and period
      * Simple main effect of period for the inward adaptation group
      * Movement accuracy deteriorated in the inward adaptation group
      * No simple main effect of period for the outward adaptation group
    - “... procedure to distort the visuomotor map did not change the kinematics and/or the movement accuracy sufficiently to explain the changes observed in the online movement correction.”
  + Gain alteration of offline correction
    - Experiment 3 – examine how distortion of the visuomotor map influenced offline movement correction
    - Two-way repeated-measures ANOVA
      * Significant interaction between group and period
      * Significant simple main effect of period in inward and outward groups
        + Aftereffect “decreased” – inward adaptation
        + Aftereffect “increased” – outward adaptation
    - Two-way repeated-measures ANOVA applied to error that each group received in visual rotation trials
      * No significant interaction between error and group
        + Amount of sensory prediction error itself did not differ between groups and between periods
    - Two-way repeated-measures ANOVA to peak velocity of handle towards central target
      * No significant main effect for group or period
      * No interaction between them
    - How participants tried to correct their movement during the visual rotation trials
      * Two-way repeated-measures ANOVA
        + Degree of correction was not significantly different before and after the intervention
      * No significant change in average of the force output from 170 – 200 ms after movement onset for main effect of period or interaction between group and period

**Discussion**

* “We hypothesized that the visuomotor map is important for feedforward control during voluntary movement and plays a pivotal role in teaching the motor system how the movement should be corrected.”
* Subjects performed as expected after a rotation (inward or outward) was gradually imposed on their reaches
  + If perturbation was abrupt, then explicit strategies may come into play.
    - All participants were unaware of perturbation
* “... we found that the degree of online and offline movement correction was altered according to the shape of the distorted visuomotor map.”
  + Inward/outward groups had a reduced/augmented corrective response
* “... feedback controller and motor adaptation system refer to the visuomotor map that is used to for feedforward control,...”
* Factors influencing the feedback response
  + Changes in kinematic of the movement to the central target
    - No statistical significant different in peak velocity of handle during movement towards central target
    - Trajectories largely overlapped
  + Increased opportunity to correct movement
    - Will change the rapid feedback response
    - Movement accuracy was maintained in the outward adaptation group (even after intervention)
    - Accuracy deteriorated by inward group
      * Needed to correct their movement more often
    - Online correction was decreased for the inward group
* Relationship between feedforward and feedback control
  + Close link between feedforward and feedback controls
  + Kinematics of probe trials remained unchanged before and after distortion of the visuomotor map
    - Shape of visuomotor map for feedforward control constrained in online movement correction
    - Feedback control gain could be enhanced or reduced according to the distortion of the visuomotor map
  + Jives with optimal feedback control theory because OFCT doesn’t specify different controllers for feedforward and feedback
* Offline movement corrections were not influenced by the alteration of online movement correction in the preceding trial
  + If online movement correction influenced offline movement correction, then alteration of offline movement correction could be partly ascribed to online movement correction in the preceding trial
  + To exclude this
    - Increased velocity (less time)
    - Tell participants to not correct
  + Online corrections were largely reduced
  + Did not observe alterations in the online corrections that were caused by distortion of the visuomotor map
  + Modulation of the online movement correction did not cause the modulation of the offline movement correction in the subsequent trial
* Influence of the shape of visuomotor map on motor adaptation
  + The motor system learns through experience
  + The visuomotor map tells the motor system how the movements should be adapted
  + The inward adaptation group demonstrated a “reduction” in aftereffect, implying that the adaptation speed could not necessarily be increased, but could be decreased.
  + Aftereffect was modulated by distortion of the visuomotor map and not the repetition of movement
    - If repetition of movement was the reason for aftereffect, then why was outward adaption showing “greater” aftereffect
* Significance of establishing visuomotor map
  + Both online and offline movement corrections reflect the shape of the visuomotor map and suggest a close link between feedforward control, feedback control, and motor adaptation
  + Motor adaptation (offline) modifies the feedforward controller, but our results indicate the influence of the motor adaptation on visuomotor map is not unidirectional, the shape of the visuomotor map is also influenced by motor adaptation.

# Comments

* Are the lines in visuomotor map truly linear?
* Comparisons between before and after intervention
  + They are comparing within group, are they making claims about between groups?
* Figure 8???
* Can you really call it force output when not truly measuring force ??
* Brush up on butterworth filter
  + Familiar, but not specifics
* Brush up on ANOVA
* Brush up on root mean-squared
* -
* Why did they do this study?
  + Known relationship between feedback and feedforward control, but nature of the relationship is not well understood
* What’s their interpretation of the results?
  + Online and offline movement corrections rely on visuomotor map to determine motor command
* Do I agree with their interpretation?
  + Yes, I think so
  + Why?
    - -
* How do these experiments fit together to answer their broader question?
  + Broader question: What is the relationship between feedforward and feedback control?
    - We know they are linked, but what links them?
  + Hypothesis – Both feedforward and feedback control refer to the visuomotor map to determine movement
    - Visuomotor map = target direction x hand direction
  + If this is true, then if the visuomotor map is changed (via adaptation [aka experiment 1]), then visuomotor map post adaptation should be able to determine the amount of feedback correction [aka experiment 2] and also determine the amount of feedforward correction [aka experiment 3]
* -
* Key take-aways
  + Online and offline corrections use the visuomotor map
* -
* ... as even subtle changes in the kinematics could influence the feedback response (Franklin et al. 2012)
  + Greater deviation after intervention would allow more opportunity for movement correction
* -
* Are the statistical analyses appropriate for the question asked?
  + Yes, wanted to compare pre to post. The question wasn’t about inward v outward, it was how does visuomotor distortion (either inward or outward) effect online and offline movement correction.
* What is the big picture?
  + Online and offline components of implicit adaptation refer to the visuomotor map

# Questions

* Experiment 1,2, and 3 protocol/procedure
  + Intervention (figure 3)
* Butterworth filters
* Force output calculation
  + 2 different calculations
    - Force output (x-component)
    - Force output \* jump size
* Root mean squared calculation
* 4C linear relationship
* Whether cursor movement deviated from the straight path to the target more or less in different groups and periods (root mean squared values of lateral deviation)