Lecture 3

Motor Control and Learning

Baptiste Caramiaux

Outline

1. Human motor control
2. Sensorimotor learning

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1. **Human motor control**
2. Sensorimotor learning

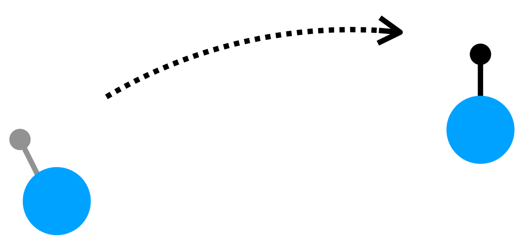
Human motor control

Introductory video of Daniel Wolpert's TED talk

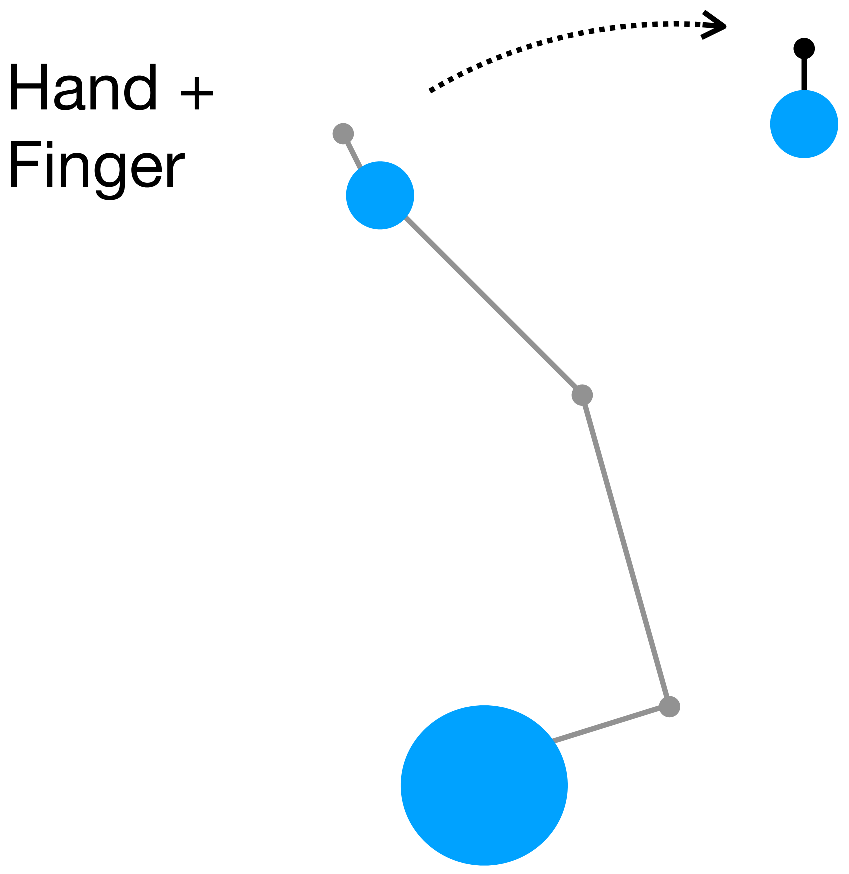
https://www.ted.com/talks/daniel_wolpert_the_real_reason_for_brains?language=fr#t-604428

What does it mean to move the hand?

Hand +
Finger



What does it mean to move the hand?



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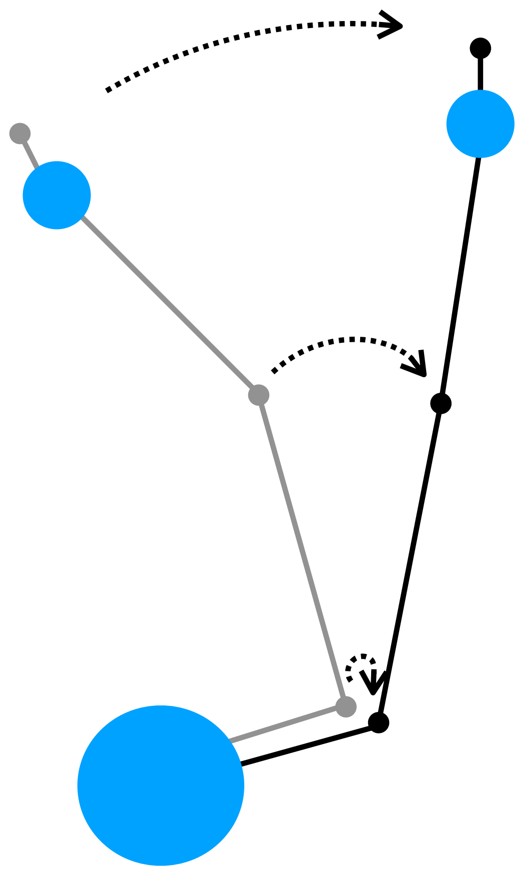
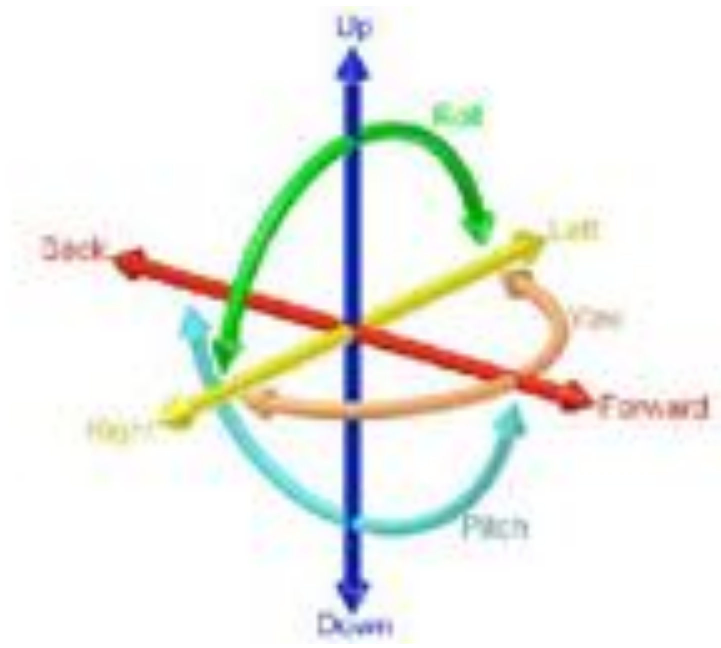


Moving one finger implies the movement of the **whole arm.**

The attention is usually focused on the **goal at end**, not the movement of each limb or joint

Degrees of freedom (DoF)

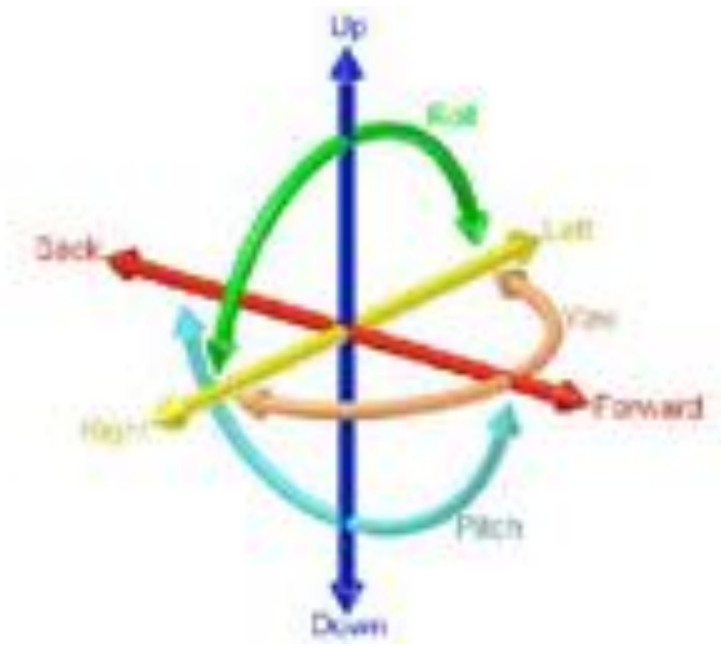
Number of DoF of a system is the number of independent variables that are required to describe the system



Degrees of freedom (DoF)

Number of DoF of a system is the number of independent variables that are required to describe the system

- Joint = 1-3 DoF
- Muscle excitation level = 1 DoF



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How many DoF does the arm have?

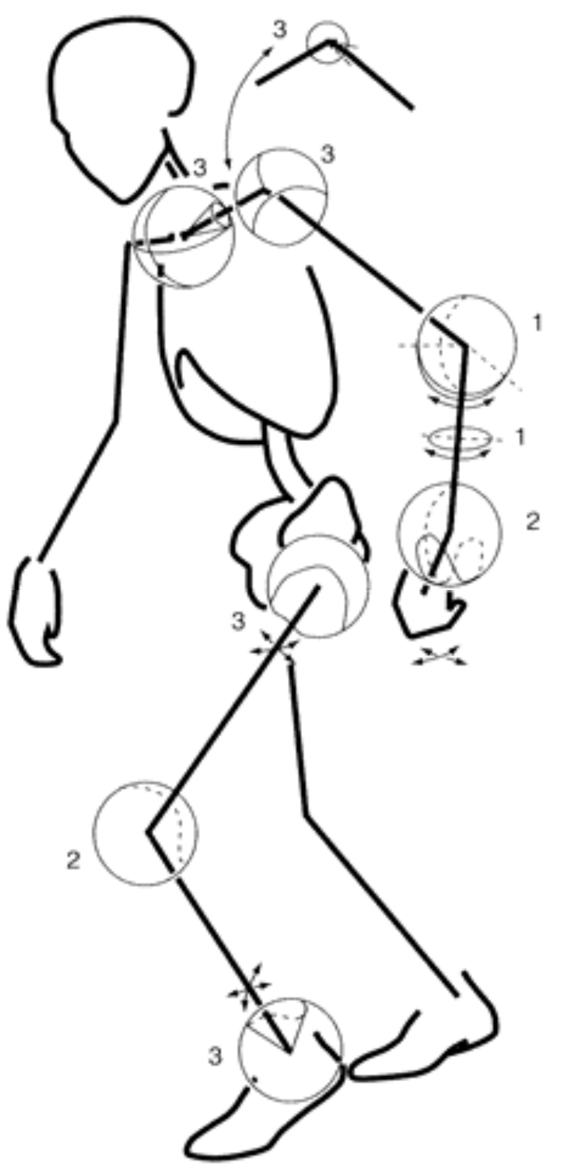
Degrees of freedom (DoF)

Number of DoF of a system is the number of independent variables that are required to describe the system

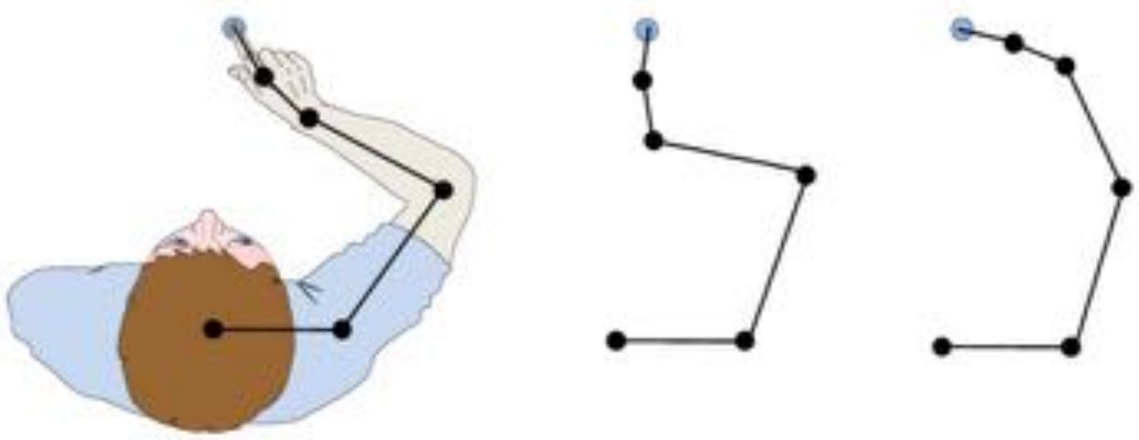
- Joint = 1-3 DoF
- Muscle excitation level = 1 DoF

How many DoF does the arm have?

- Joint level: 7 DoF
- Muscular level: 26 DoF



Redundancy (or abundance)



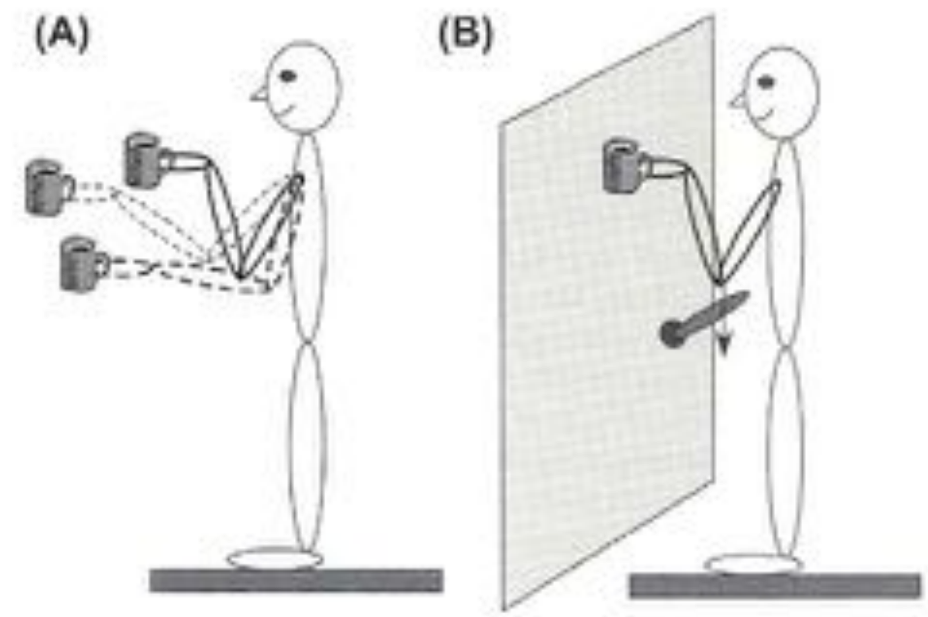
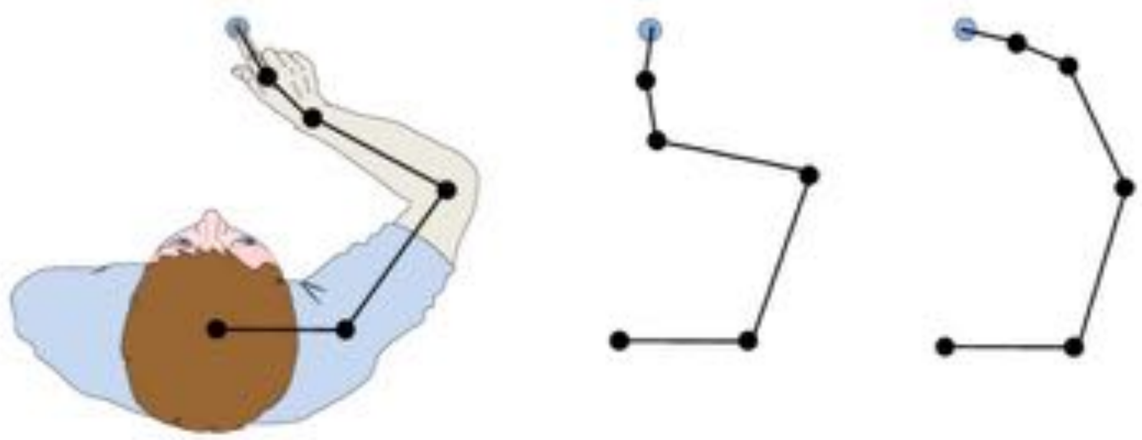


Figure 4.3 A person can carry a mug filled with coffee in the hand using variable joint configurations (three such configurations are shown in panel A). If the person comes to a closed door, he or she can open the door by pressing on the handle with the elbow without spilling the coffee (B).

Redundancy (or abundance)



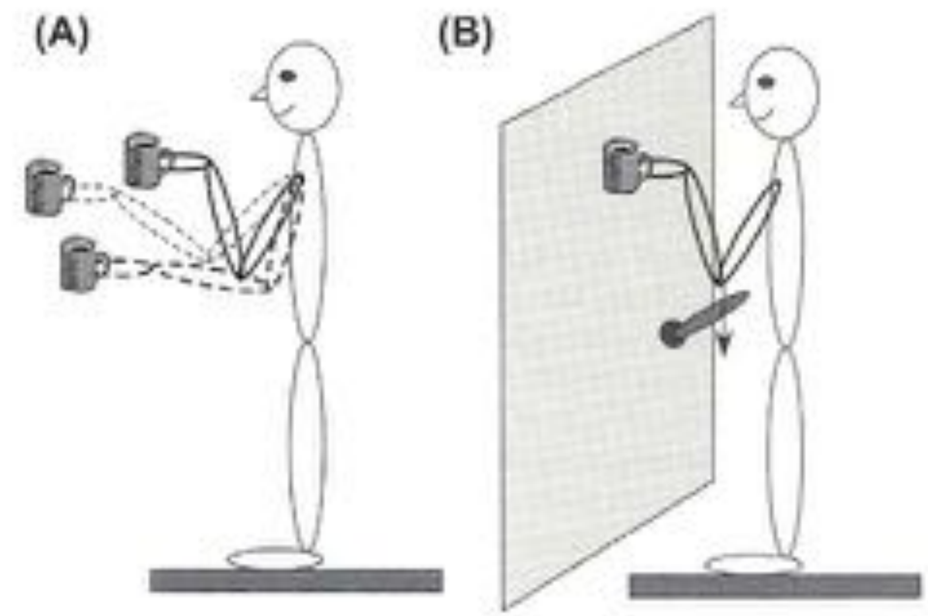


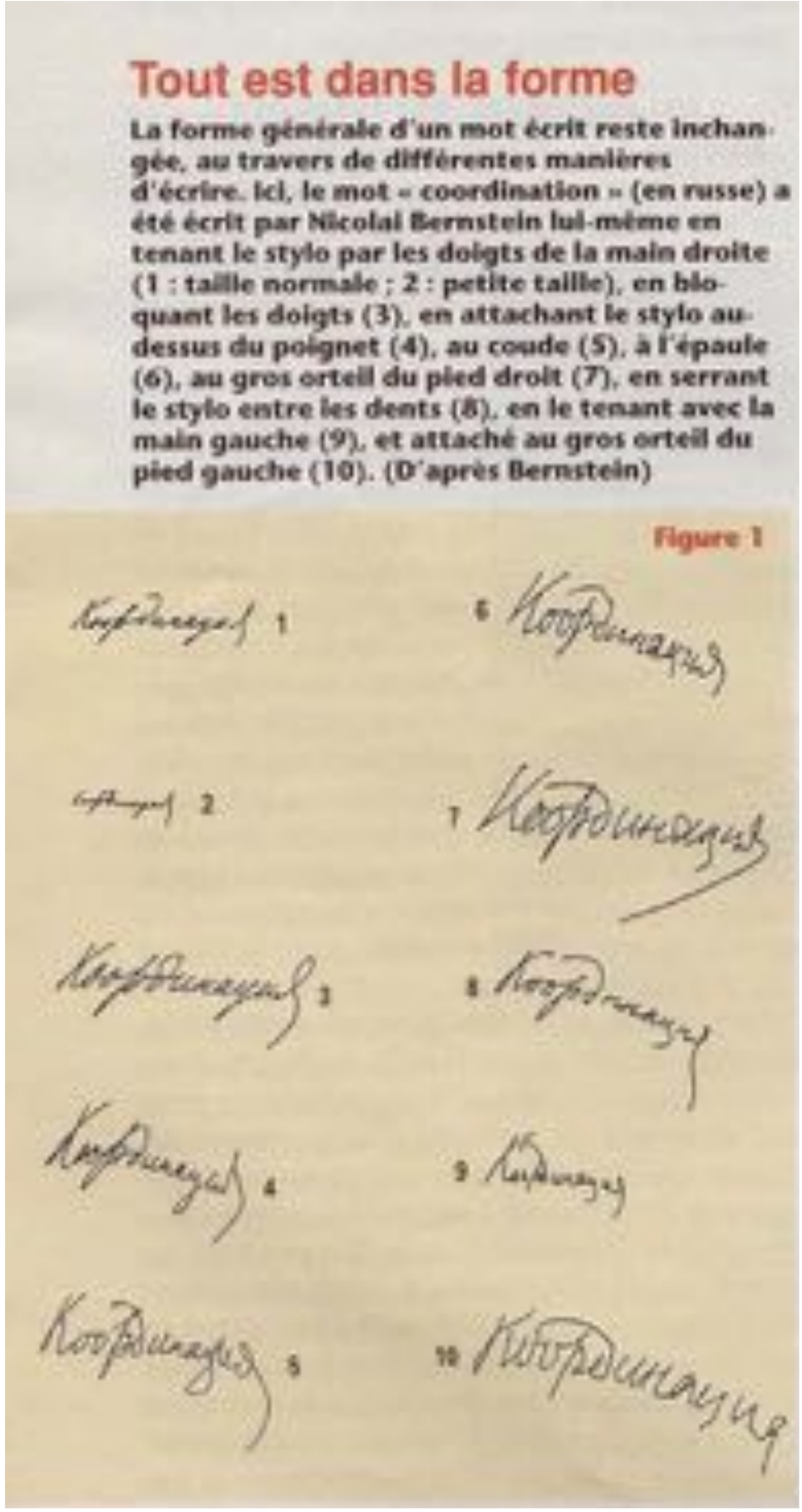
Figure 4.3 A person can carry a mug filled with coffee in the hand using variable joint configurations (three such configurations are shown in panel A). If the person comes to a closed door, he or she can open the door by pressing on the handle with the elbow without spilling the coffee (B).

Redundancy / **abundance** enables adaptability

Adaptability: capacity to adjust/alter motor behavior in new conditions so that the goal is achieved

Motor equivalence

« On désigne par 'équivalence motrice' une propriété simple et remarquable du cerveau : celle qui permet de faire le même mouvement avec des effecteurs très différents. Par exemple, je peux écrire le lettre A avec le main, ou le pied, ou même la bouche ; je peux même dessiner un A en me promenant sur le plage! » (Berthoz, 1996)



Motor equivalence

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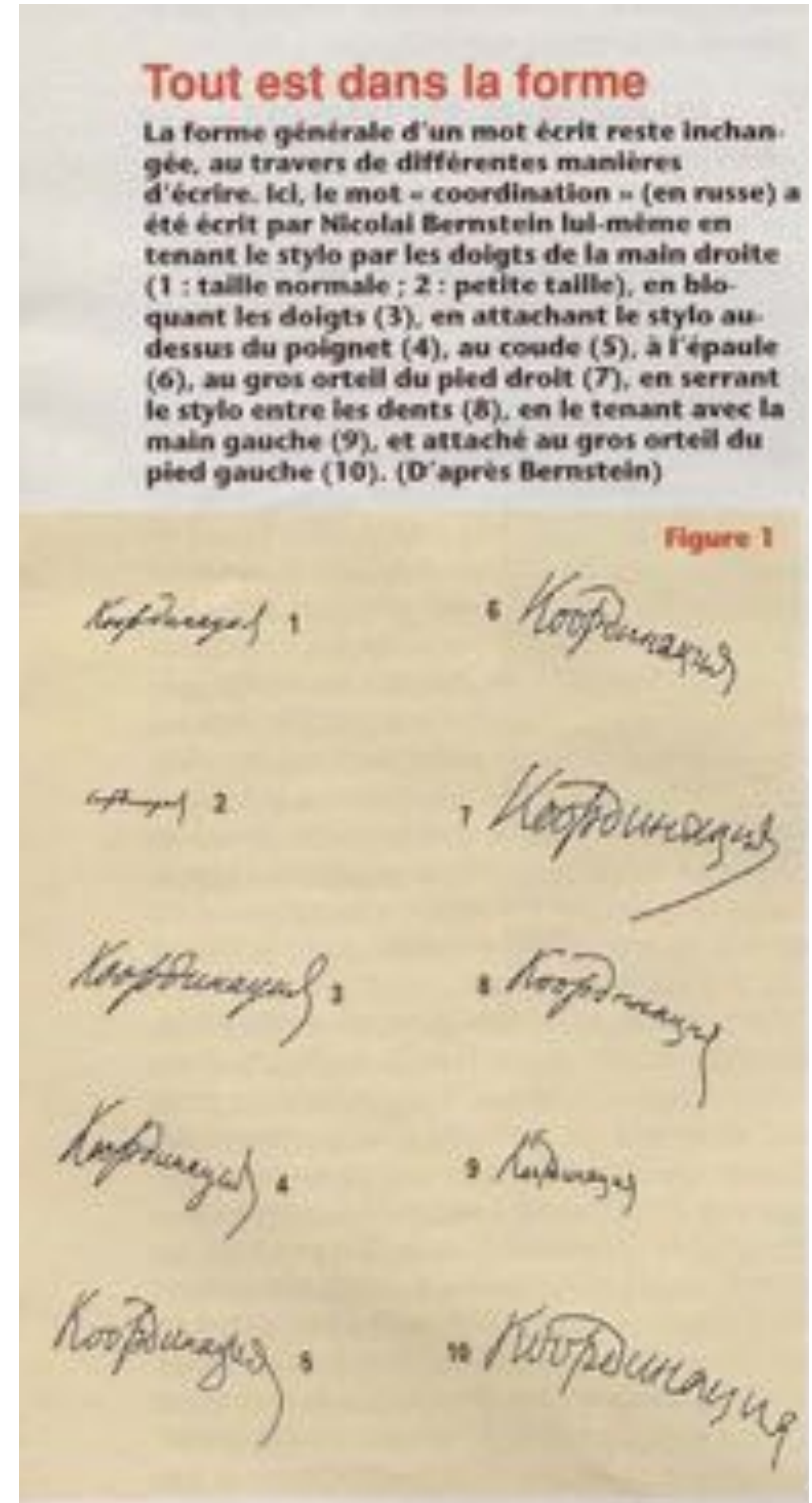
Actions are therefore encoded in the CNS in terms that are more abstract than commands to specific muscles.



Tout est dans la forme

La forme générale d'un mot écrit reste inchangée, au travers de différentes manières d'écrire. Ici, le mot « coordination » (en russe) a été écrit par Nicolai Bernstein lui-même en tenant le stylo par les doigts de la main droite (1 : taille normale ; 2 : petite taille), en bloquant les doigts (3), en attachant le stylo au-dessus du poignet (4), au coude (5), à l'épaule (6), au gros orteil du pied droit (7), en serrant le stylo entre les dents (8), en le tenant avec la main gauche (9), et attaché au gros orteil du pied gauche (10). (D'après Bernstein)

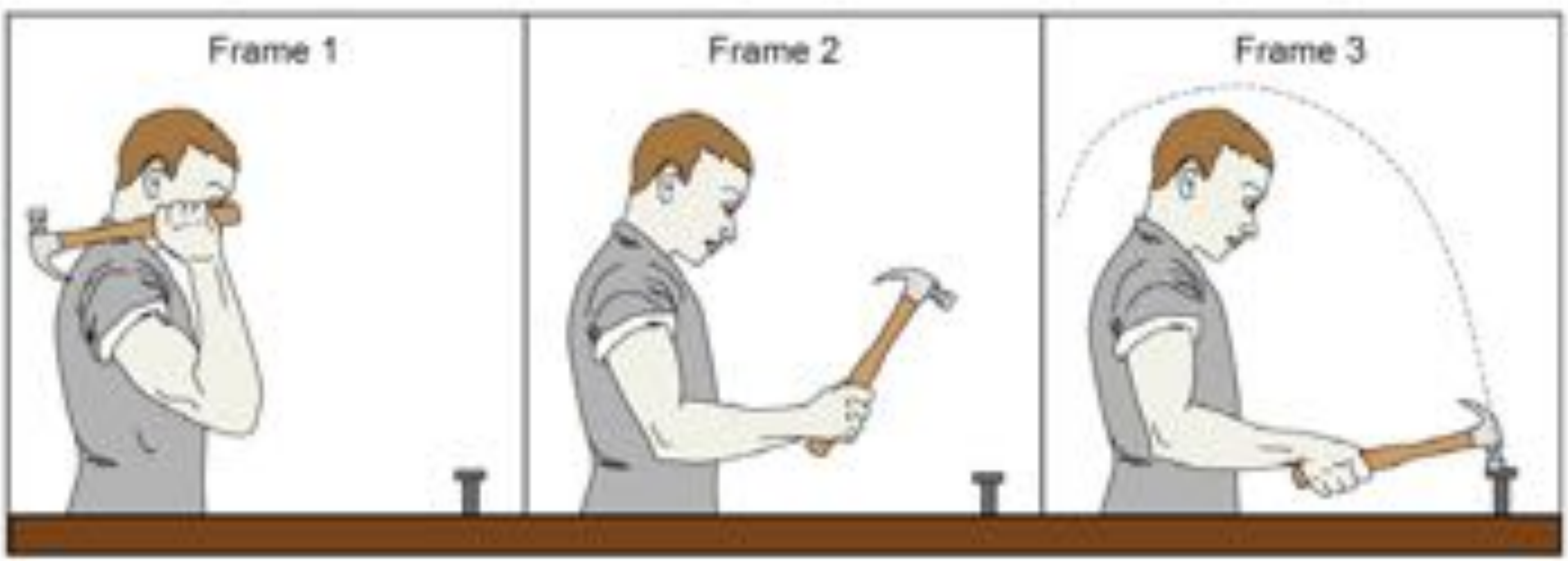
Figure 1

Bernstein's first experiments

https://www.youtube.com/watch?v=yDxPJlBqWuM

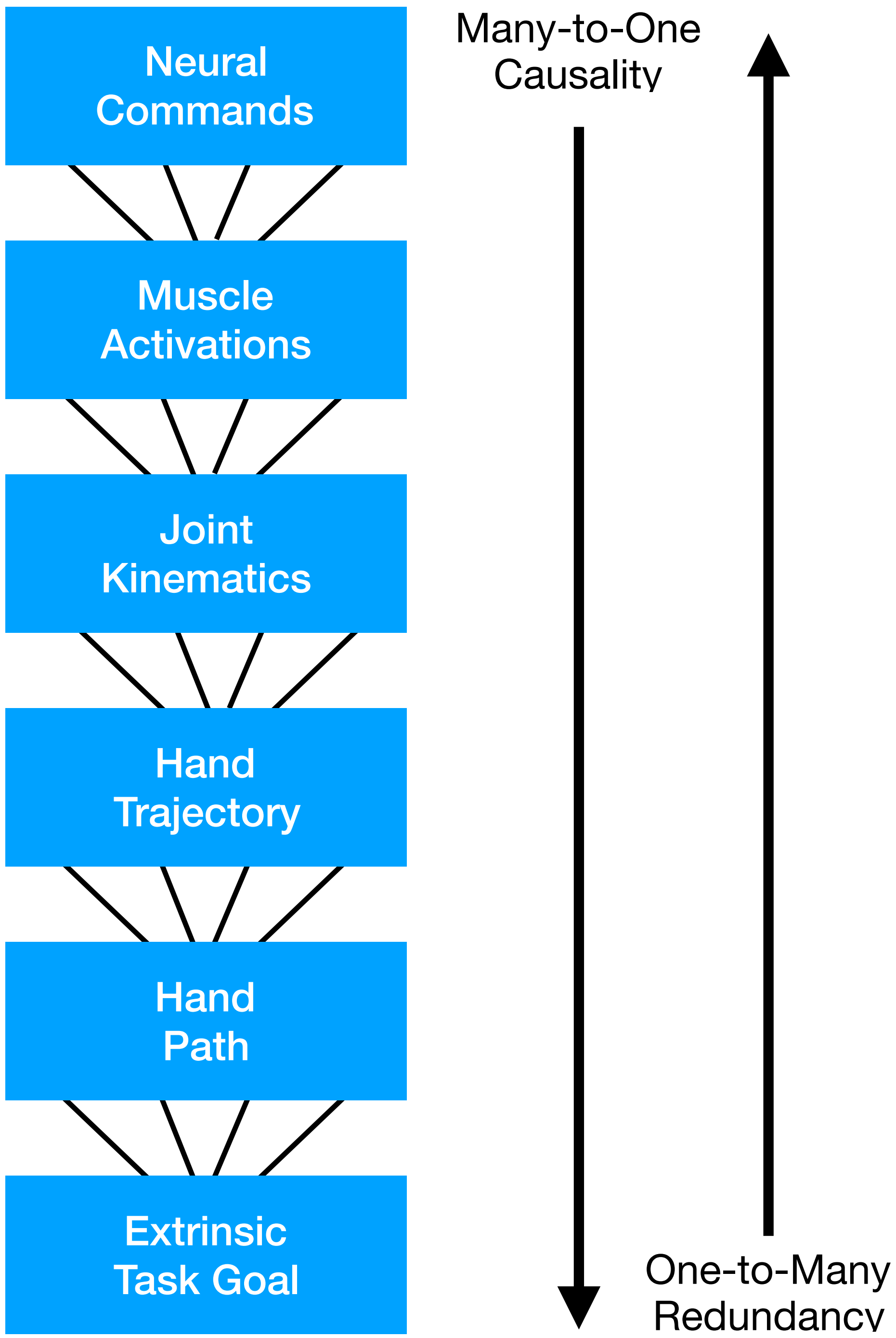
Motor equivalence

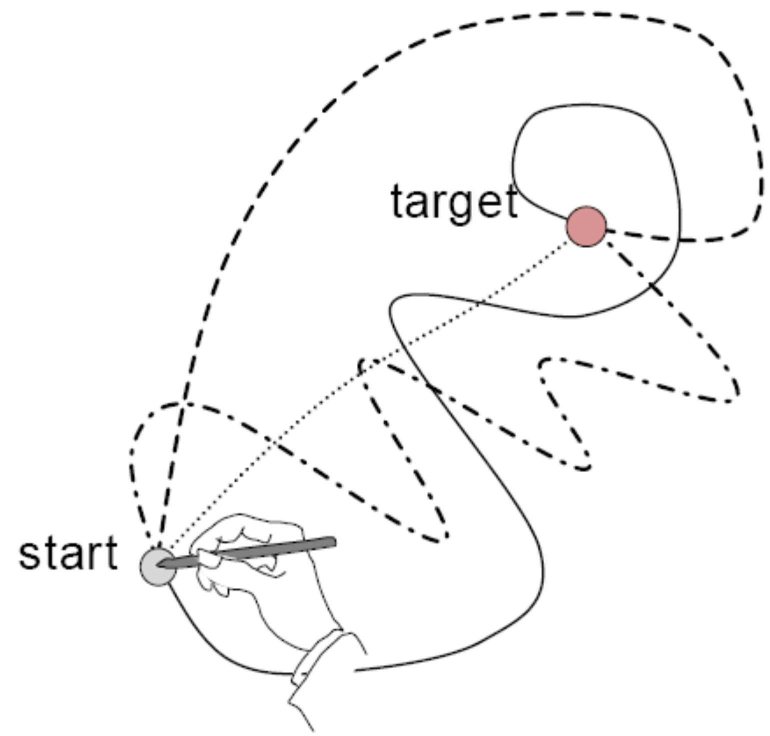
Person striking a nail: The hammer trajectory is similar from one trial to another



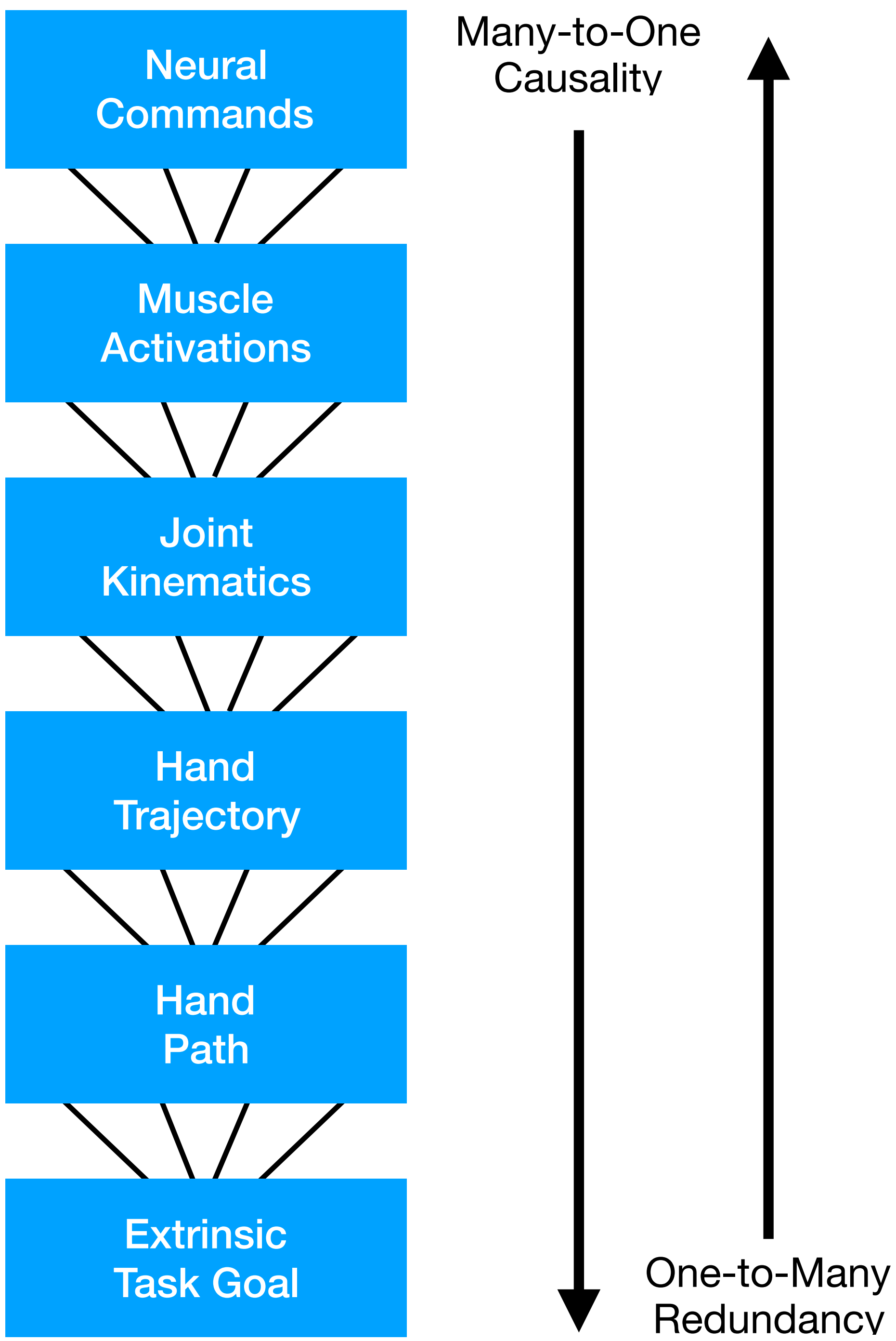
More variability at joint level than at hammer level.

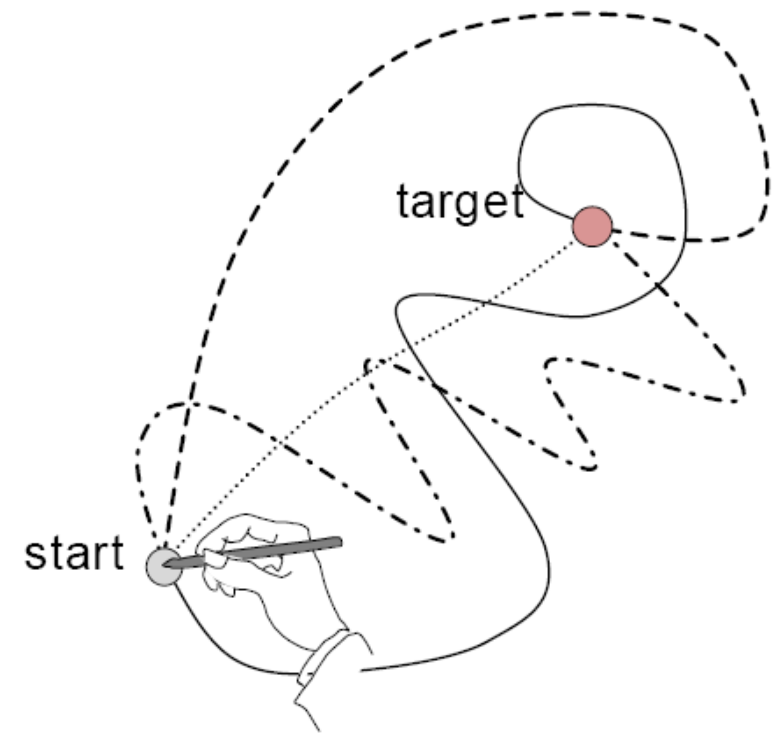
How does the brain solve the DoF problem?





How does the brain solve the DoF problem?





Adding some neural constraints

Examples of kinematic constraints:

- **Fitts' law**
- **2/3 power law**

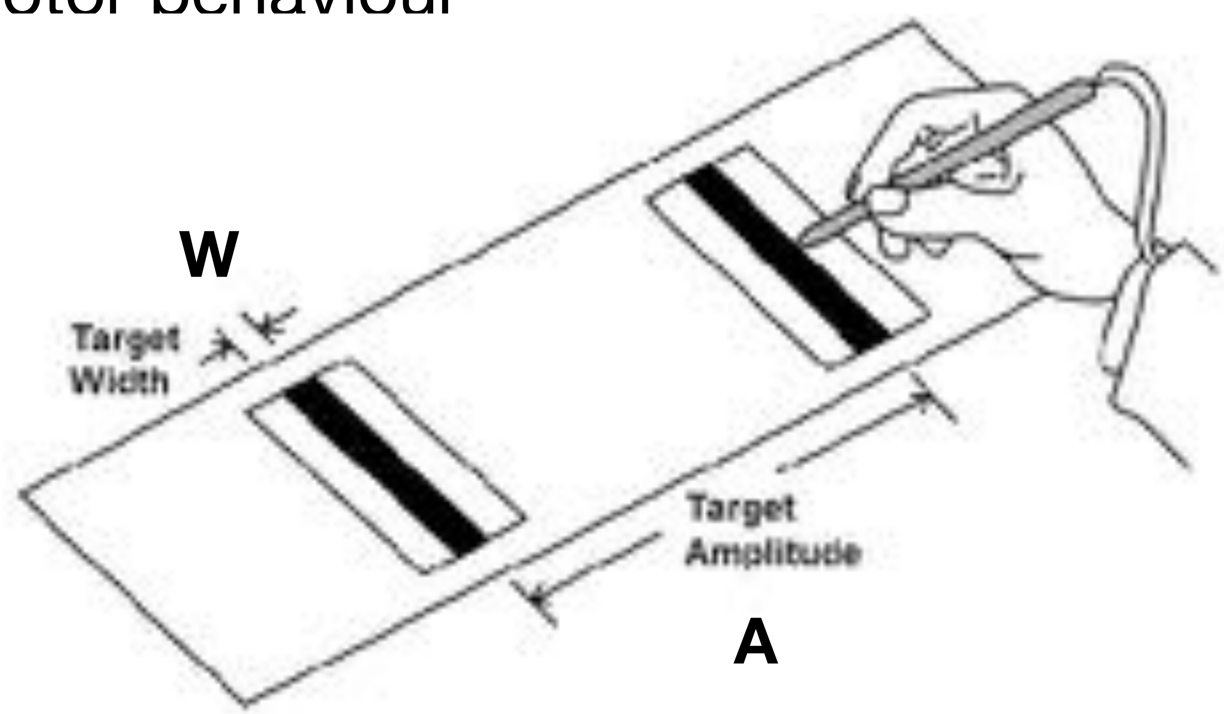
Fitts' law

Fitts' law: speed-accuracy trade-off in situations where the goal is to move as quickly as possible to reach or touch a target, with the minimal amount of error.

(Fitts 1954): landmark publication in motor behaviour

Study procedure:

- Moving alternatively between two targets
- Width of the targets (W) and amplitude (A) of the movement are manipulated

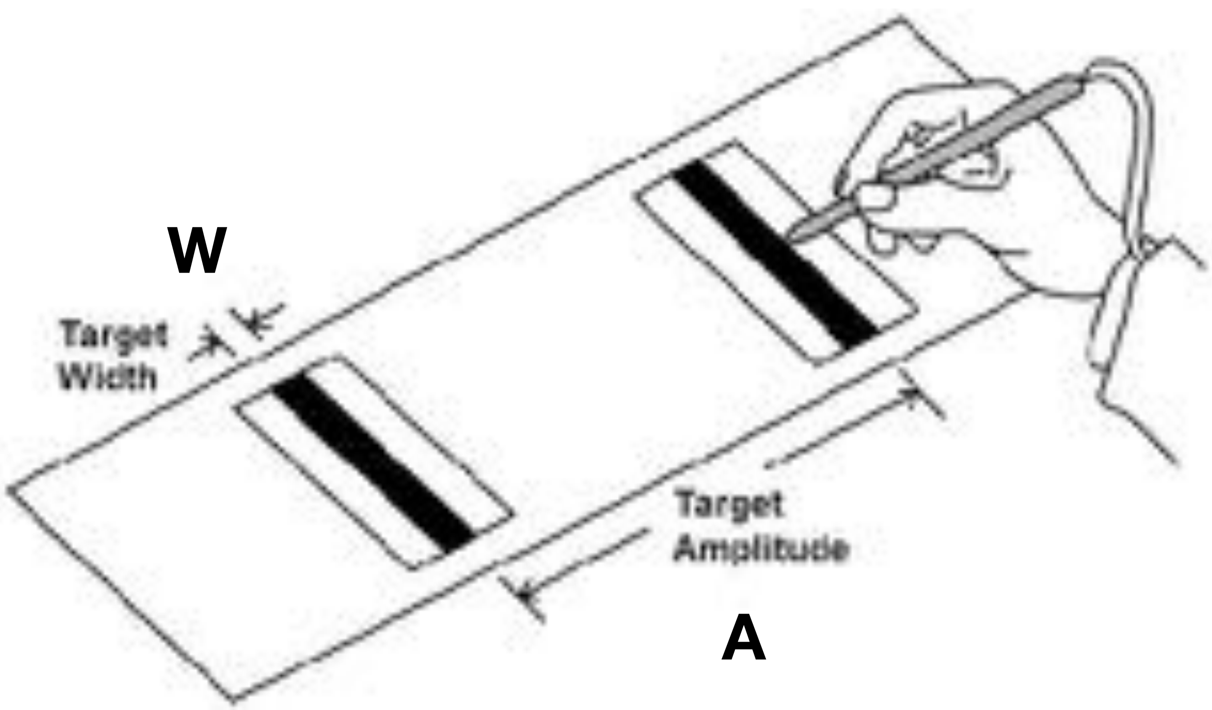


Fitts (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47, 381-391.

Fitts' law

The relationship between the amplitude (A), the target width (W) and the average movement time between 2 taps (MT) is:

$$MT = a + b\log_2(2A/W)$$



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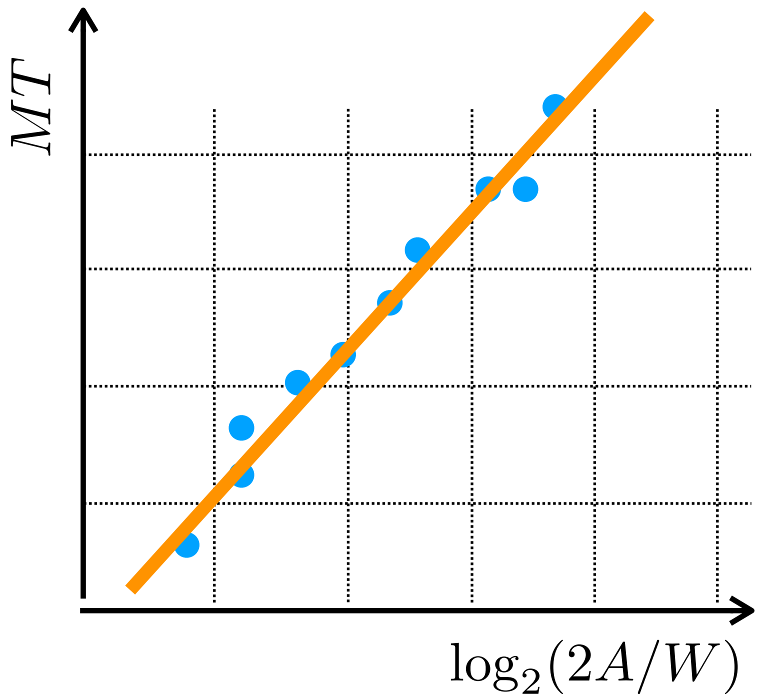


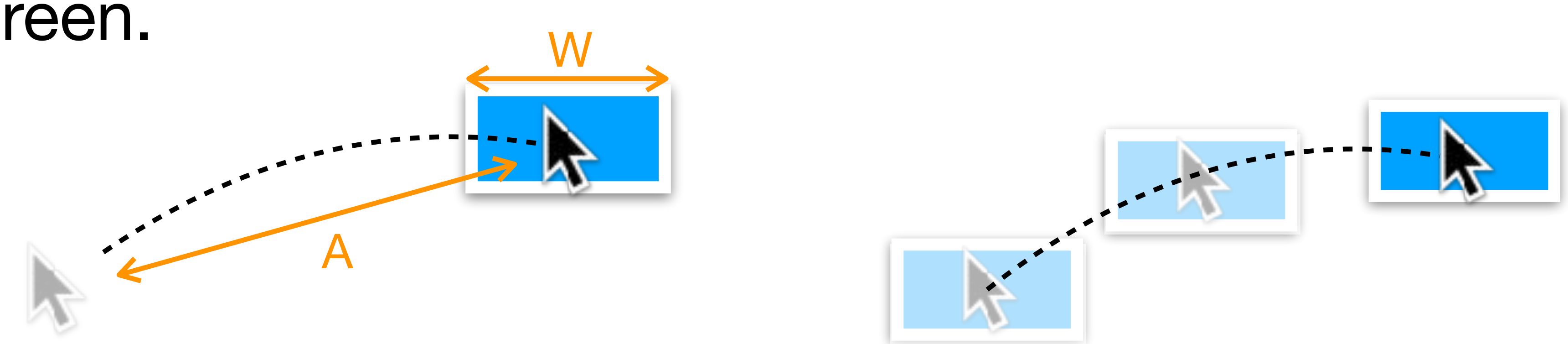
$\log_2(2A/W)$: Index of difficulty

a, b : Empirical constants

Fitts (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47, 381-391.

Applications in HCI

Can model the action of **pointing** and **dragging** elements (such as icons) on a screen.



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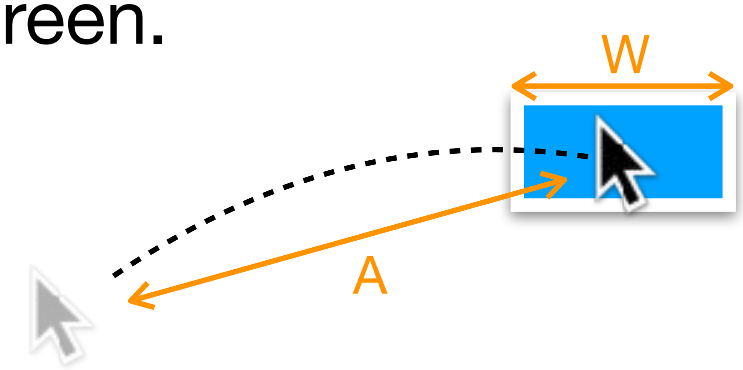
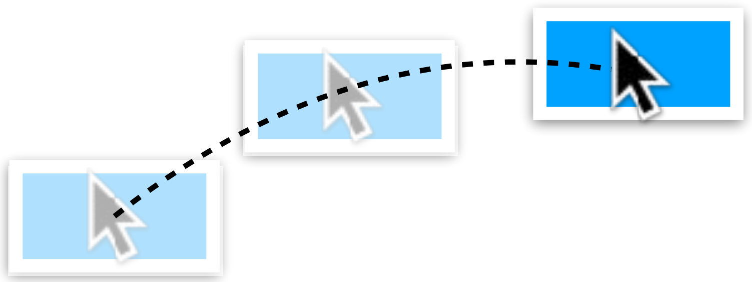
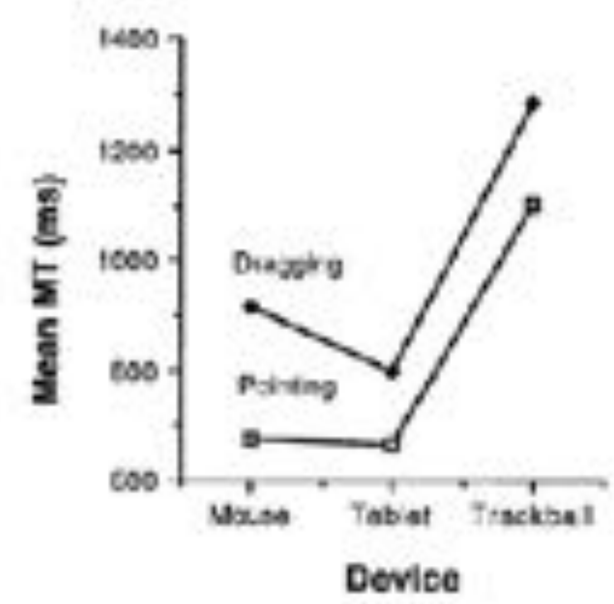




Application: comparing input devices
(MacKenzie et al. 1991)



MacKenzie, S.I., Sellen, A. And Buxton, W. A comparison of input devices in elemental posting and dragging tasks. *CHI'91*

2/3 power law

2/3 power law: the relationship between the movement kinematics and the movement geometry

Lacquaniti, F., Terzuolo, C. A., & Viviani, P. (1983). The law relating kinematic and figural aspects of drawing movements. *Acta Psychologica*, 54, 115-130.

Viviani, P. And Flash, T. (1995). Minimum-Jerk, Two-Thirds Power Law, and Isochrony: Converging Approaches to Movement Planning. *Journal of Experimental Psychology*, 21(1), 32-53

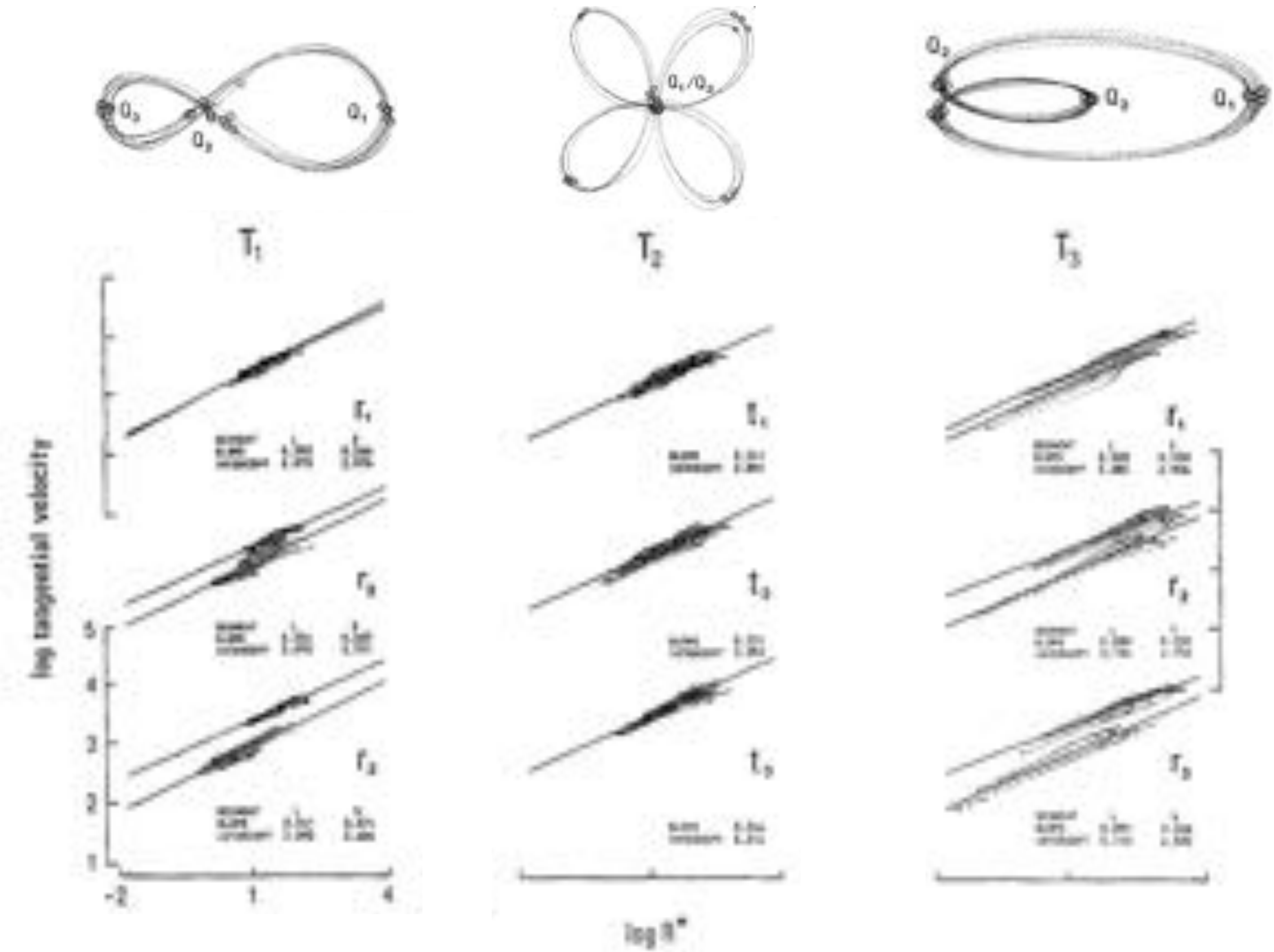
2/3 power law

The angular velocity is proportional to the 2/3 power of the curvature:

$$A(t) = kC(t)^{2/3}$$

Where: A=V/R is the angular velocity, C=1/R is the curvature, R being the radius of curvature. So the law can be written:

$$V(t) = kR(t)^{1/3}$$



Viviani, P. And Flash, T. (1995). Minimum-Jerk, Two-Thirds Power Law, and Isochrony: Converging Approaches to Movement Planning. *Journal of Experimental Psychology*, 21(1), 32-53

Video example

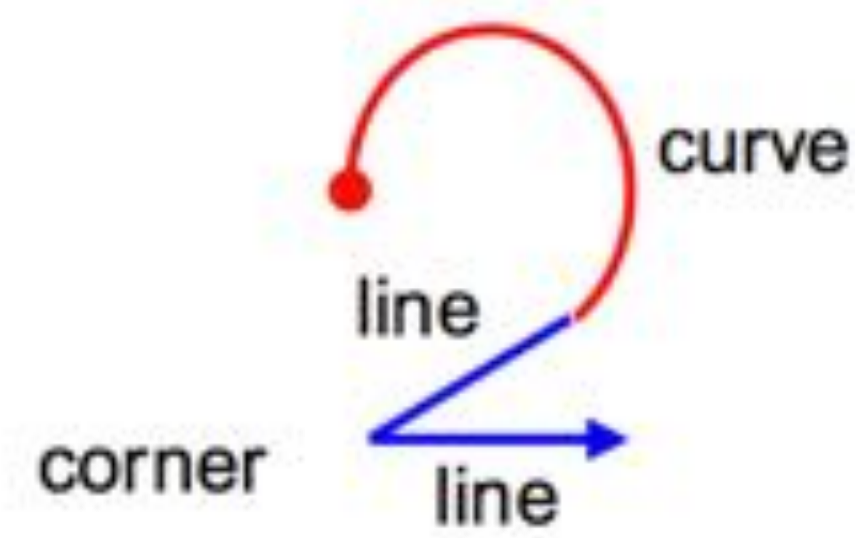
Production and perception: Tamar Flash's MIT talk (8'17)

http://mcgovern.mit.edu/news/videos/tamar-flash-2013-mcgovern-institute-symposium

Applications to HCI

CLC model by Cat & Zhai 2007 (see Lecture 2)

$$T = \sum T(\text{line}) + \sum T(\text{corner}) + \sum T(\text{curve}).$$



The production time of the smooth curve is computed from Viviani's power law:

$$T = \frac{1}{k} \int_0^L R^{-1/3}$$

Cao, X., Zhai, S. Modeling Human Performance of Pen Stroke Gestures. *CHI'07*

How does motor control is achieved?

Sensory-based regulation of movements

- Closed-loop control system

Central regulation of movements

- Open-loop control system

Closed-loop control

Reference mechanisms: specific aim

System samples the environment (feedback)

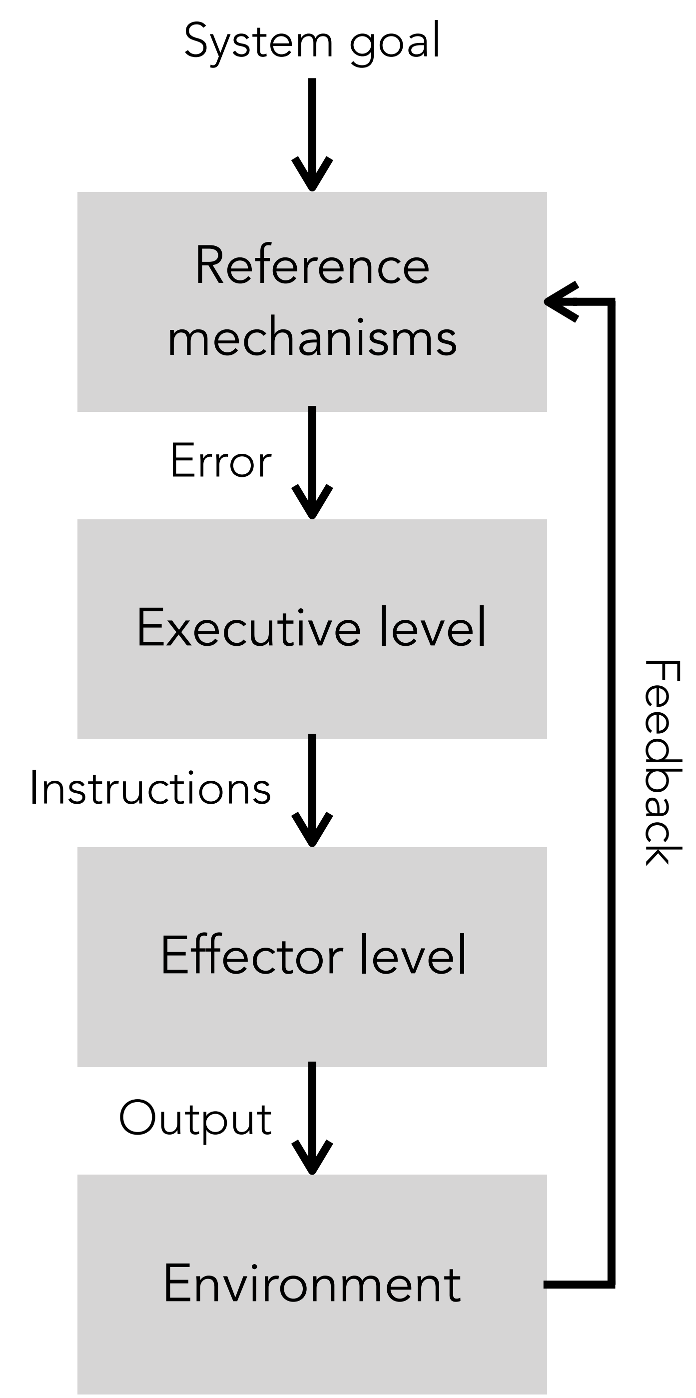
Comparison between goal and feedback

Error is passed through the executive level, making decisions

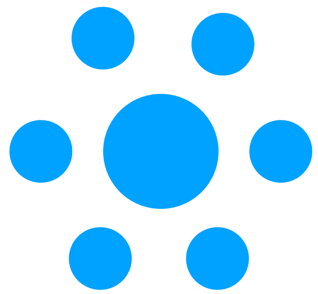
If error large enough, instructions are sent

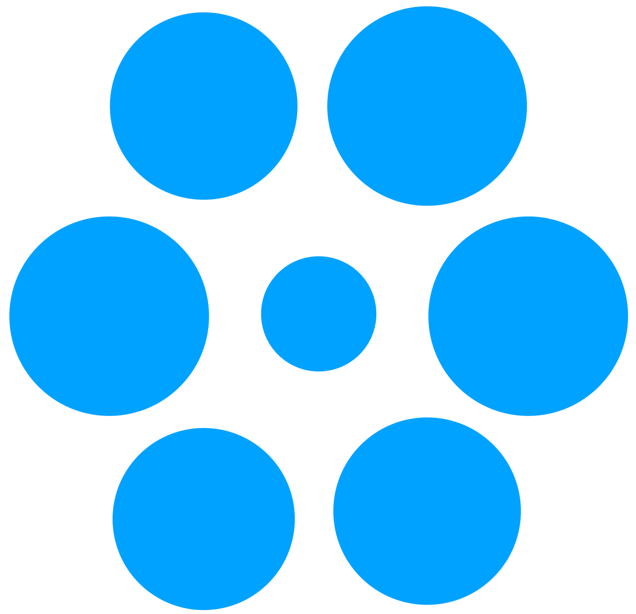
Effective actions are then taken

=> Using **receptors**: eye, ear, proprioceptors…



Is perception driving production?





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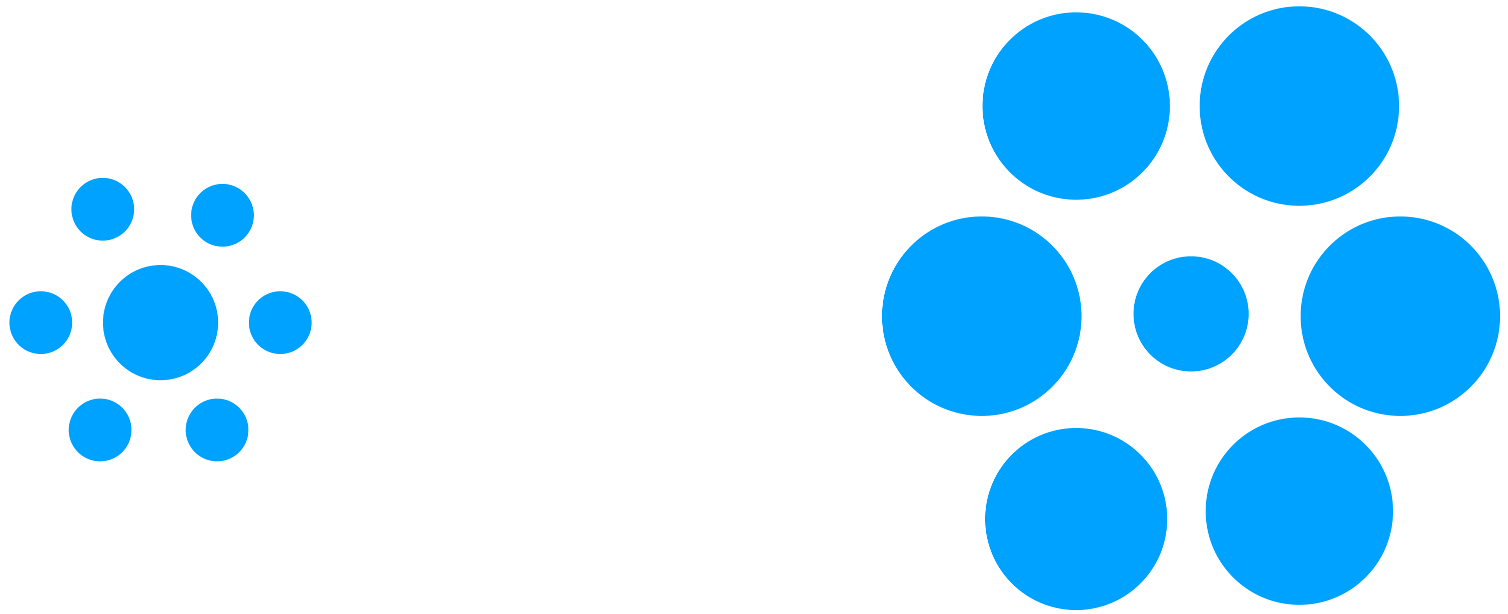


Task: pointing at the central circle

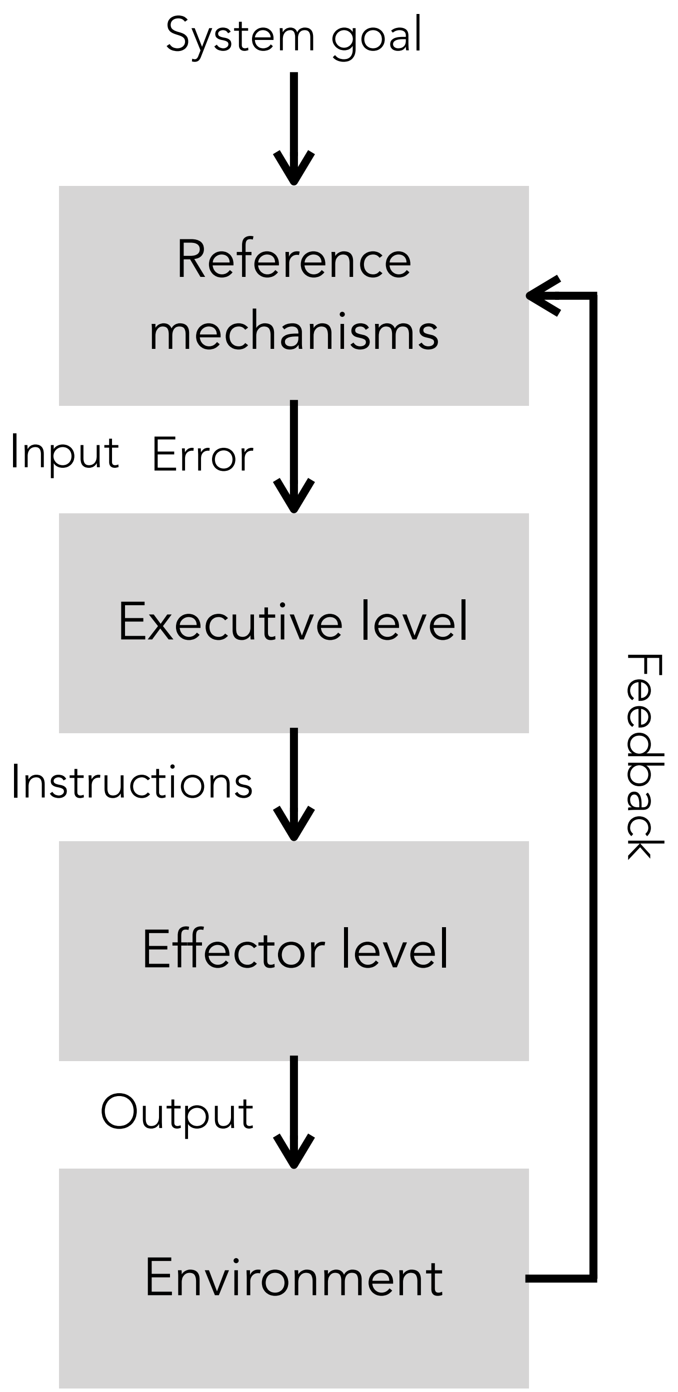
Expected result: movement time decreases if circle bigger (although perceived, Fitts' law: $MT = a + b\log_2(2A/W)$)

Actual result: **no difference** in MT!

Is perception driving production?

Caramiaux, B., Bevilacqua, F., and Schnell, N.(2010). Towards a gesture-sound cross-modal analysis. *Gesture in Embodied Communication and Human-Computer Interaction*, 158-170

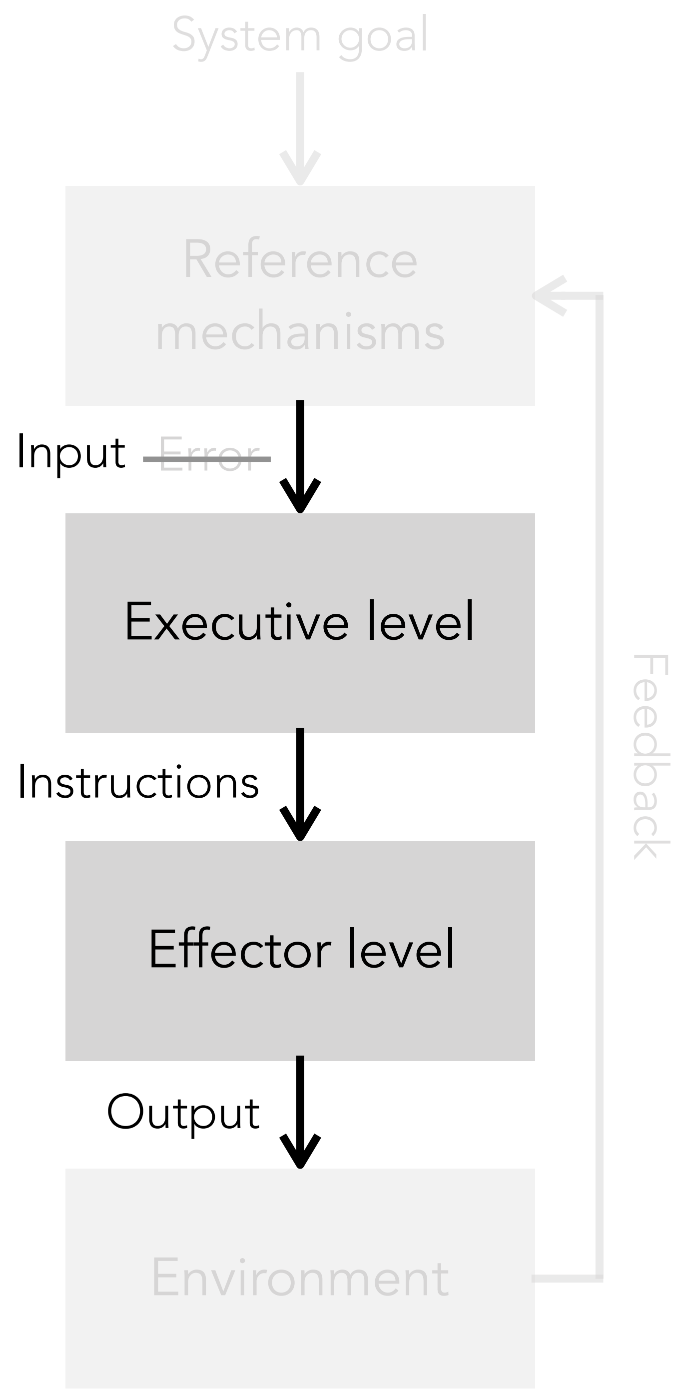
Open-loop control



Open-loop control

Obey to some movement programs

No immediate modification of such programs (no feedback)



Rapid movements

Art Tatum

Rapid movements

Rapid movements: action initiated and completed in less than 150ms

Processing sensory information in closed-loop system is too slow for such movements

Degree of freedom problem

Other strategies, such as motor program (Schmidt, 1975)

Schmidt, R.A. (1975). A schema theory of discrete motor skill learning. *Psychological Review*, 82, 225-260

Outline

1. Human motor control
2. **Sensorimotor learning**

Motor learning

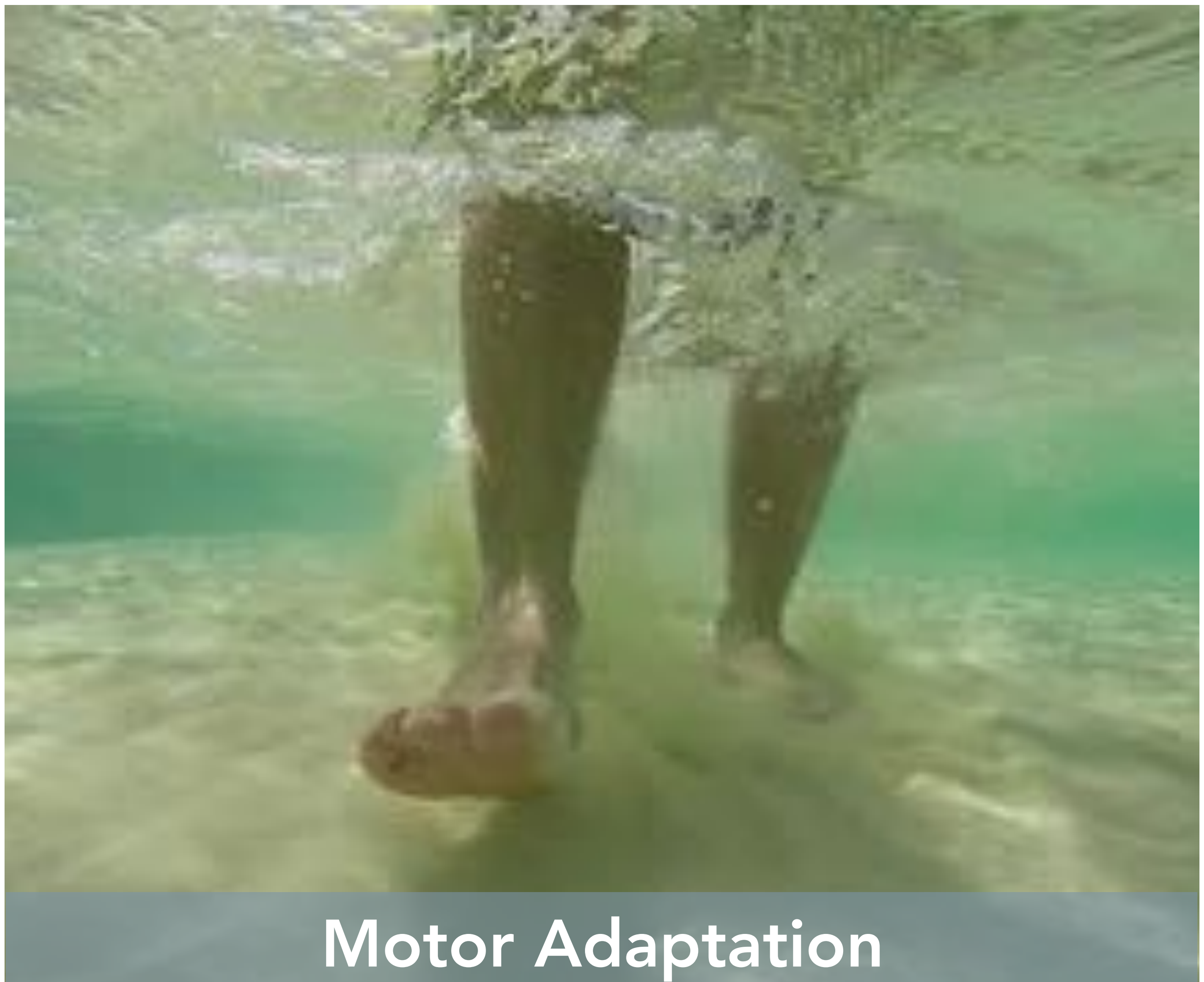
Motor control is interested in **processes** that make **skilled performance** possible.

Motor learning is interested in changes in skill as a results of **practice** or **experience**.

Definition

- Motor learning is a set of processes associated with the practice or experience leading to relatively permanent changes in the capability for skilled movement.
(Schmidt, Lee. *Motor control and learning: A behavioural emphasis*. Champaign IL, Human Kinetics. 2006)

Forms of learning



Motor Adaptation

Motor Skill Acquisition

Motor adaptation

Obligatory mechanism from a single trial
(Srimal et al., J. Neurophysiol. 2008)

Motivational feedback influences motor adaptation
(Galea et al., Nature Neuroscience 2015)

Skill acquisition

Improvements in accuracy or speed in a wide variety of tasks

(Diedrichsen et al., 2015)

Elements of reinforcement learning

Linked to decision making

The backwards brain bicycle

https://www.youtube.com/watch?v=MFzDaBzBIL0

Relevance for gesture-based interaction

Focus on skill acquisition

- Gesture-based interaction is usually interested in relying on user's existing skills (handwritting, drawing, etc…)
- Facilitate quick acquisition of simple skills to be used in UI
- Foster extended learning for novice to expert transition

Law of practice

"Law of practice": More practice leads to more learning!

Law of practice

"Law of practice": More practice leads to more learning!

Practice and measures of performance tend to follow a logarithmic function

Newell, K.M., and Rosenbloom, P.S. (1981). Mechanisms of skill acquisition and the law of practice. *Cognitive skills and their acquisition*.

Law of practice

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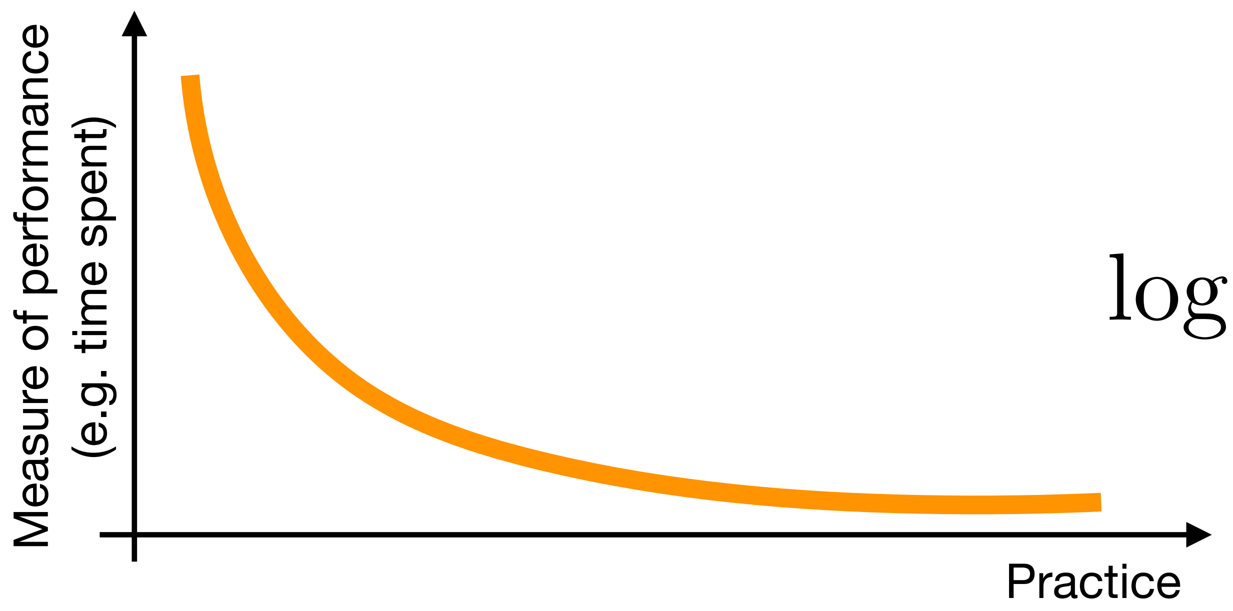


$$T = aP^{-b}$$

$$\log(T) = \log(a) + -b\log(P)$$

Newell, K.M., and Rosenbloom, P.S. (1981). Mechanisms of skill acquisition and the law of practice. *Cognitive skills and their acquisition*.

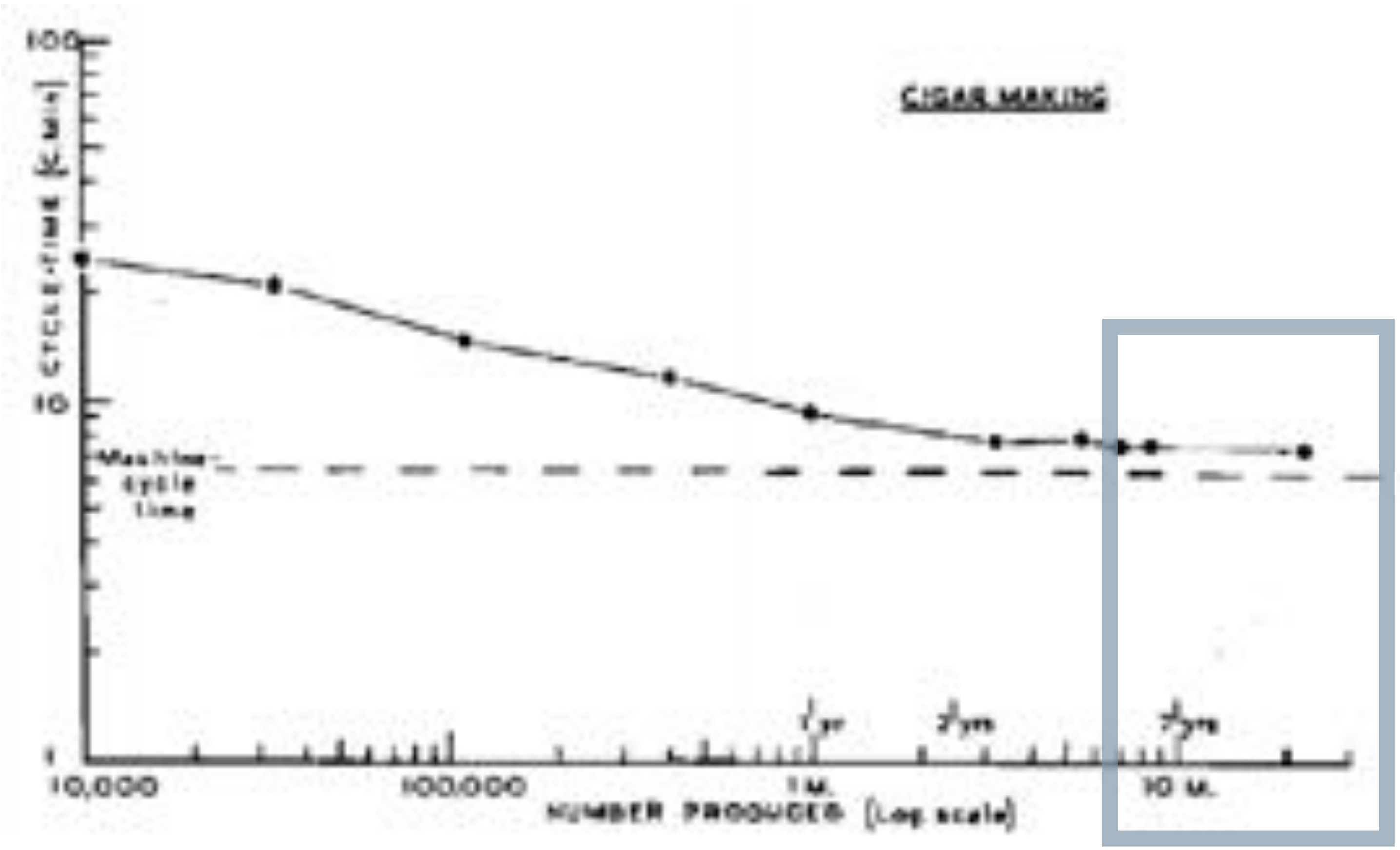
Can learning be completed?

Not really…

Can learning be completed?

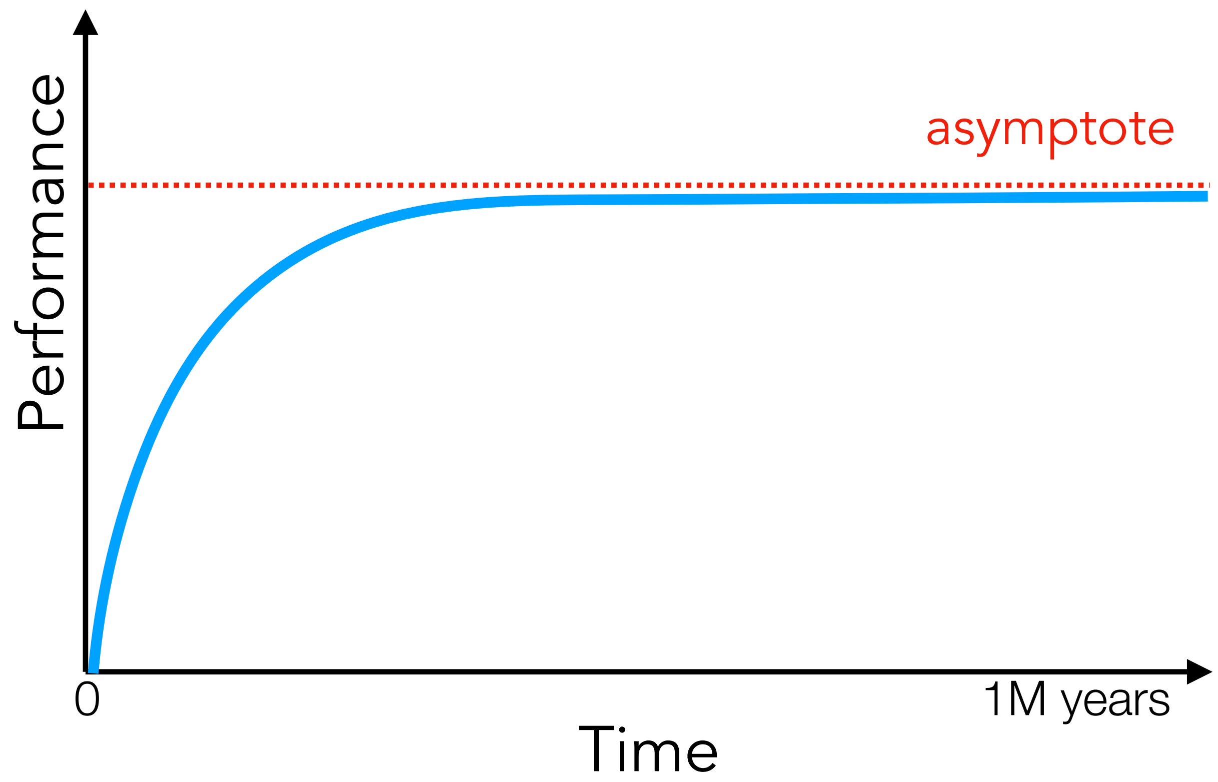
Not really…

Example: cigar rolling with a hand-operated jig (Crossman, 1959)

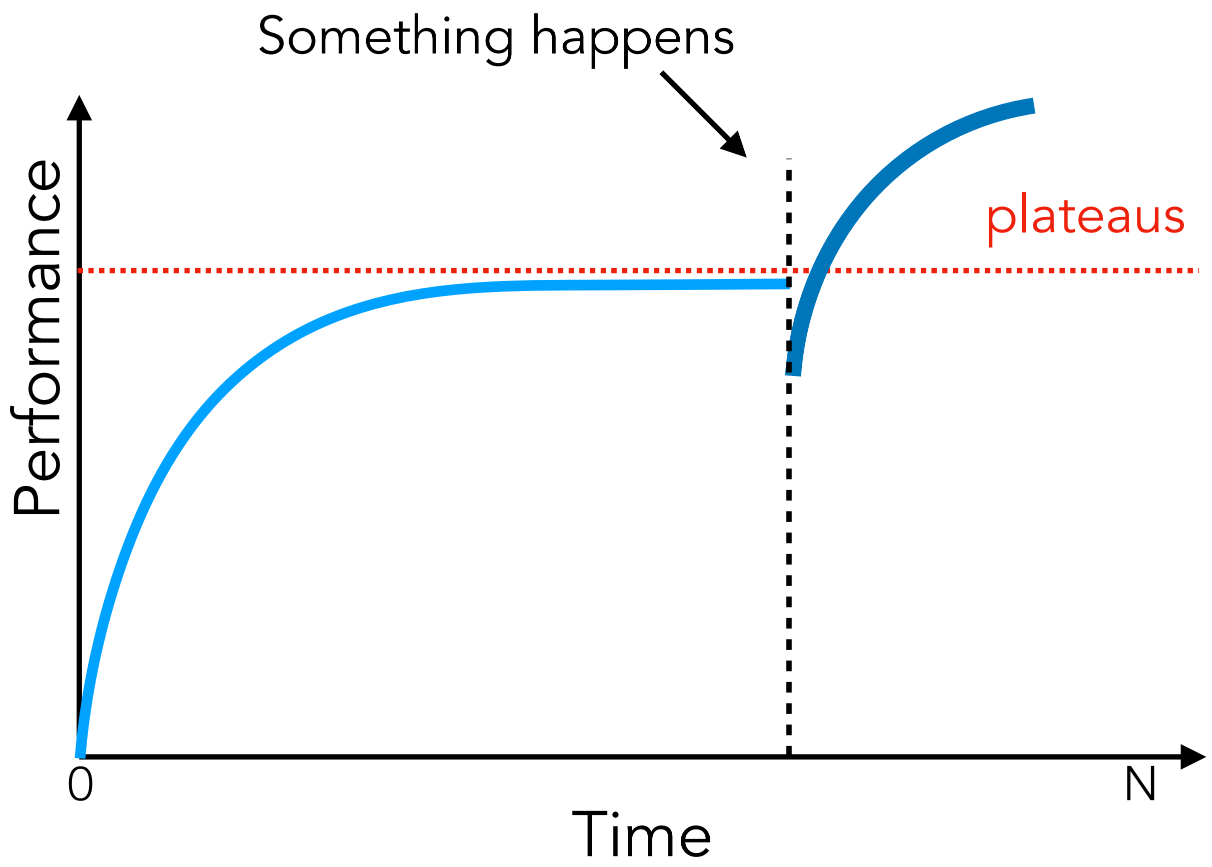


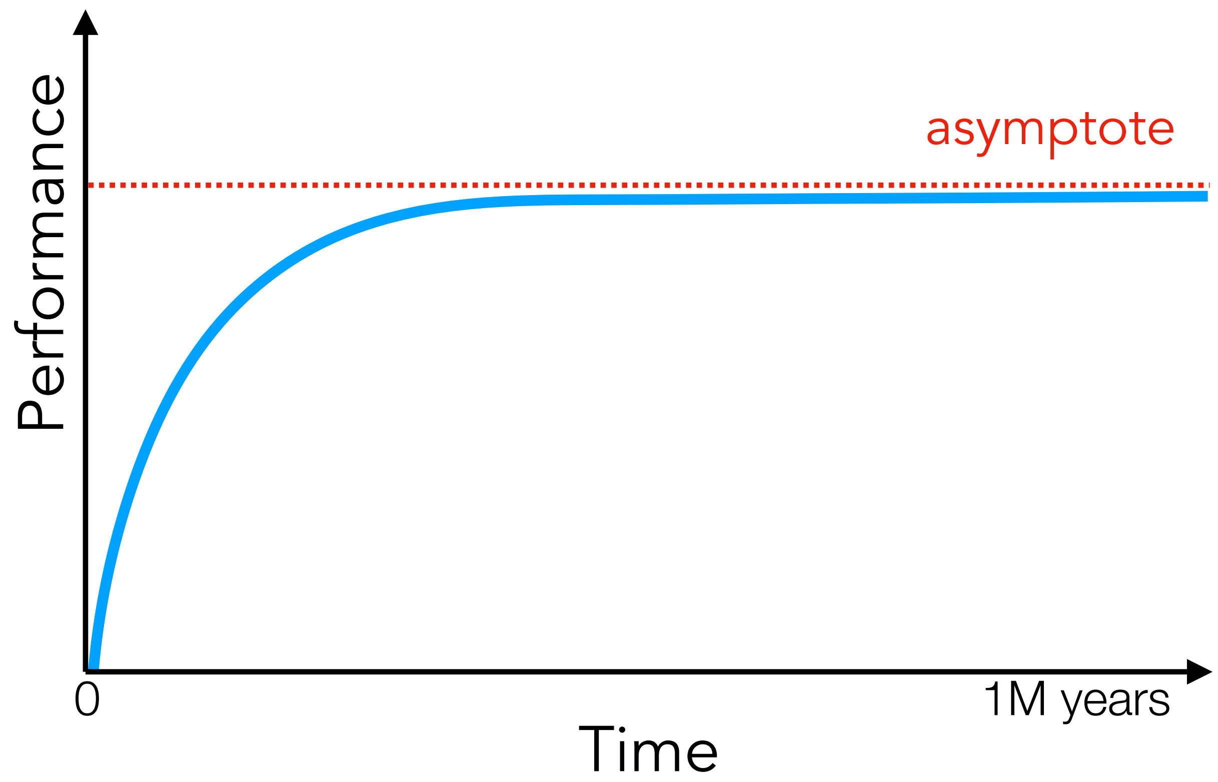
Crossman, E.R.F.W. (1959). A theory of the acquisition of speed-skill. *Ergonomics*, 2:2, 153-166

Plateaus vs. Asymptotes



Plateaus vs. Asymptotes

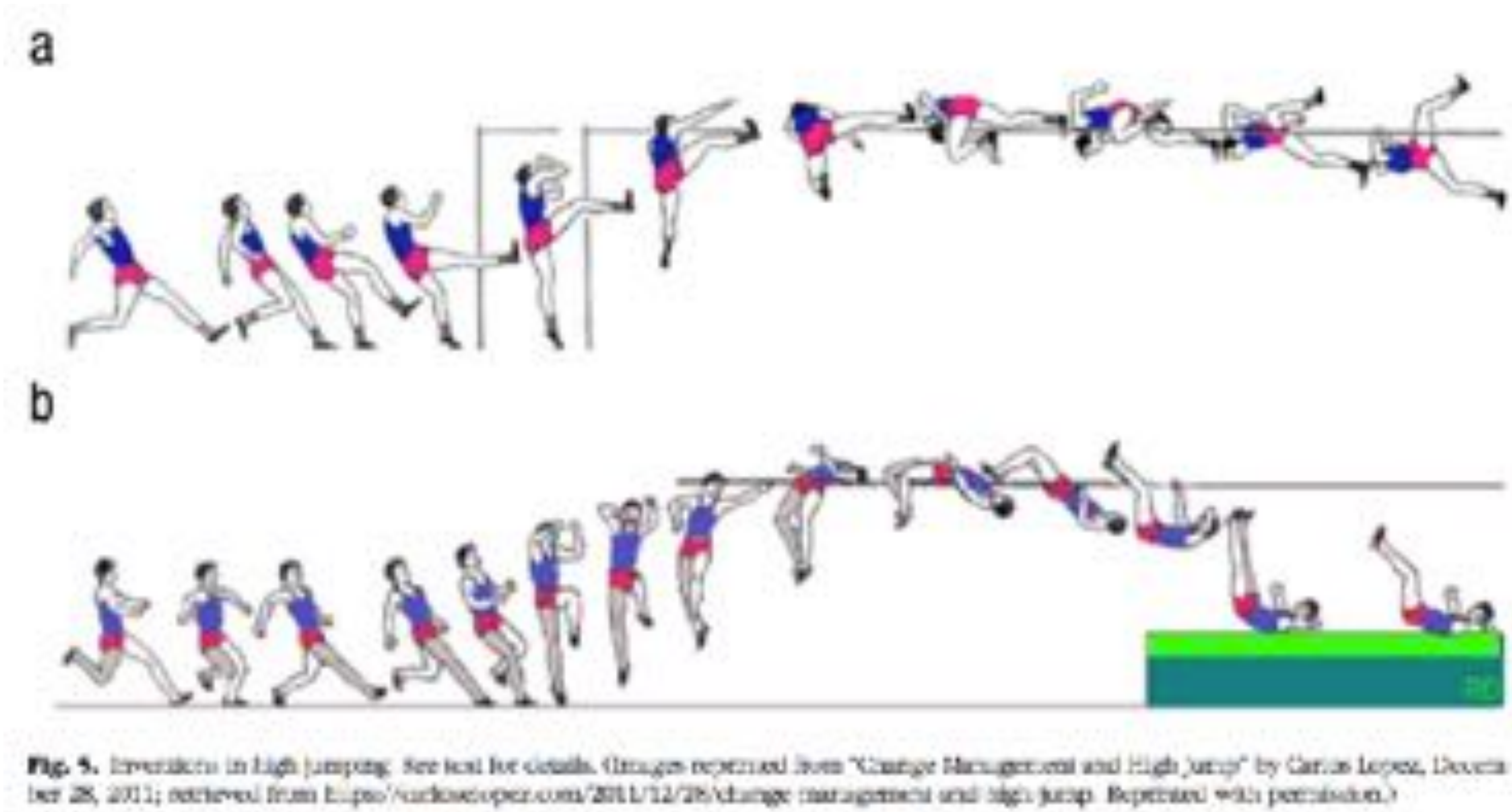




Plateaus vs. Asymptotes: example

Gray, W. (2017). Plateaus and Asymptotes: Spurious and Real Limits in Human Performance. *Current Directions in Psychological Science*, 26 (1), pp. 59-67

Plateaus vs. Asymptotes: example



Record
Increased
by 10cm

Gray, W. (2017). Plateaus and Asymptotes: Spurious and Real Limits in Human Performance. *Current Directions in Psychological Science*, 26 (1), pp. 59-67

Deliberate practice

Practice can have different meanings

Deliberate practice can be defined as:

- “activities that have been specially designed to improve the current level of performance […]. Deliberate practice requires effort and is to inherently enjoyable. Individuals are motivated to practice because practice improves performance.” (Ericsson et al. 1993)

Deliberate practice can be “on the task” or “off the task”

Ericsson, K.A., Krampe, R.Th., and Tesch-Römer, C. (1993). The role of deliberate practice in the acquisition of expert performance. *Psychological Review*, 100, 363-406

Exercice

“Off-task” practice considerations?

“On-task” practice considerations?

“Off-task” practice considerations?

- Motivation
- Verbal information
- Perceptual learning
- Observational learning
- Mental practice

“On-task” practice considerations?

- Distribution of practice
- Variability of practice
- Scheduling practice
- Part vs. whole practice
- Guidance

(Schmidt, Lee. *Motor control and learning: A behavioural emphasis*. Champaign IL, Human Kinetics. 2006)

“Off-task” practice considerations?

- Motivation
- Verbal information
- Perceptual learning
- Observational learning
- Mental practice

Design Insights

“On-task” practice considerations?

- Distribution of practice
- Variability of practice
- Scheduling practice
- Part vs. whole practice
- Guidance

(Schmidt, Lee. *Motor control and learning: A behavioural emphasis*. Champaign IL, Human Kinetics. 2006)

Part vs. Whole practice

Marking: execution of parts of the whole movement (full-out)

- Imperfect movement, used in rehearsals

David Kirsh's work on marking in Dance (video)

Stages of motor learning

Cognitive stage

- “What is to be done?”
- Actions to be taken to achieve the goal

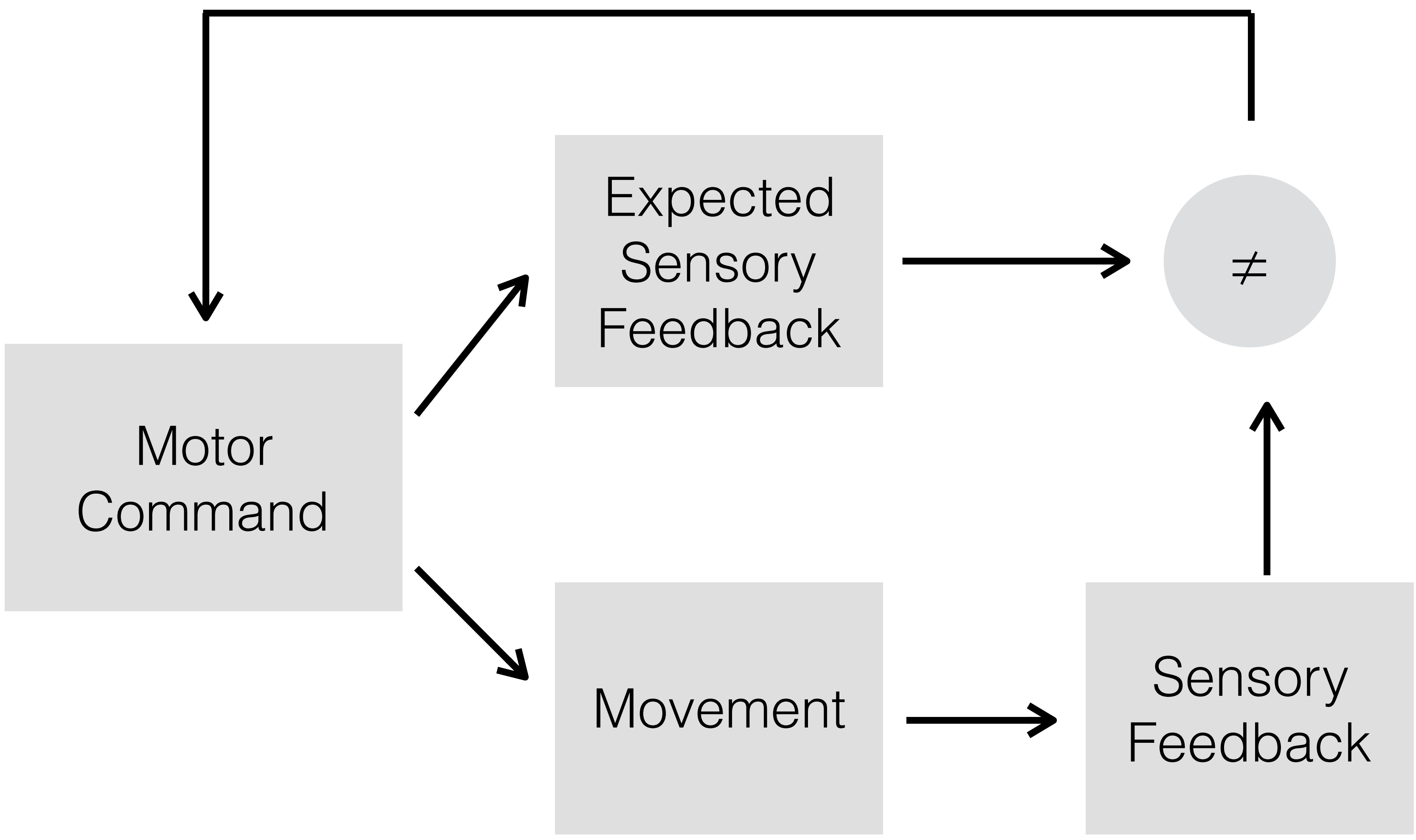
Associative/Fixation stage

- Effective way of doing the task is determined
- “How the is skill is performed?”

Automatic stage

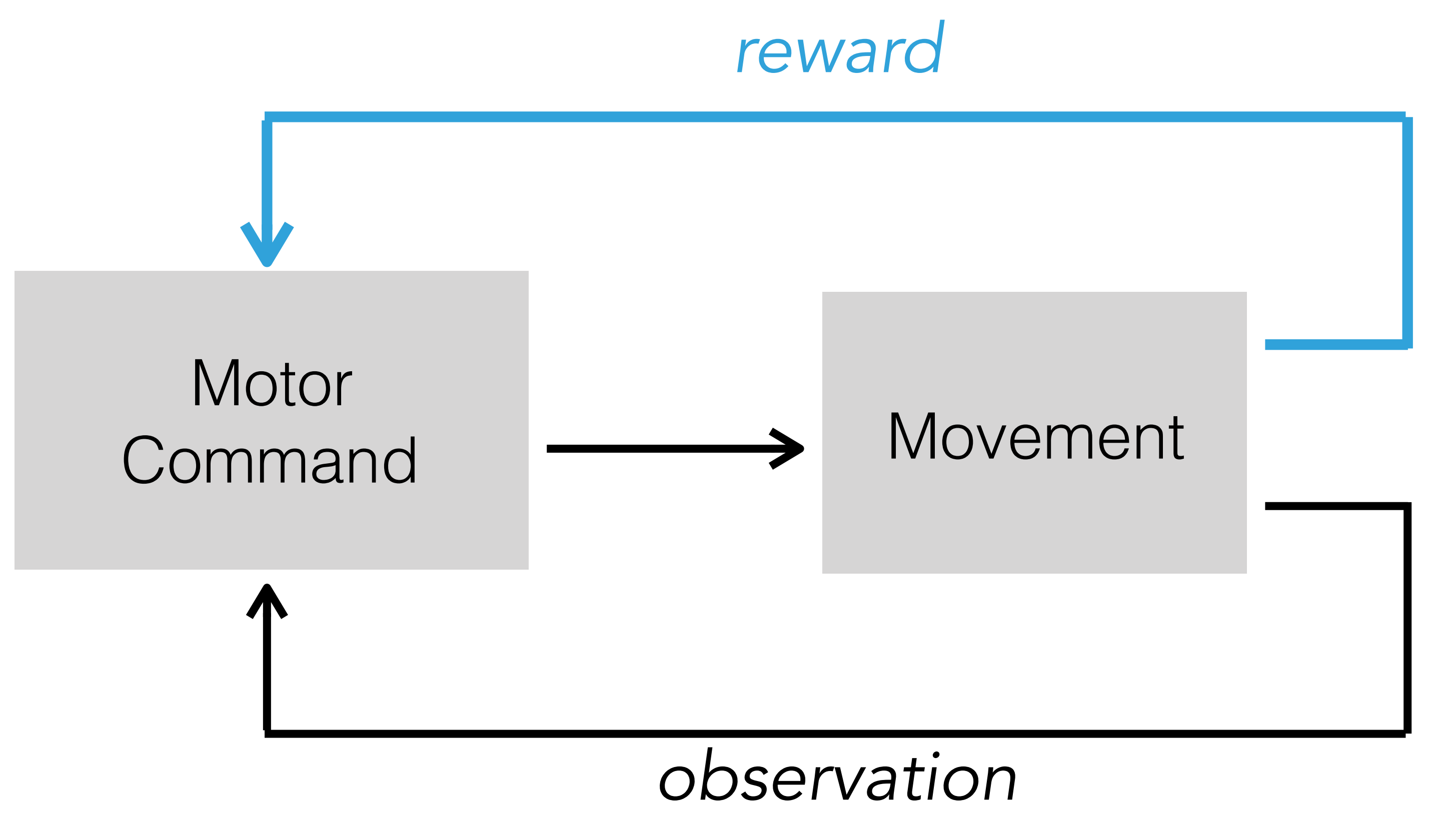
- Skill can be realised with less interference from other activities

Error-based learning



Motor Adaptation

Reward-based learning



Motor Skill Acquisition

Intrinsic feedback

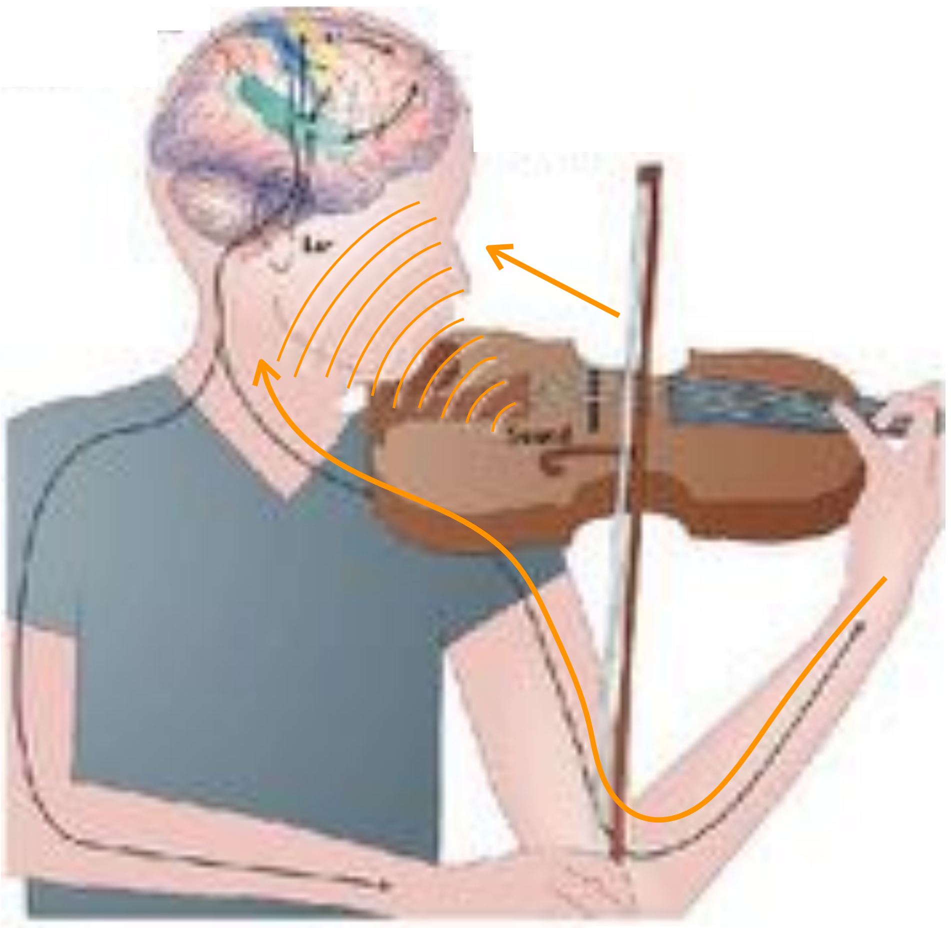
Intrinsic feedback is provided by sensory systems

Intrinsic feedback

Intrinsic feedback is provided by sensory systems

Feedback from:

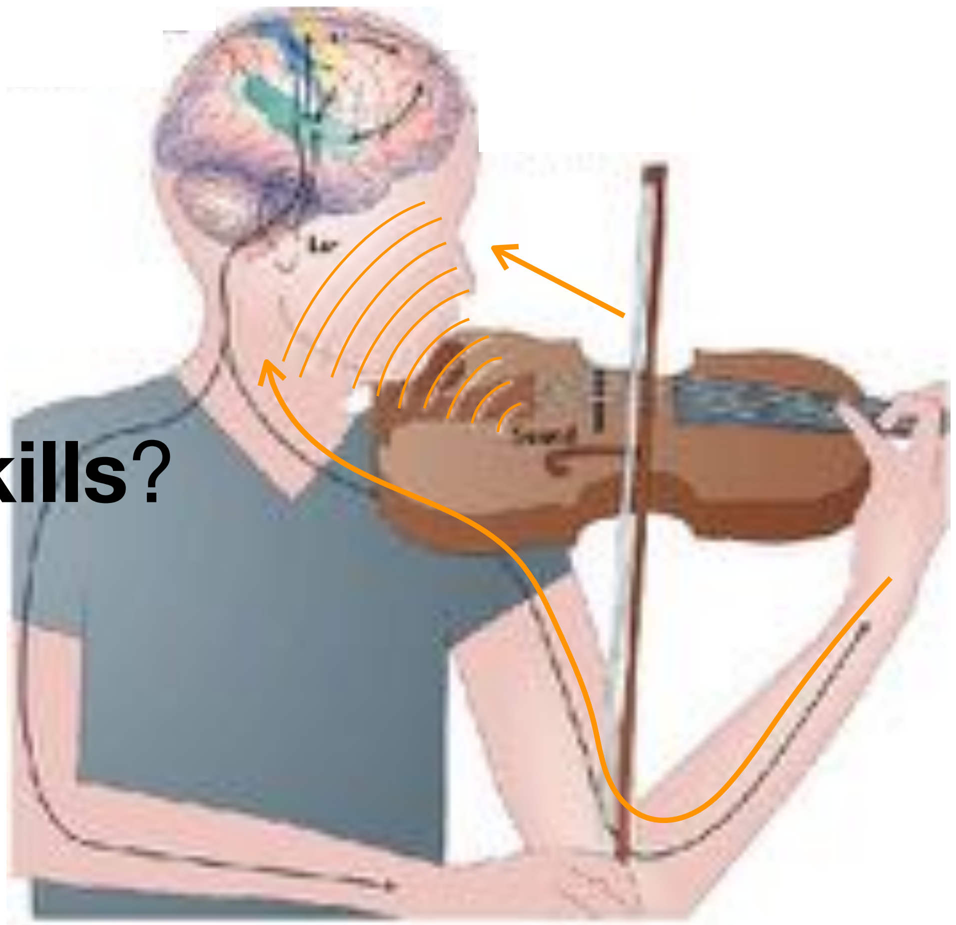
- Vision
- Auditory
- Proprioception
- Touch



From (Zatorre et al. 2007)

Intrinsic feedback

Is that **enough to learn new motor skills**?



From (Zatorre et al. 2007)

Knowledge of results

Knowledge of results (KR) is a **feedback** about the **outcome** of the movement w.r.t the goal

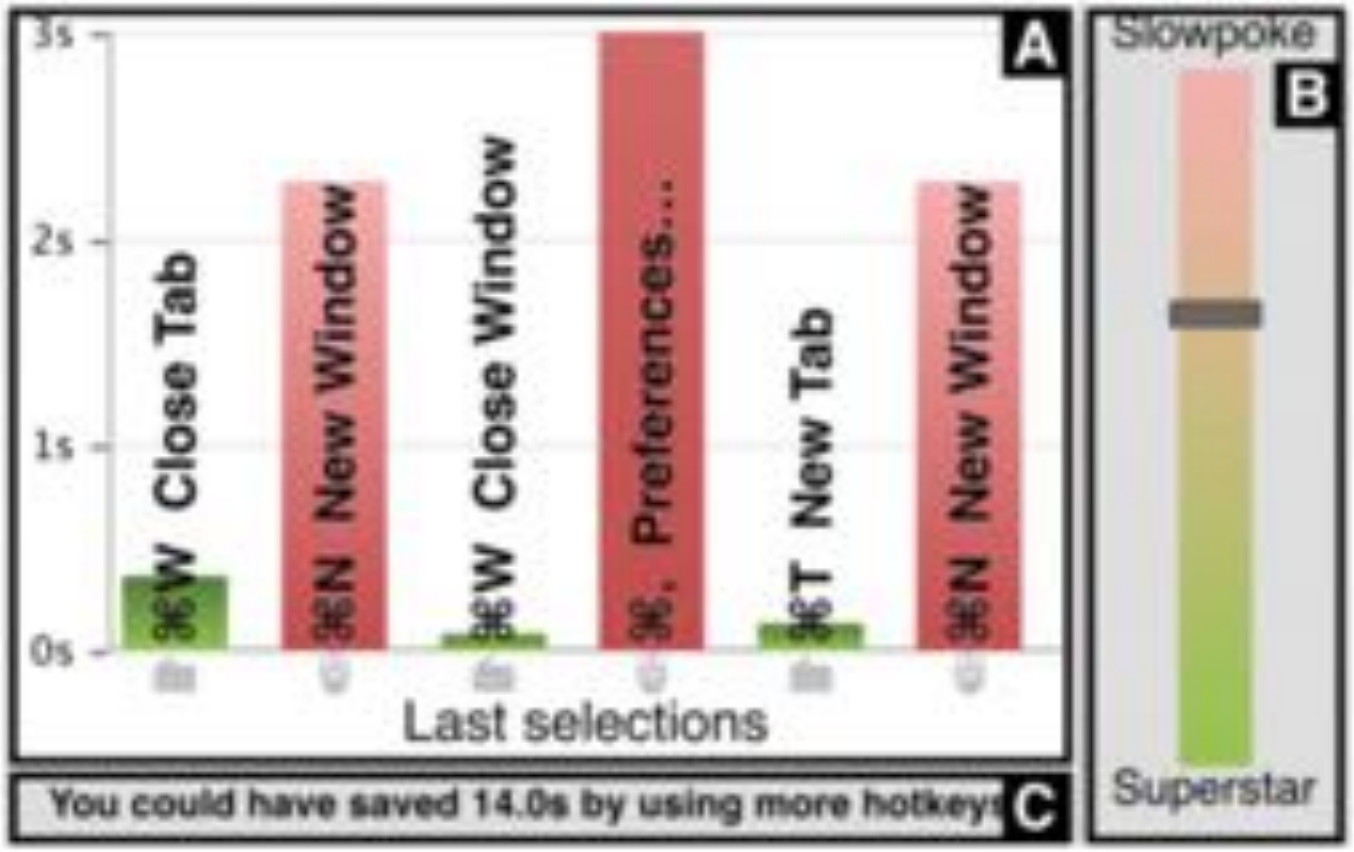
Exemples:

- "you missed the target"
- "you have drawn a circle instead of a square"
- "your score is 99/100"

Feedback is extrinsic, and can be a reward (reinforcement)

Knowledge of results

Exemple in HCI: “skillometer”



Malacria, S., Scarr, J., Cockburn, A., Gutwin, C., and Grossman, T. Skillometers: Reflective widgets that motivate and help users to improve performance. *UIST’13*

Reward and/or punishment

Reward and/or punishment

From (Galea et al., 2015)

- Punishment caused faster learning (to a fixed visuomotor rotation)
- Reward caused greater memory retention
- Punishment was associated with faster readaptation

Galea, J., Mallia, E., Rothwell, J. and Diedrichsen, J. (2015). The dissociable effects of punishment and reward on motor learning. *Nature Neuroscience*

Knowledge of performance

Feedback on how the movement has been produced

Exemple:

- “Your shoulder was too low”
- “Bend more the knees before jumping"

Extrinsic feedback that can be visual, auditory, verbal etc…

Exemples

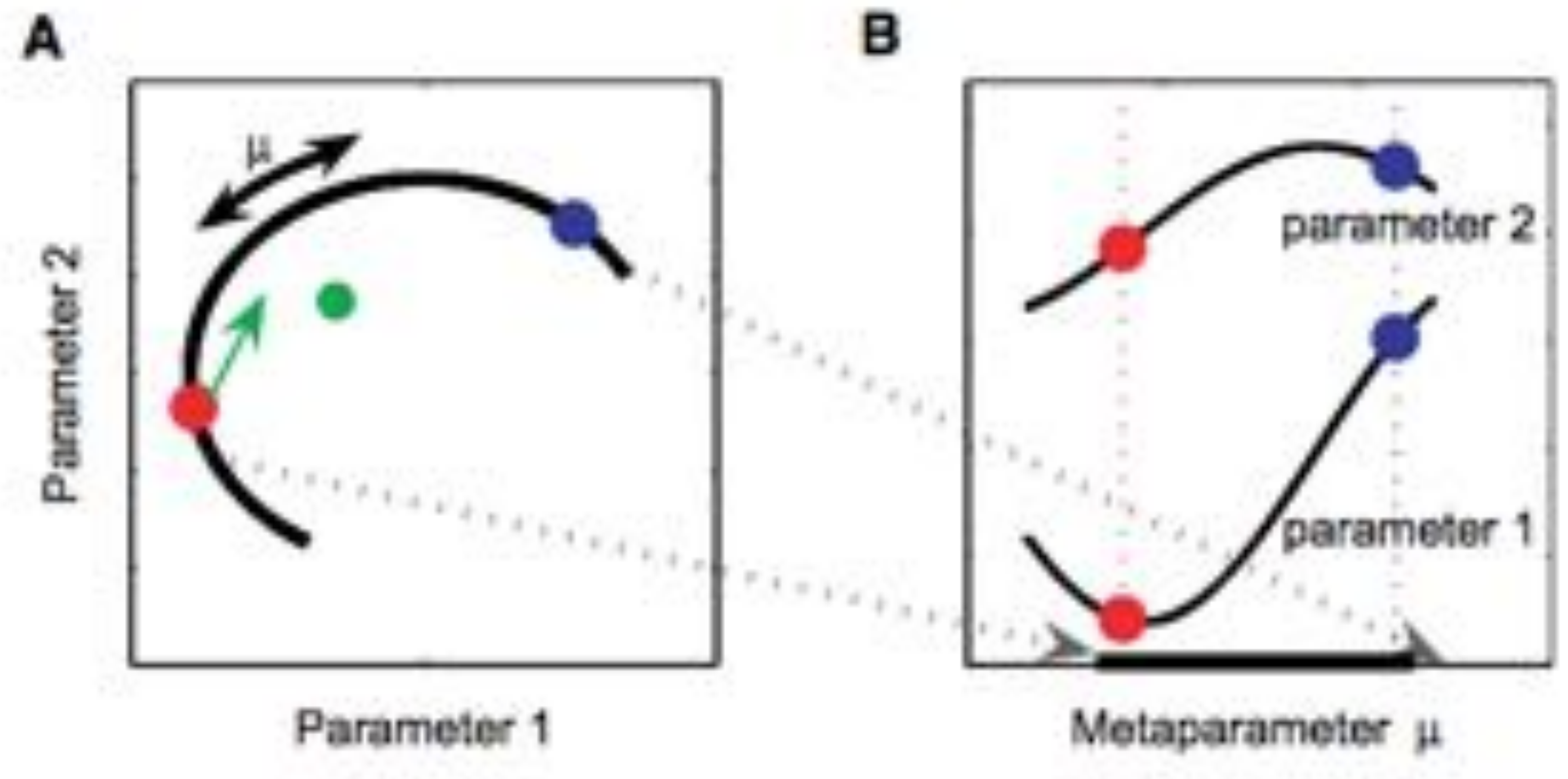
Mirror in a dance class provides feedback about the performance

Retention and transfer

The backwards brain bicycle example: coming back to a "normal" bicycle

https://www.youtube.com/watch?v=MFzDaBzBIL0

Structure learning



Braun, D.A., Aersten, A., Wolpert, D.M., and Mehring, C. (2009). Motor task variation induces structure learning. *Current Biology*, 19, 352-357