Motor learning - defined as cumulative continuous change in behavior through practice.

There are many levels of motor learning:

1. Infants motor learning
   - Learning transfer function
     born w/ lots of neurons → shed over the years → tuning
     This tuning/pruning is important for "learning" - don't die, can't learn.
     - Walking, reaching, manipulating etc.

2. Adult motor learning
   a. Skill acquisition - sports, music
   b. Adaptation (to the env, short term?)
      → one-time adaptation - lifting milk carton
      → multi-time adaptation - playing tennis in the wind

3. Adult re-learning after neurological or physical injuries

   quantitatively: what can we see? what can we use
to measure learning? what should this axis be?

   similar to infant's learning?
A quick history.

What can be measured depended on the technology available.

First concrete analysis of motor learning (late 1800's → ~ 1950)

- Measured task-oriented outcomes:
  - # of steps taken for walking (babies)
  - # of balls hit into the tennis court.
  - Variability of the outcome (e.g., darts)

1950 ~ 1980 More technology → more quantitative measurement

- Could measure joint angles (w/ markers/videos)
  (encoded/pots for joints)
- Muscle activation level (EMG)

But there were problems

- Skill learning (such as tennis) takes a long time for observation.
- The difference between novice-experts was not obvious in joint angles or EMG's.
  - Experts didn't have "the movement" as the perfected movement.
  - Experts joint angles/EMGs were as variable (if not higher) as some stereotypical movements
So since 1980's neuroscientists paid attention to multiple time adaptation to external perturbation rather than skill learning because

1) changes occur more rapidly
2) external perturbation to adapt is controllable.
3) gives insight toward skill learning.

First set of these experiments

Prism adaptation (Jeanmerod, 1988)

Train w/ No Prism.

After training → prism that shifts the visual filed by 30°.

Also move the target so it appears 0° from them.
Real

Subject's view

First throw
Real

Subject's view

After 50 throws
Real

when subjects are asked, they don't know their arm is so off!

Removal of prism → First throw (after putting target back in place)

where do you think the dart will go?
In 1993, Shadmehr & Mussa-Ivaldi created a force-field adaptation paradigm.

A planar robot can produce a force in the x-y plane. Also, record movements and display on the computer screen.

Eight outward movements are executed.

- 10 cm long
- w/ no perturbation

Movements were straight.

When an external force field was produced by the robot, the arm movements are distorted. Like swimming in river w/ current or playing tennis in the wind.
Specifically, Shadmehr & Mussa-Ivaldi applied curl viscous field.

\[ \mathbf{F}_{ext} = \mathbf{B} \cdot \nabla \times \mathbf{v} \]

where \( \mathbf{B} = \begin{bmatrix} 0 & -b \\ b & 0 \end{bmatrix} \)

Magnitude \( \rightarrow \) prop. to velocity
direction \( \rightarrow \) perpendicular to the movement.

First time in force field

2nd, 3rd, 4th times

24th time / direction

adaptation to the force field

- assuming we are optimizing smoothness.

(Mussa-Ivaldi & Gandolfo 1993)

plotted velocity profile

correlation w/ nonperturbed profile

ave of four subjects

- 0.0

\[ t \]

- 24 trials
Of course, there are other parameters that may be related to neural adaptation.

Matsuzaka (1997)

Initial moving angle
Assuming neurons encode moving directions.

\[ \theta (\text{deg}) \]

\[ \sim 30^\circ \]

\[ < 2\text{deg.} \]

Camillo Podda-Schioppa (1999)

Neuronal preferred direction
(remember Georgopoulous's work)

Single neuron

Ambiguity can be eliminated w/ population of neurons.
Recording from a single neuron during training

How do we adapt to the externally applied force field?

\[
\begin{bmatrix}
\text{traj}_{\text{shoulder}} \\
\text{traj}_{\text{elbow}}
\end{bmatrix} = \underbrace{\text{arm dynamics}}_{\text{externally applied force field}} + \underbrace{\text{Tint}}_{\text{internally constructed field}}
\]

\( \text{Tint} = 0 \) before training. To observe \( \text{Tint} \), we can turn \( \text{Text} = 0 \) suddenly.

Similar to what I found in external measurement.
after adaptation in force

after sudden removal of force

this change is called "aftereffect" of the adaptation

Unlearning

- For learning, to get to the 90% tile of baseline takes ~ 20 trials/direction.
- For unlearning (remove the force), it takes only ~3~5 trials/direction.

What happens if only force trials were experienced, no aftereffect was recorded. Went home for the day & came back the next day to see the aftereffect? I guess!
we talked a little bit about unlearning last time.

- Learning the curl force field for the first time takes ~24 trials/direction.
- Returning to the baseline movement in no force condition takes ~3 trials/direction.

BUT is this wash out process really unlearning?

When subjects were exposed to the same force field for the second time immediately following washout, subjects readapt to the FF much quicker than the first time.

So the previous training effect was NOT completely unlearned.

So how would we completely washout learned effect & how do we assure retaining learned info?
Shadmehr et al. (1996) retrograde interference

1. Use negative transfer to completely erase learned effect.

\[
\begin{pmatrix}
0 & -b \\
-b & 0
\end{pmatrix}
\]

192 trials total

\[
\begin{pmatrix}
0 & b \\
-b & 0
\end{pmatrix}
\]

192 trials total

Subjects do worse in this field than the first field due to "negative transfer".

Go home, sleep, come back 24 hrs later

Original cue field

How long will it take till these PP is learned?
The same length as the first time exposed to the FF.

Last lecture, I told you that if they trained the 1st FF only and came back the next day, they exhibit some aftereffects. Not only that, they were able to react to the same FF very fast and achieved additional adaptation.
So is it that if an opposite information is introduced at some point in life time, do the learned information get erased completely?

That seems crazy.

So is it time dependent?

If there was some time between the original & opposite f.f. training, would it make any difference in retaining the original f.f. information?

Yes!

gohome, sleep, 24 hours from original exposure...

--- original
--- 5min later
--- 1hr later
--- 4hr later

Magic number when curves are statistically difference from the original curve.
This phenomenon is called "consolidation" of memory.

Talking about memory in motor learning is unavoidable yet opens many cans of worms that most motor control community stay away from. (But it's very interesting.)

IE.

what if they spend 4 hrs between two f.f, but went home and didn't sleep all night?

& the re-adaptation is slower.

Memory consolidation is heavily linked to sleep.

Similar but slightly different memory related issue => mental imaging training used for sports too.

1st day: original f.f.

2nd day: nothing

came in & visualize the original f.f.

3rd day test

Test