MOVEMENT DISORDERS

Emmanuel Guigon

Institut des Systèmes Intelligents et de Robotique
Université Pierre et Marie Curie
CNRS / UMR 7222
Paris, France

emmanuel.guigon@upmc.fr
e.guigon.free.fr/teaching.html

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3. Stroke and rehabilitation

BCI/BMI

DEFINITION — EPIDEMIOLOGY

- **Acute focal injuries to the brain**

— in ~85% of the cases, interruption to the blood supply (ischemic): neuronal degeneration (infarct)
— bleeding (hemorhagic): no tissue destruction, possible restitution

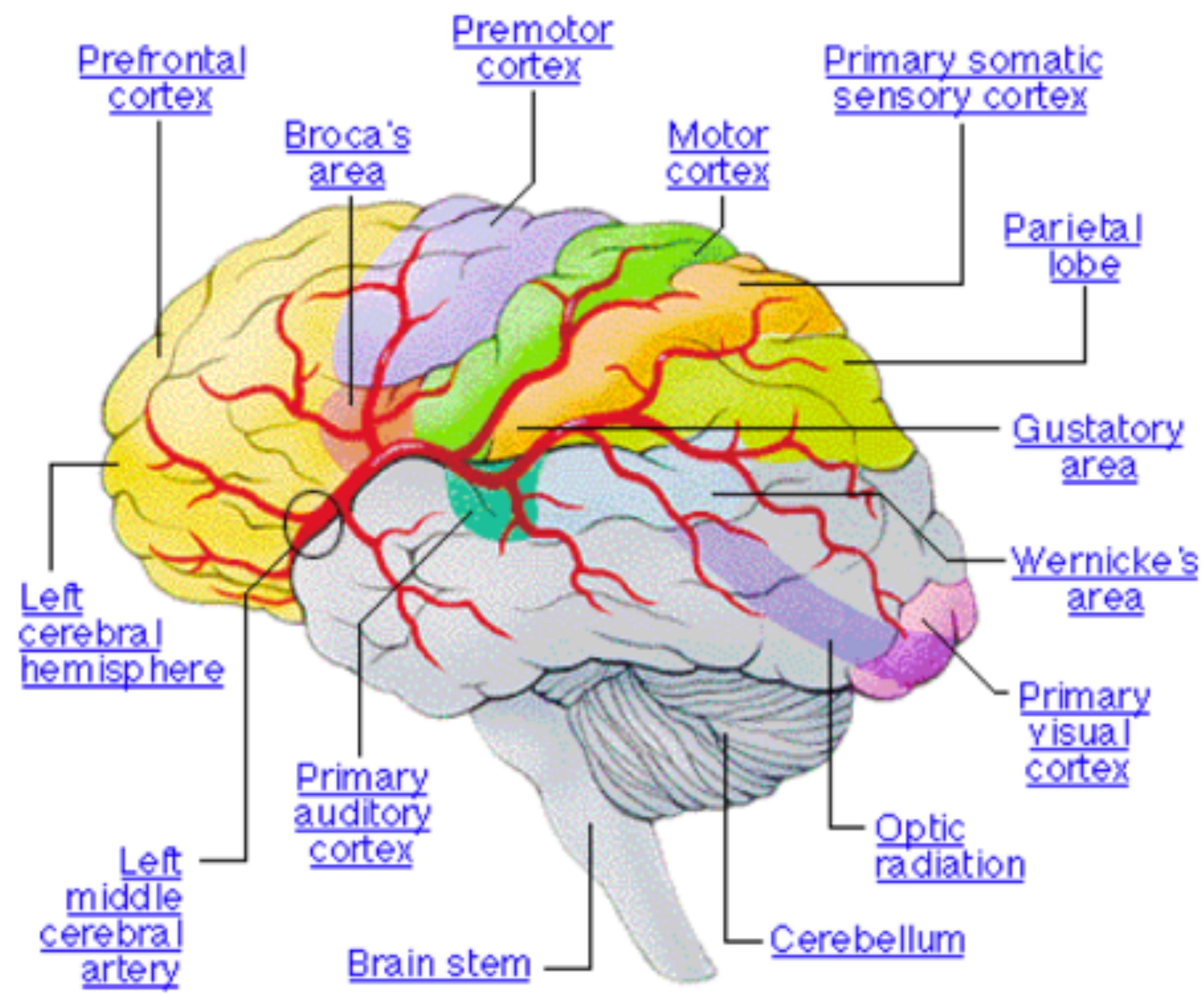
- **Prevalence**

— ~700 000/year in the United States
— 3rd leading cause of death
— leading cause of disability
— 90% of stroke survivors have a deficit
— 2/3 in people older than 65

"MOTOR" STROKES

Territory of the middle cerebral artery

— blood supply to sensory and motor systems, temporal and parietal cortex, thalamus, basal ganglia



MOTOR SYMPTOMS

- **Paresis/hemiparesis**

— loss of power of any muscle group
— abnormally slow and clumsy movements
— complete loss: plegia or paralysis

- **Spasticity**

— change in reflexes to muscle stretch with a strong velocity component
— emergence of pathological reflexes and uncontrolled spasms
— increase in muscle tone
— impairment of voluntary motor function

SYMPTOMS

SYMPTOMS	DEFINITION	stroke	PwPD	cbm
akinesia	paucity of movements, delayed movement initiation		X	
apraxia	difficulties in movement planning			
ataxia	lack of coordination in absence of muscular weakness			X
bradykinesia	slowness and reduced amplitude of movements		X	
dysdiadochokinesia	impaired repetitive alternating movements			X
dysmetria	irregularity of movements with undershoots/overshoots			X
hypotonia	low muscle tone			X
hyperreflexia	**reduced sensory threshold and larger reflex amplitudes**	X		
paresis	**weakness of voluntary movements**	X		
postural instability	wide base stance and gait, inability to stand without support			X
rigidity	steady increase in resistance to passive stretch		X	
spasticity	**hypertonia, increased resistance to passive stretch**	X		
tremor	intention (during movement) or resting		X[1]	X[2]

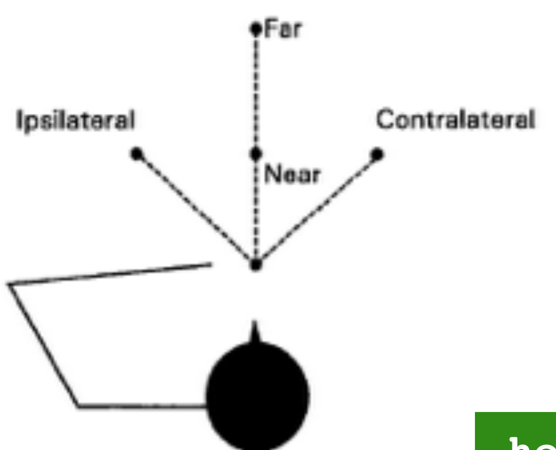
(1) rest tremor

(2) intention tremor: absent during rest, provoked by voluntary movements

MOTOR DEFICITS

Coordination

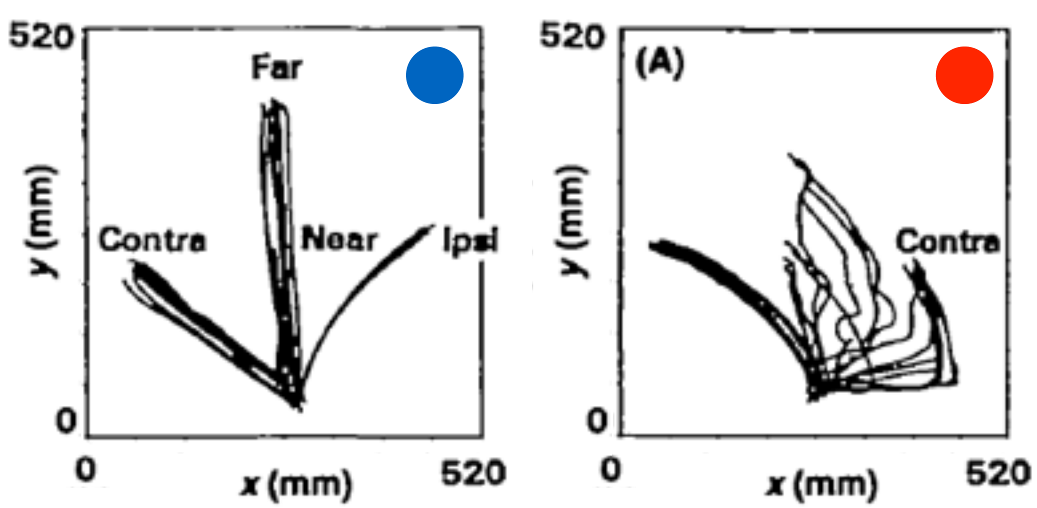
arm movements in 2D space



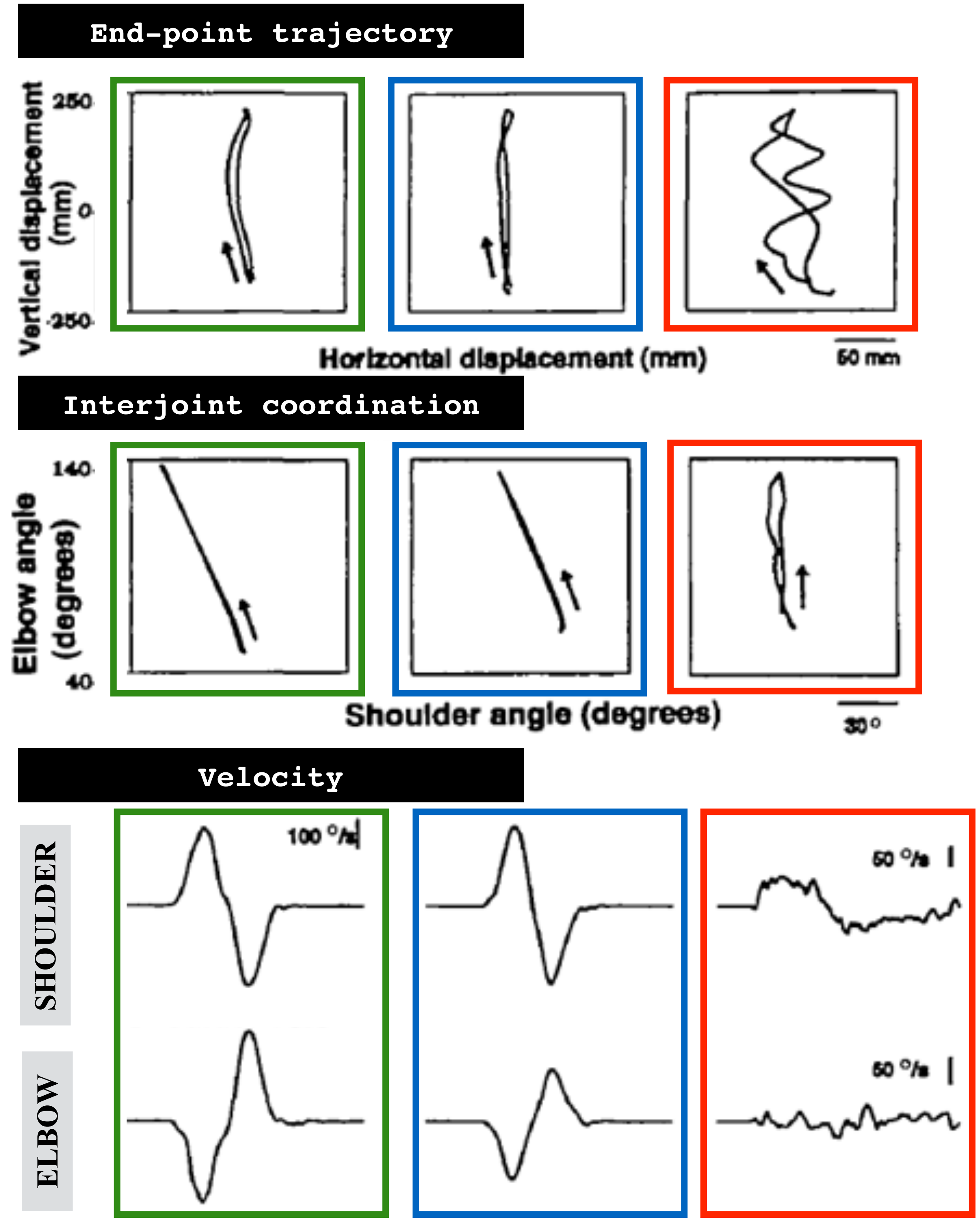
healthy control

non-affected arm

affected arm



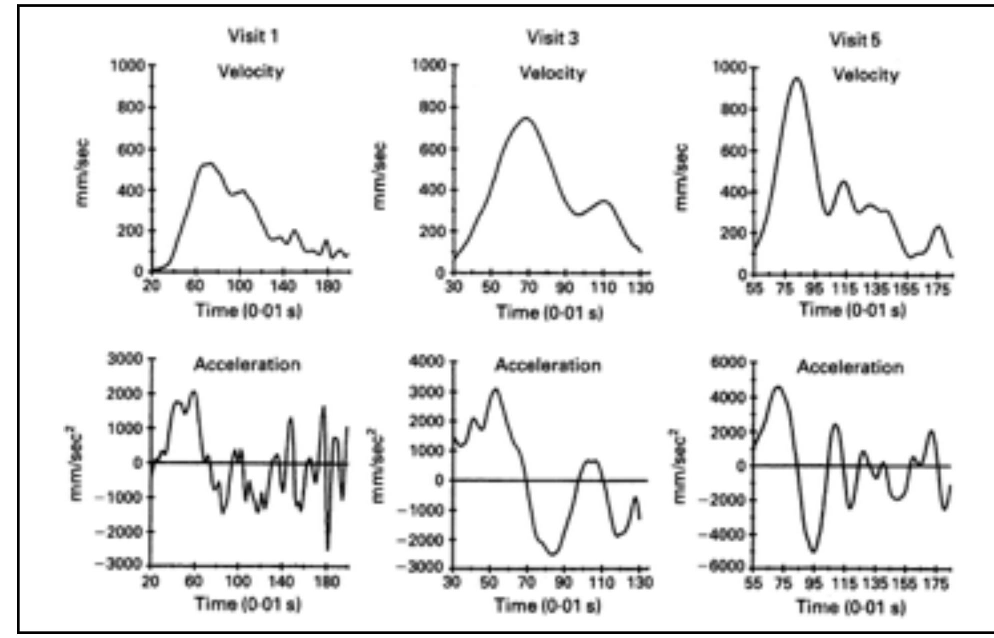
— Levin, 1996, *Brain* 119:281



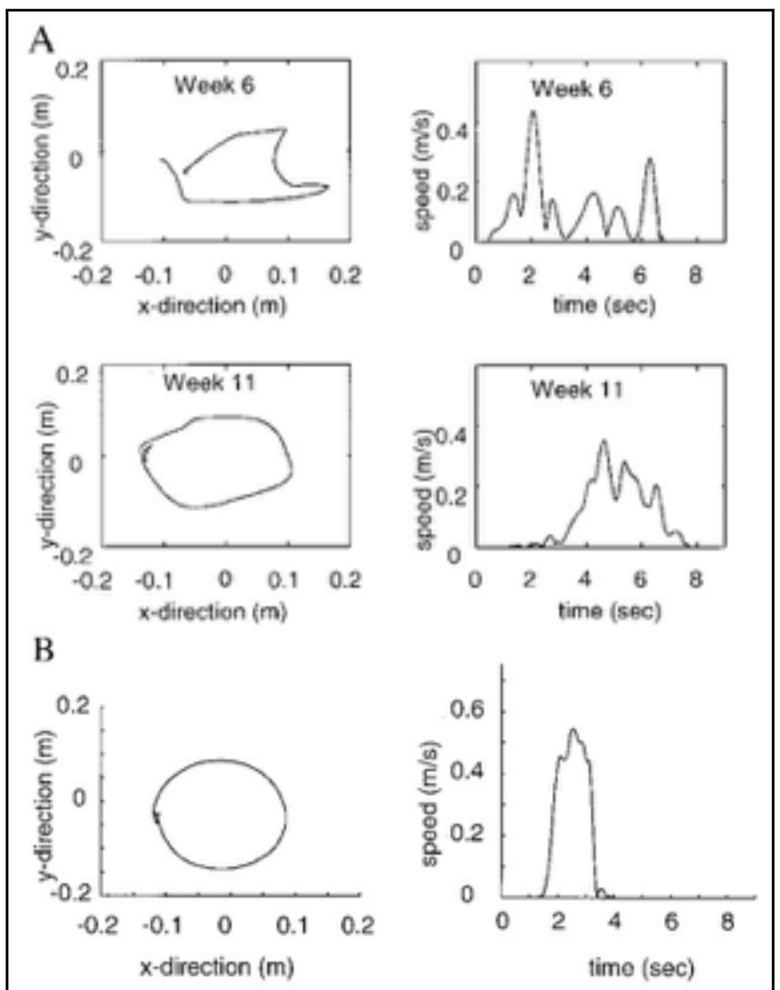
MOTOR DEFICITS

Segmentation

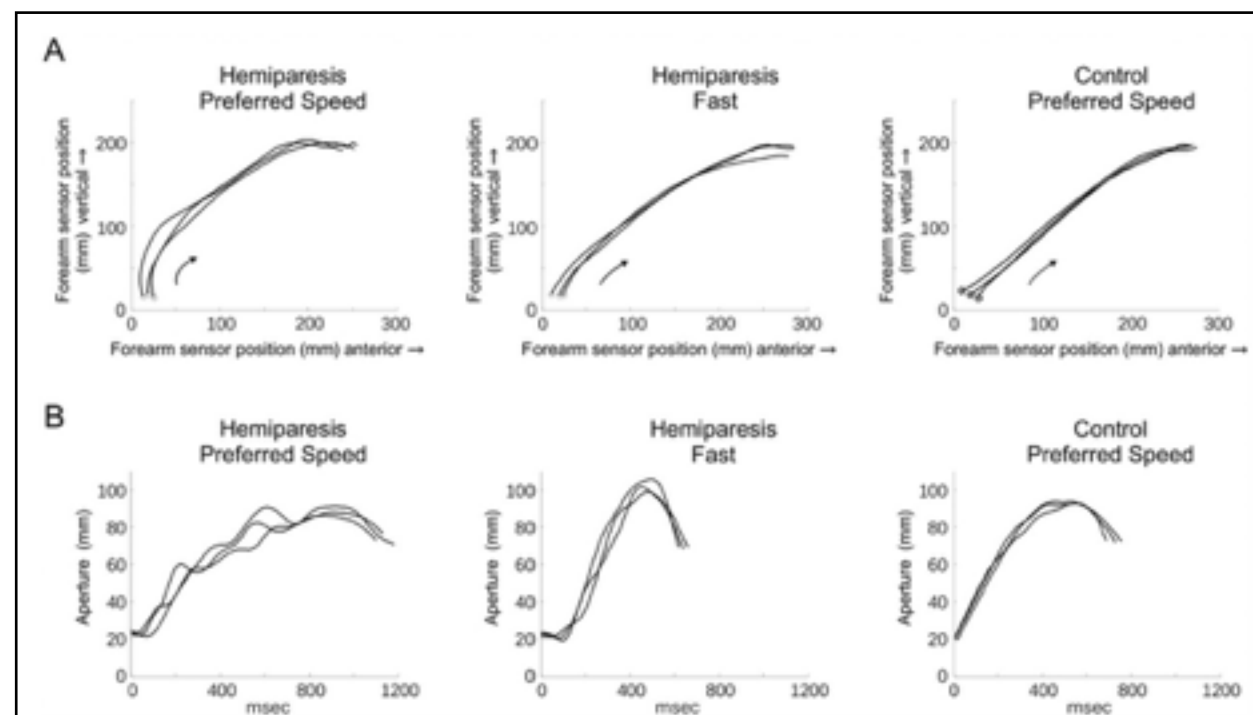
arm movements in 2D/3D space



— Trombly, 1993, *J Neurol Neurosurg Psychiatr* 56:40



— Krebs et al., 1999, *Proc Natl Acad USA* 96:4645



— DeJong et al., 2012, *Neurorehabil Neural Repair* 26:362

STROKE RECOVERY

- **Definition**

improvements in abilities over time, at any of the ICF levels (*World Health Organization's International Classification of Functioning, Disability, and Health*), regardless of how these improvements occurred

- **Restitution/substitution (*true recovery*)**

undamaged brain regions are recruited, which generate commands to the same muscles as were used before the injury
e.g. unmasking, through training, of pre-existing corticocortical connections (redundant pathways)

- **Compensation**

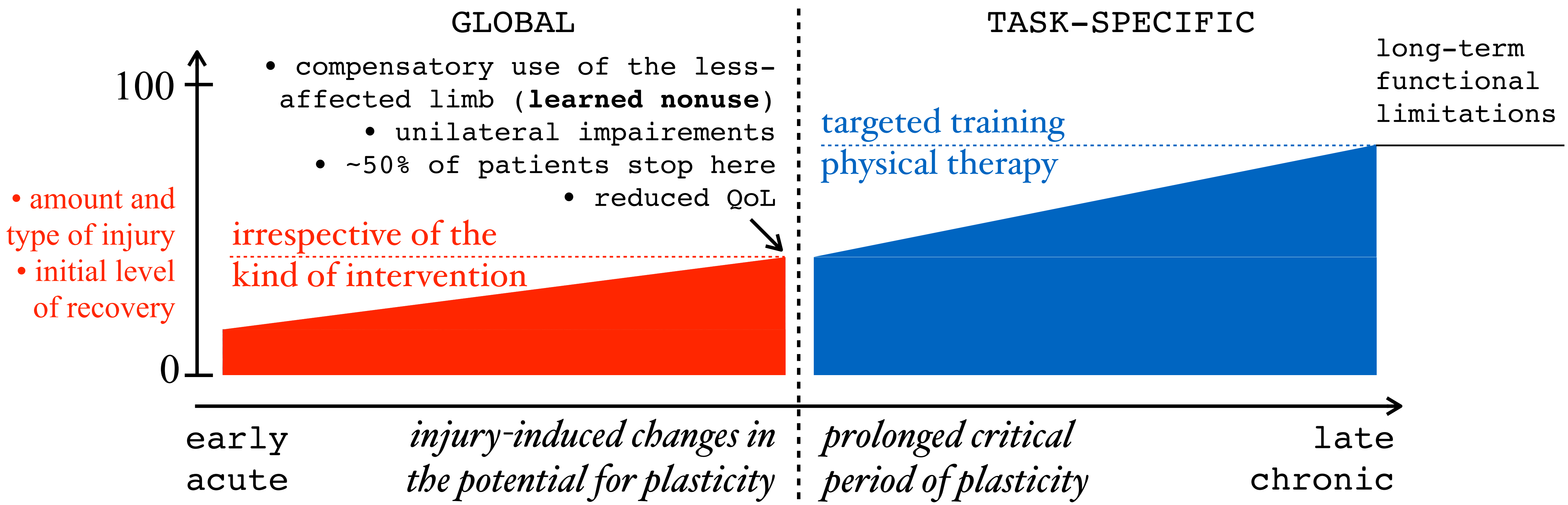
use of structures and/or functions different from those used before the injury to achieve a movement goal
e.g. using the less-affected arm

STROKE RECOVERY

- **Spontaneous recovery (——)**
  plasticity, brain reorganization (e.g. activation of undamaged regions in the opposite hemisphere)

- **Training-dependent recovery (——)**
  task-specific targeted training

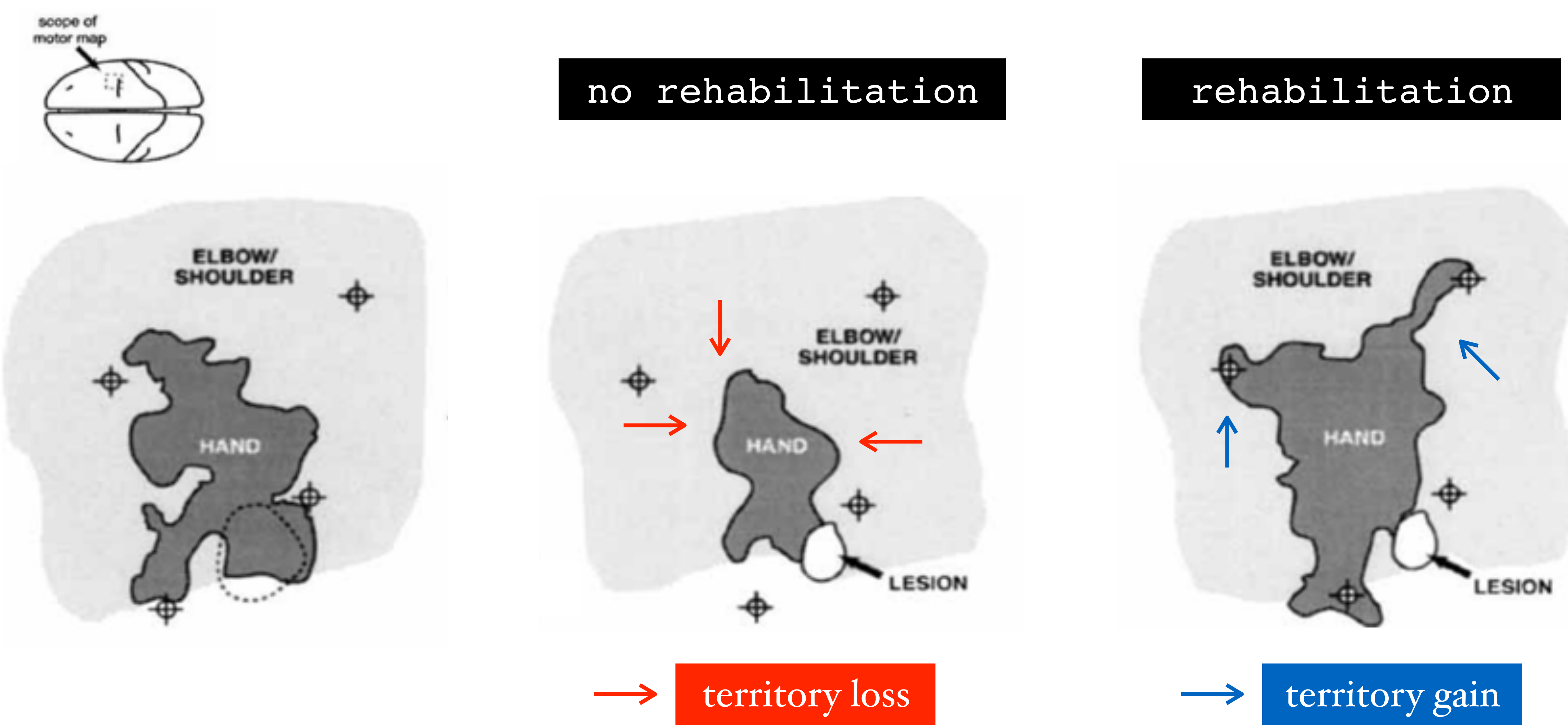
learned nonuse
- concurrent decrease of spontaneous used of the impaired side
- preference for the less affected side learned as a result of unsuccessful repeated attempts in using the affected side



PLASTICITY

Localized lesion in primary motor cortex

behavioral retraining: retrieve food pellets from small wells



— Nudo et al., 1996, *Science* 272:1791

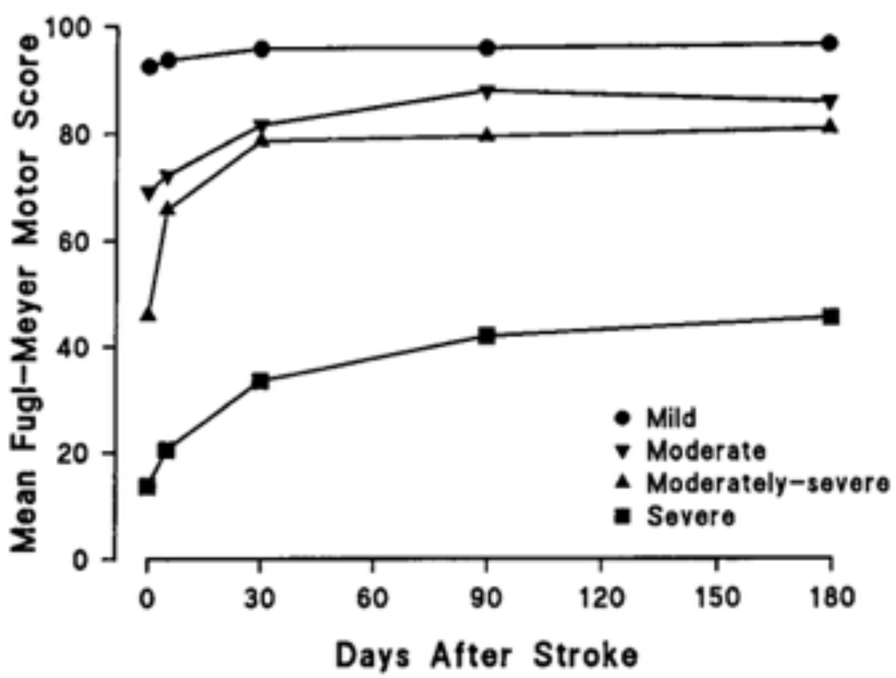
microstimulation maps

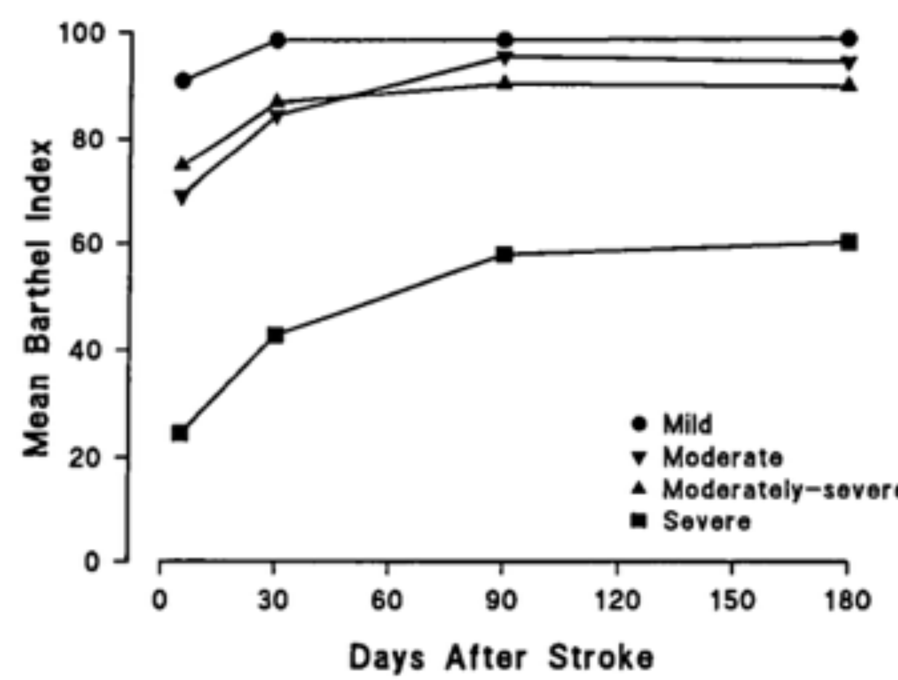
STROKE RECOVERY ASSESSMENT

Scores

— **Fugl-Meyer Assessment** to quantify the sensorimotor impairment (*motor function*, *sensory function*, *balance*, *range of motion of joints*, *joint pain*) on an ordinal scale (0=no; 1=partial; 2=full)

— **Barthel ADL index**: 10 variables describing activities of daily living (ADL) and mobility



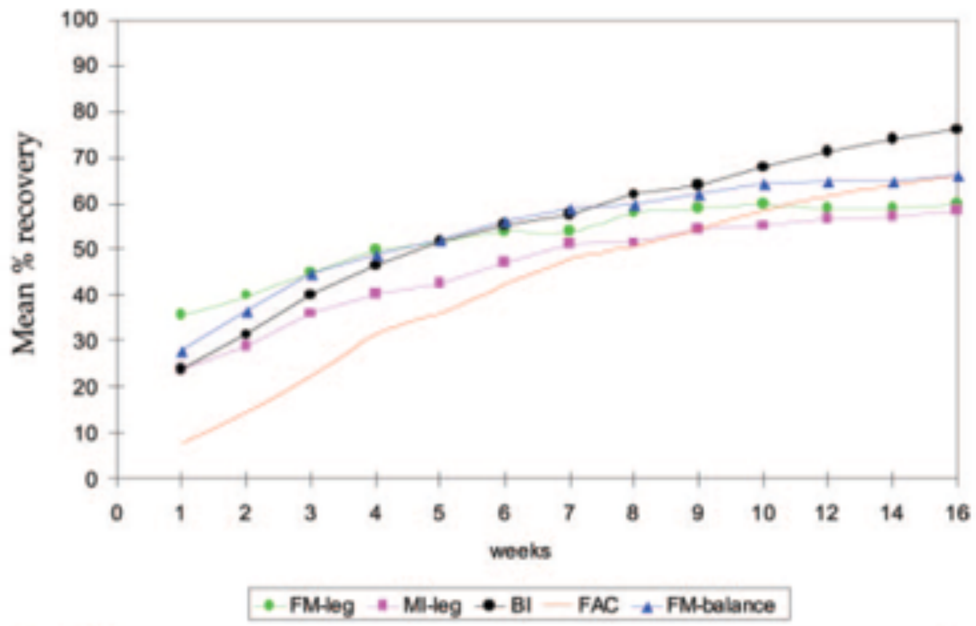


— Duncan et al., 1992, *Stroke* 23:1084

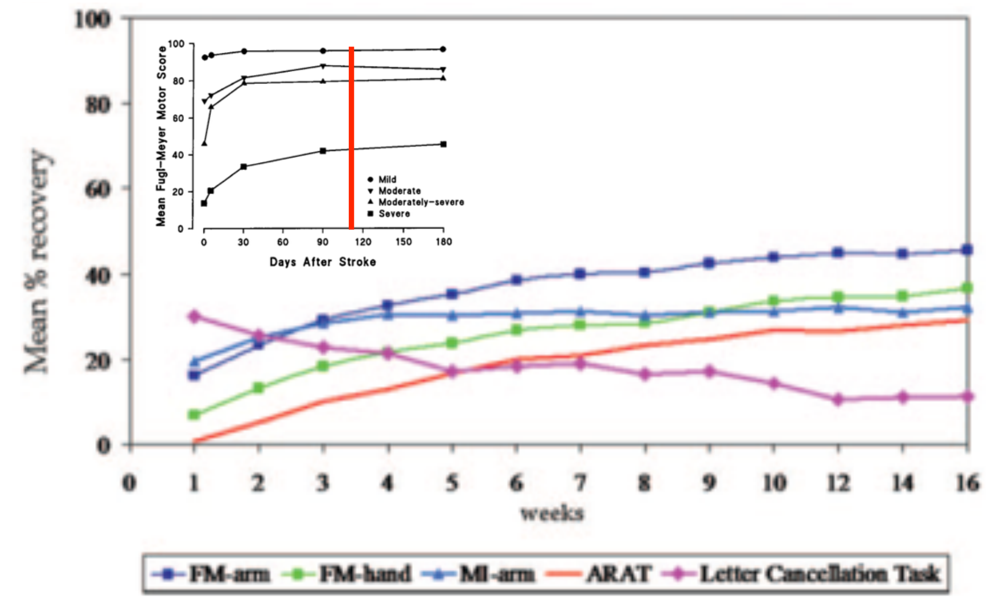
STROKE RECOVERY ASSESSMENT

Time-dependent recovery

lower limb



upper limb



FM = ***Fugl-Meyer***
(balance: sitting, standing)

MI = ***Motricity Index***
(measure of strength)

BI = ***Barthel Index***
(ADL)

FAC = ***Functional Ambulation Capacities***
(walking)

ARAT = ***Action Research Arm Test***
(recovery of dexterity)

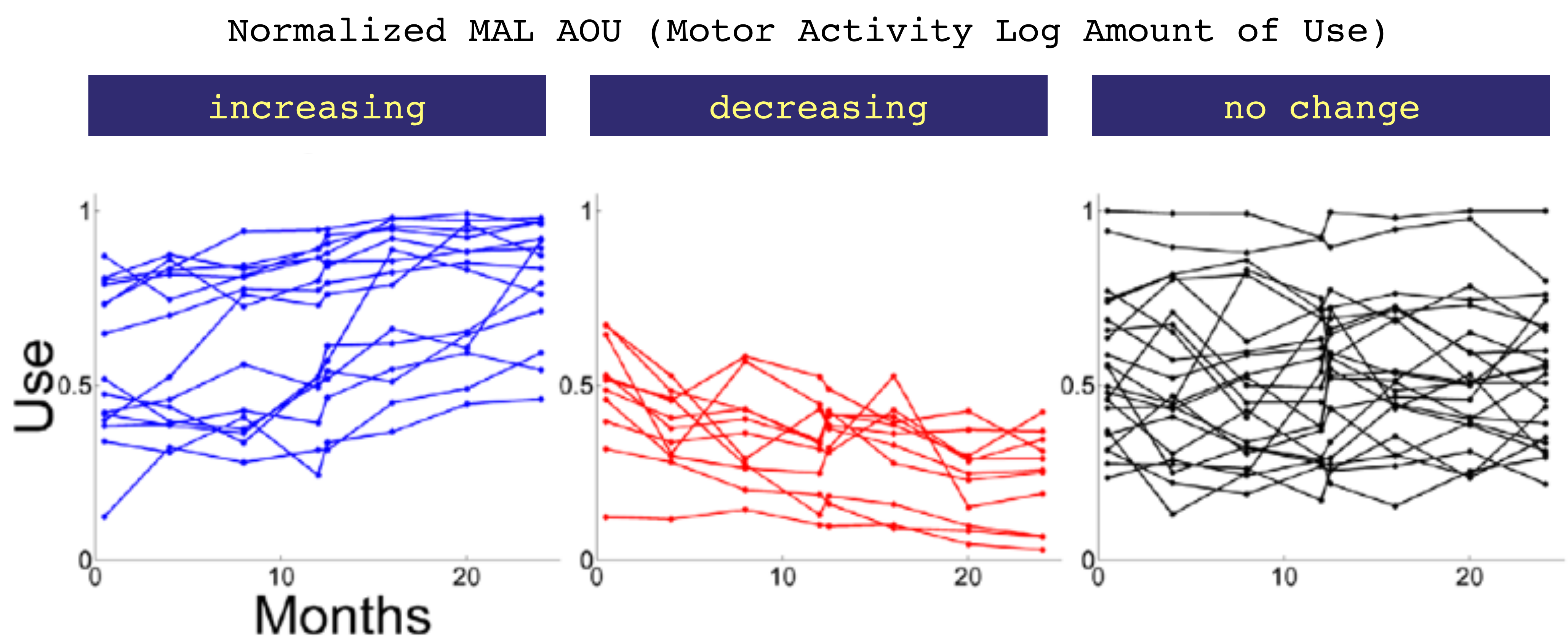
LCT = ***Letter Cancellation Task***
(presence of neglect)

— Kwakkel et al., 2006, *Stroke* 37:2348

STROKE RECOVERY ASSESSMENT

Individual variability in arm use after motor training

normalized use in immediate group of EXCITE data



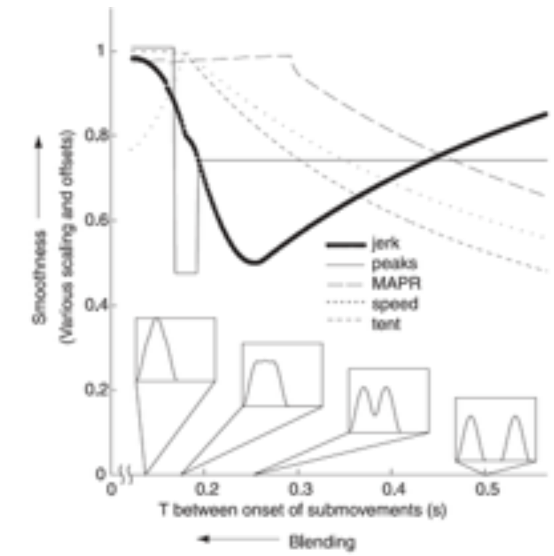
— Hidaka et al., 2012, *PLoS Comput Biol* 8:e1002343

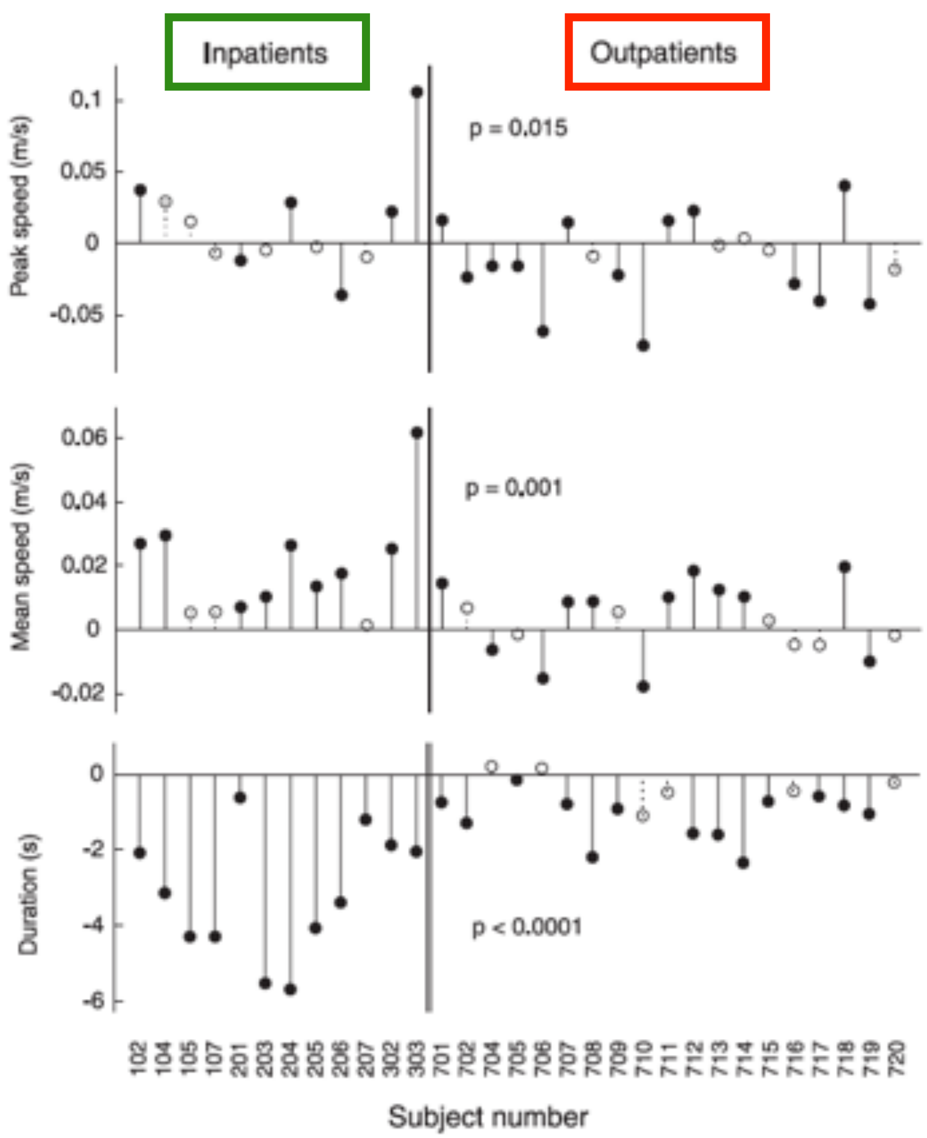
STROKE RECOVERY

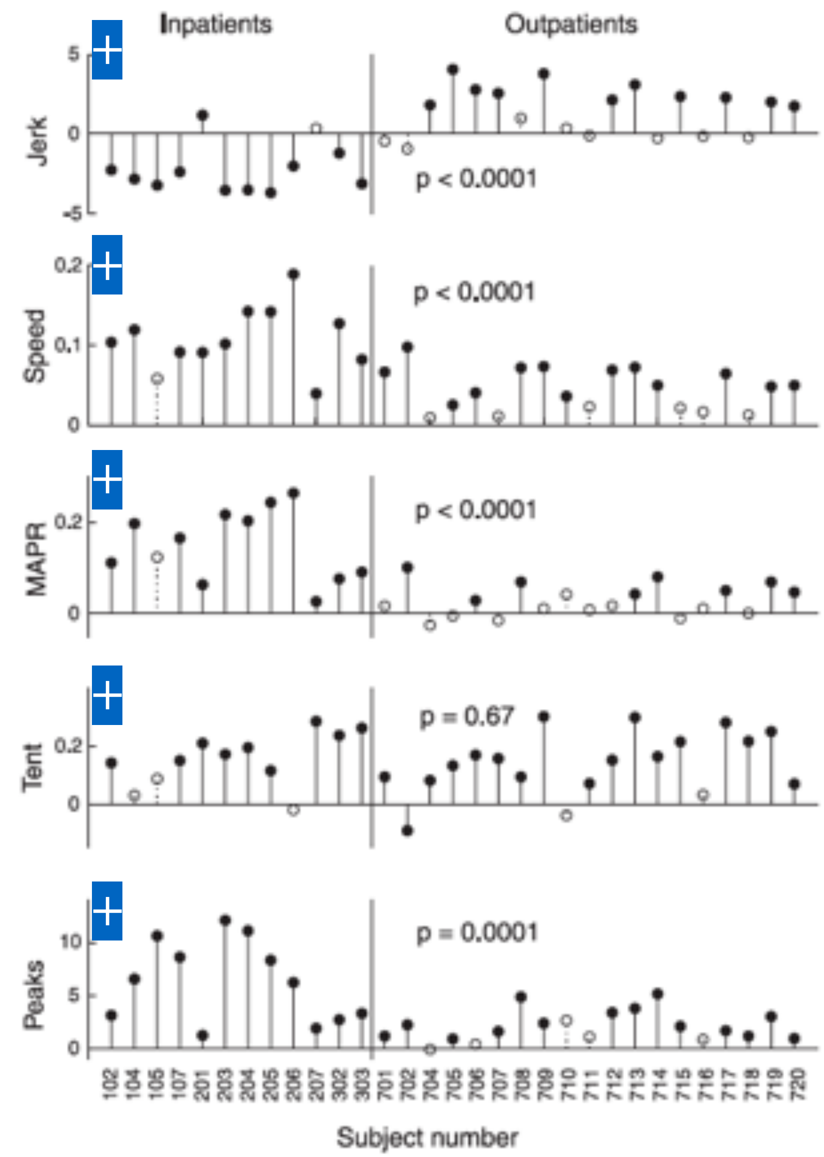
- **Smoothness**

robot therapy — 5 h/week for 4 weeks (**acute**), 3 h/week for 6 weeks (**chronic**)

— Rohrer et al., 2002, *J Neurosci* 22:8297



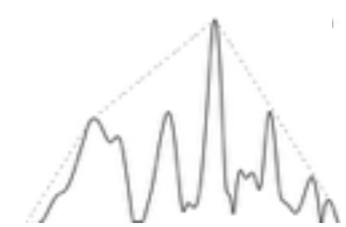




+ smooth

$$\frac{\text{mean speed}}{\text{peak speed}}$$

mean arrest period ratio
proprotion of time above a threshold velocity



negative of the number of velocity peaks

SMOOTHNESS METRICS

1. normalized mean absolute jerk

$$\eta_{\text{nmaJ}} \triangleq \frac{1}{(t_2 - t_1)v_{\text{peak}}} \int_{t_1}^{t_2} \left| \frac{d^2 v}{dt^2} \right| dt$$

$$v_{\text{peak}} \triangleq \max_{t \in [t_1; t_2]} v(t)$$

2. peak metrics

$$\eta_{\text{pm}} \triangleq -\# \{v_{\text{maxima}}\}$$

$$\text{where } \{v_{\text{maxima}}\} \triangleq \left\{ v(t) : \frac{dv}{dt} = 0 \text{ and } \frac{d^2 v}{dt^2} < 0 \right\}$$

3. dimensionless jerk

$$\eta_{\text{dj}} \triangleq -\frac{(t_2 - t_1)^3}{v_{\text{peak}}^2} \int_{t_1}^{t_2} \left| \frac{d^2 v}{dt^2} \right|^2 dt$$

4. spectral arc length

$$\eta_{\text{sal}} \triangleq -\int_0^{\omega_c} \sqrt{\left(\frac{1}{\omega_c}\right)^2 + \left(\frac{d\hat{V}(\omega)}{d\omega}\right)^2} \, d\omega$$

$$\hat{V}(\omega) \triangleq \frac{V(\omega)}{V(0)}$$

$V(\omega)$ Fourier spectrum of v

$$\omega_c = 20 \text{ Hz}$$

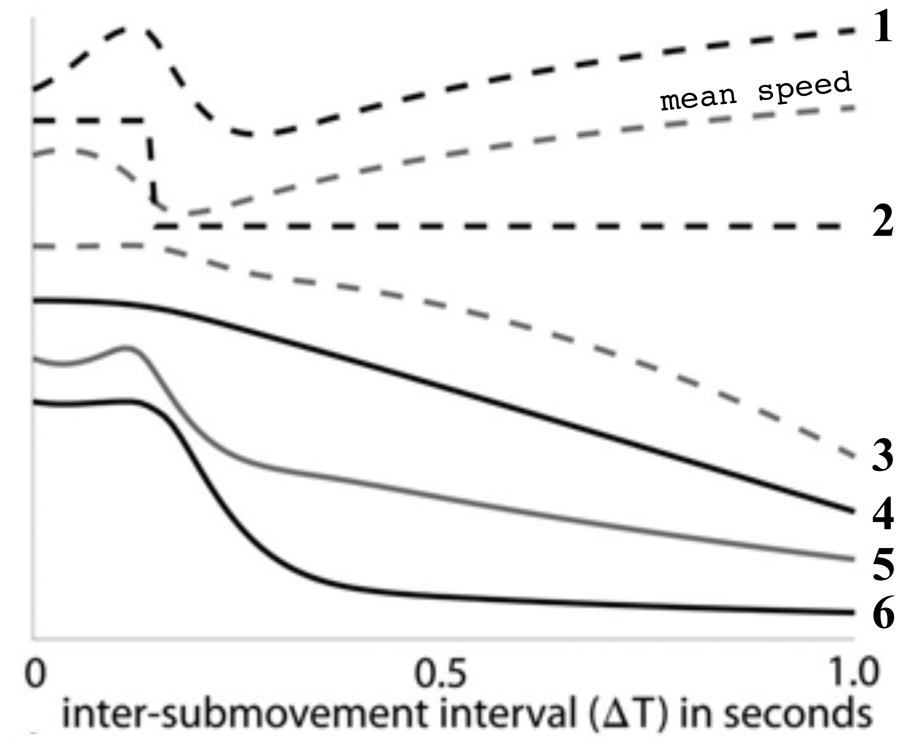
5. log dimensionless jerk

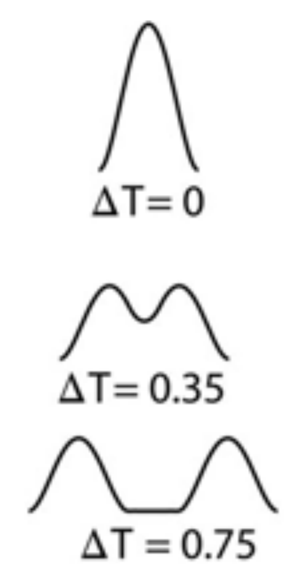
$$\eta_{\text{ldj}} \triangleq -\ln \left(\frac{(t_2 - t_1)^3}{v_{\text{peak}}^2} \int_{t_1}^{t_2} \left| \frac{d^2 v}{dt^2} \right|^2 dt \right)$$

6. speed arc length

$$\eta_{\text{spal}} \triangleq -\ln \left(\int_{t_1}^{t_2} \sqrt{\left(\frac{1}{t_2 - t_1}\right)^2 + \left(\frac{d\hat{v}}{dt}\right)^2} \, dt \right)$$

$$\hat{v}(t) \triangleq \frac{v(t)}{v_{\text{peak}}}$$





— Balasubramanian et al., 2012, *IEEE Trans Biomed Eng* 59:2126

STROKE REHABILITATION

- **Goals**

— **general**: relearning how to move to carry out essential needs
— **specific**: improve function and use of the affected arm, avoid learned nonuse to prevent "rehabilitation in vain"

- **Methods**

— physical and occupational therapy
— robot-aided rehabilitation

- **Principles**

"relearn" motor control through motor learning (as in development and skill acquisition)

REHABILITATION METHODS

- **Arm ability training**

developed for patients who complain of clumsiness or decreased coordination even though they have normal neurological examination; oriented toward ADLs (activities of the daily life)

- **Constraint-induced movement therapy**

restraint of the less-affected limb for 90% of waking hours, massed practice with the affected limb for 6 hours a day

- **Interactive robotic therapy**

intensive, real-time assistive or resistive interactions with a robotic device which induce motor learning

EFFECTS OF ROBOTIC THERAPY

- **Conclusion from a multicentre, parallel-group trial**

training with an arm robot is safe and improves body functions, activities, and participation (i.e., social functioning) equally as well as the same amount of conventional therapy offered by a therapist

- **Avantage**

robots do not get tired, can generate more repetitions than can a therapist in the same time, offer accurate feedback about patients' performance, and can be fun to use

- **Drawback**

cost-effectiveness trade-off?

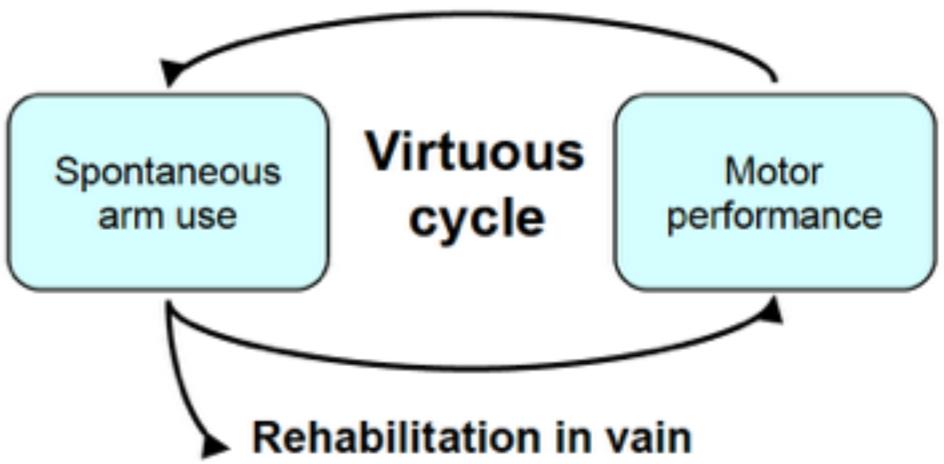
— Kwakkel and Meskers, 2014, *Lancet Neurol* 13:132

MODELING RECOVERY

The threshold hypothesis

— if therapy (or spontaneous recovery) sufficiently increases performance above a threshold, patient will enter a virtuous cycle, in which motor performance and spontaneous arm use reinforce each other

— if not, patient enters a vicious cycle in which compensatory movements with the other limb further develops, and rehabilitation can be "in vain"



— Han et al., 2008, *PLoS Comput Biol* 4:e1000133

MODELING RECOVERY

Description of the model

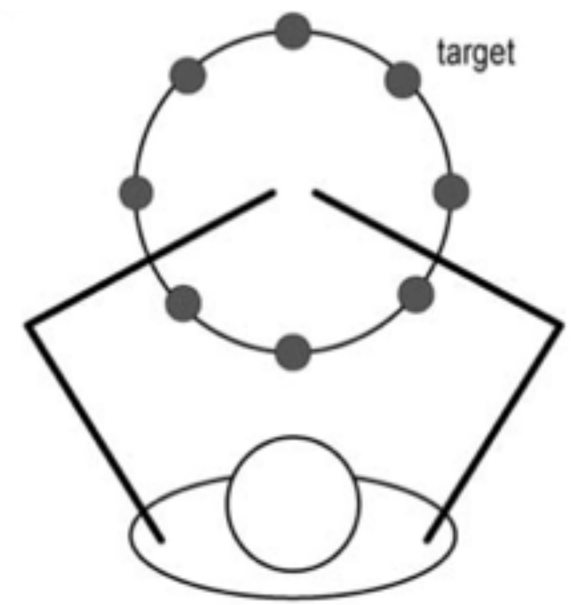
— reach to random targets on a circle

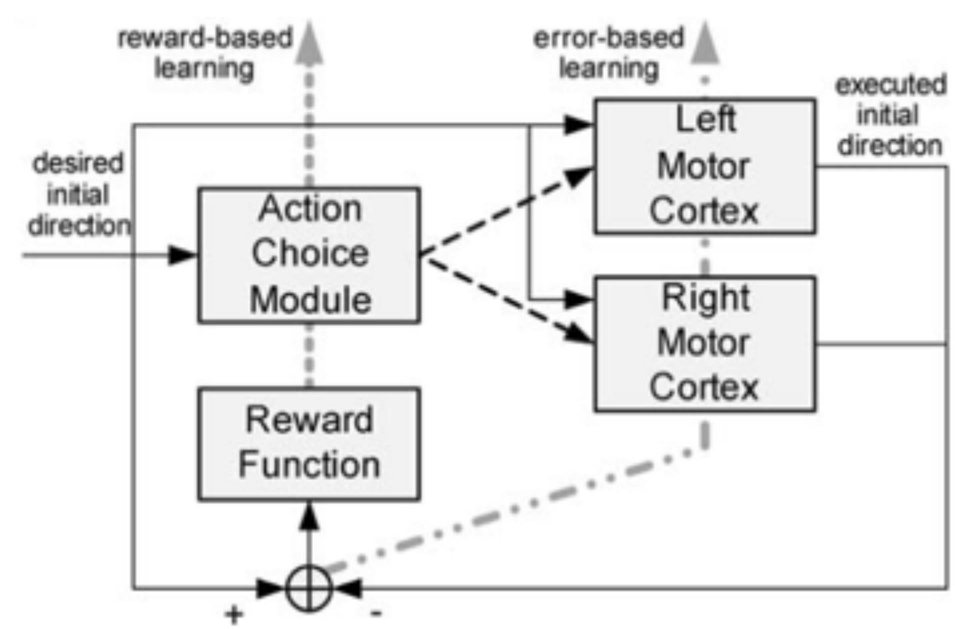
— **Action Choice Module**: decide which arm to use (directional bias)
➜ *reward-based learning*

— **Motor Cortex**: calculate movement direction (directional error)
➜ *error-based learning*

— **stroke** = lesion of motor cortex

— **recovery** = relearning after stroke





— Han et al., 2008, *PLoS Comput Biol* 4:e1000133

MODELING RECOVERY

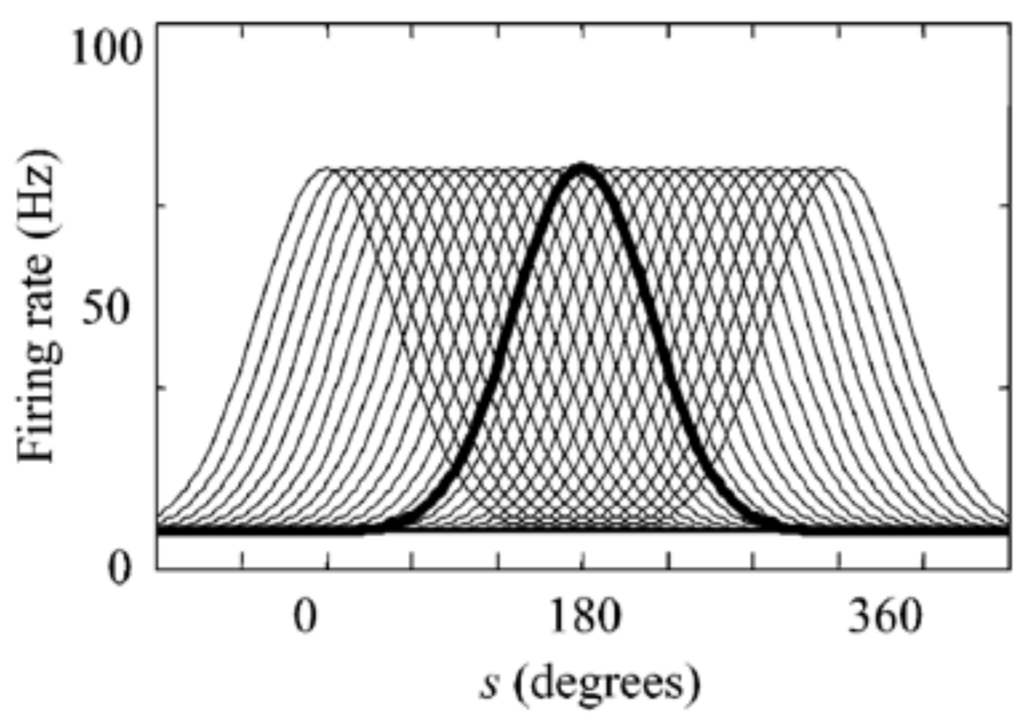
Neural coding in the motor cortex

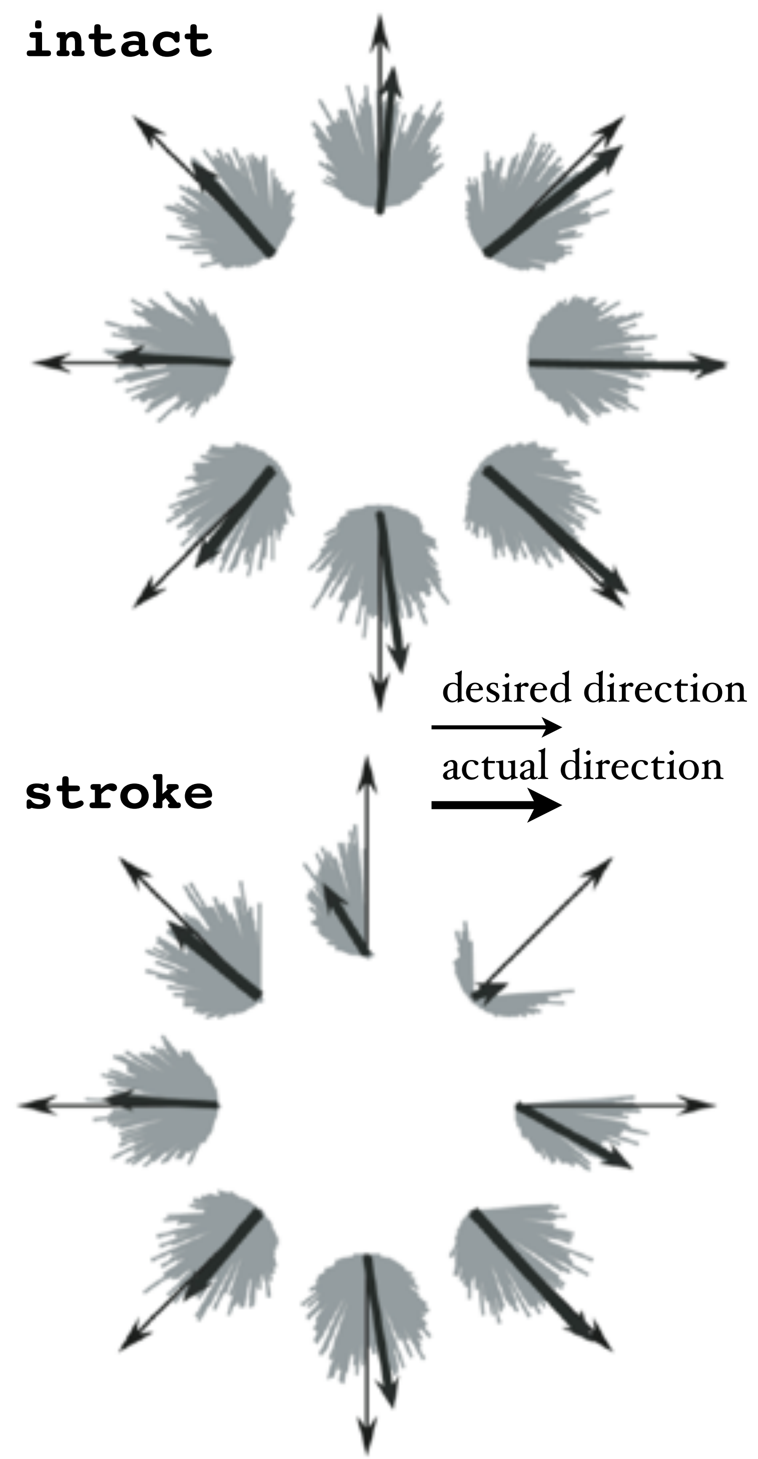
set of directionally tuned neurons

$$y^i = \left[\cos(\theta_\mathrm{d} - \theta_\mathrm{p}^i) + \text{noise}\right]^+$$

θ_p^i preferred direction

θ_d reaching direction





MODELING RECOVERY

- **Plasticity in the motor cortex**

a learning rule induces changes in cells' preferred direction

$$\theta_{\mathrm{p}}^{i} \leftarrow \theta_{\mathrm{p}}^{i} + \alpha_{\mathrm{SL}}(\theta_{\mathrm{d}} - \theta_{\mathrm{e}})y^{i} + \alpha_{\mathrm{UL}}(\theta_{\mathrm{d}} - \theta_{\mathrm{p}}^{i})y^{i}$$

θ_{p}^{i}	preferred direction
θ_{d}	reaching direction
θ_{e}	population direction

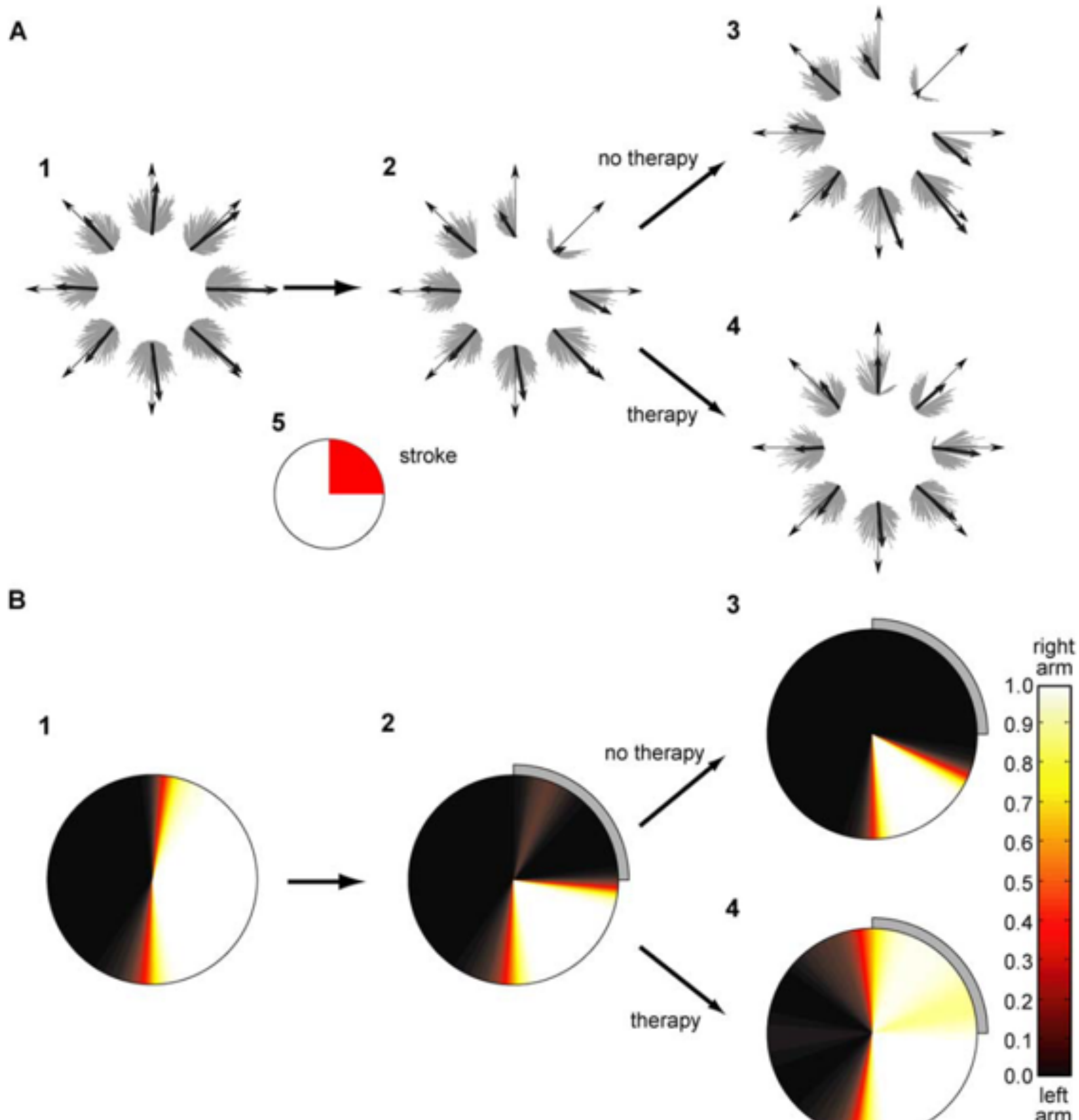
supervised learning
minimize directional error

unsupervised learning
orient the preferred direction toward the reaching direction

- **Action Choice Module**

— select one movement by comparing action values
— reward = accuracy + comfort

MODELING RECOVERY



four phases

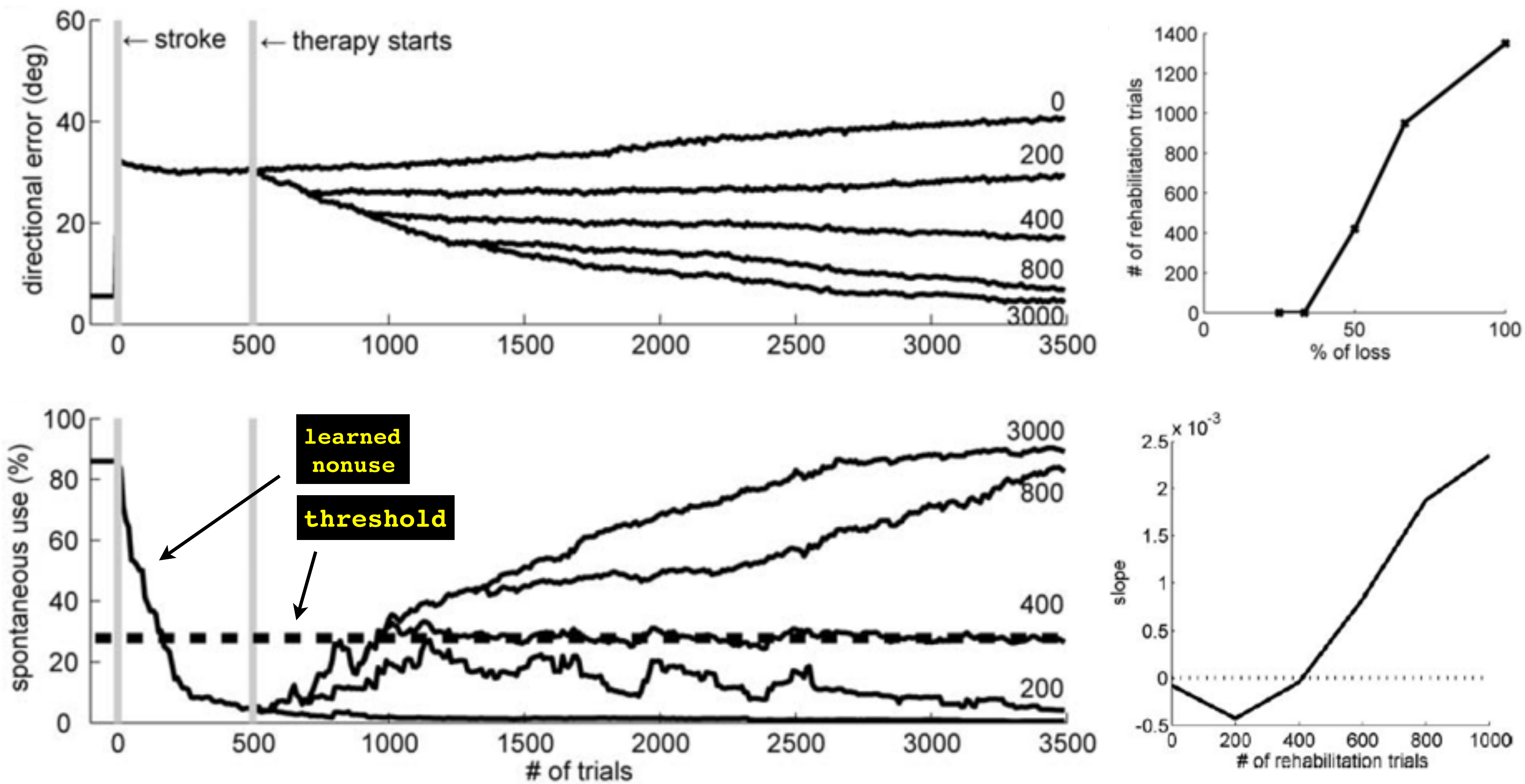
(1) acquisition of normal bilateral reaching = 2000 *free choice trials*

(2) acute stroke phase = 500 *free choice trials*

(3) rehabilitation, forced use condition = *variable number of trials* [0-3000]

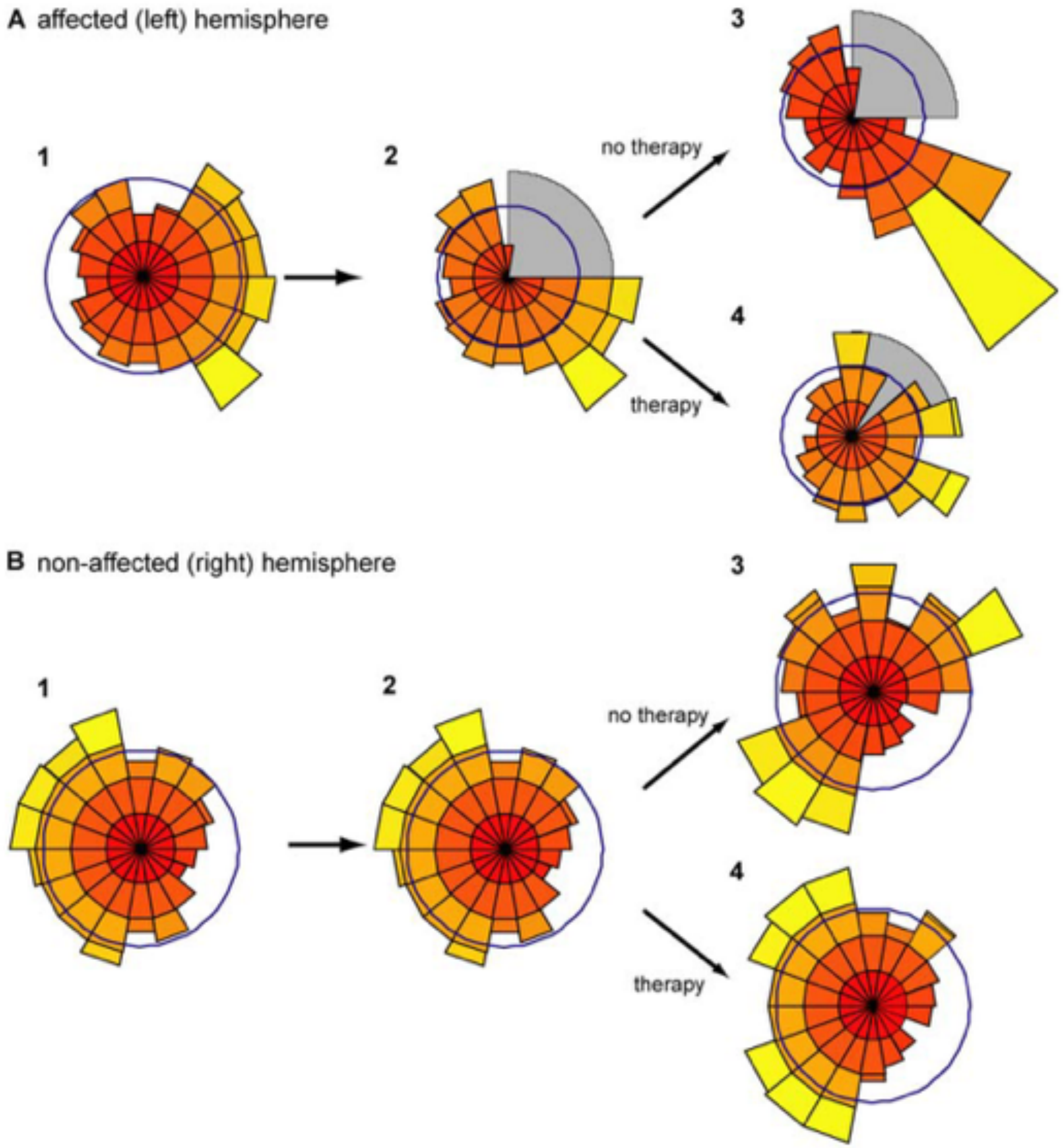
(4) chronic stroke phase = 3000 *free choice trials*

MODELING RECOVERY



therapy duration 0, 200, 400, 800, 3000

MODELING RECOVERY



BRAIN COMPUTER/MACHINE INTERFACE

• Principle

record electrical signals directly from the nervous system to enable communication or control over technological devices

• Electrical signals

— ***myoelectric interfaces***: controlled by signals recorded from muscles

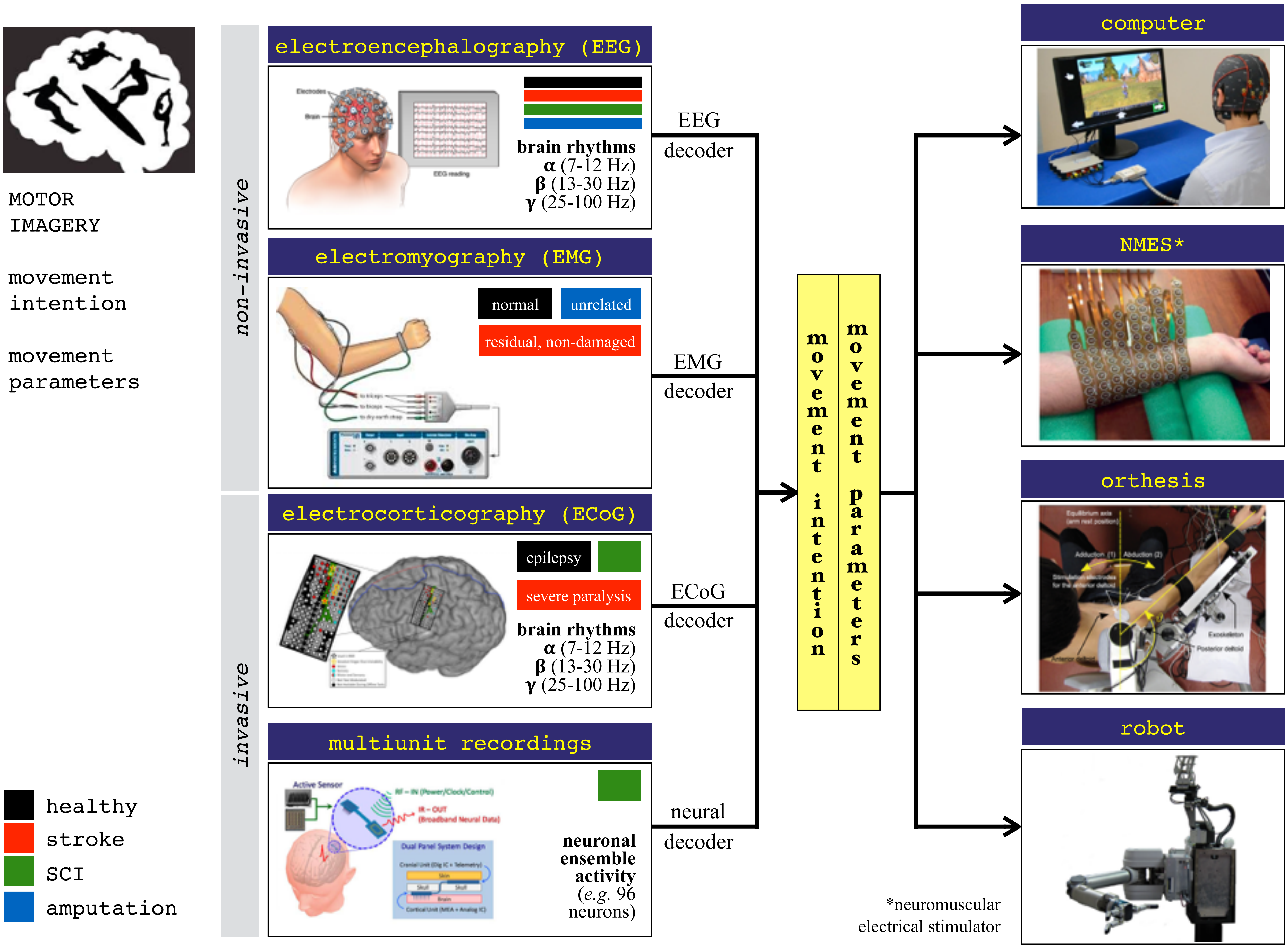
— ***neural interfaces***: controlled directly from the brain (EEG/MEG, neurons)

• Devices

— computer (*e.g.* move a cursor, select a letter)

— prosthesis

— external robotic system


MOTOR IMAGERY
movement intention
movement parameters
healthy
stroke
SCI
amputation
non-invasive
invasive
electroencephalography (EEG)
brain rhythms
α (7-12 Hz)
β (13-30 Hz)
γ (25-100 Hz)
electromyography (EMG)
normal
unrelated
residual, non-damaged
electrocorticography (ECoG)
epilepsy
severe paralysis
brain rhythms
α (7-12 Hz)
β (13-30 Hz)
γ (25-100 Hz)
multiunit recordings
neuronal ensemble activity (e.g. 96 neurons)
EEG decoder
EMG decoder
ECoG decoder
neural decoder
movement intention
movement parameters
computer
NMES*
orthesis
robot
*neuromuscular electrical stimulator

BCI/BMI AND NEUROFEEDBACK

- **Principle**

provide real-time feedback of certain features of brain signals

- **Goal**

learn to modulate brain activity through operant conditioning

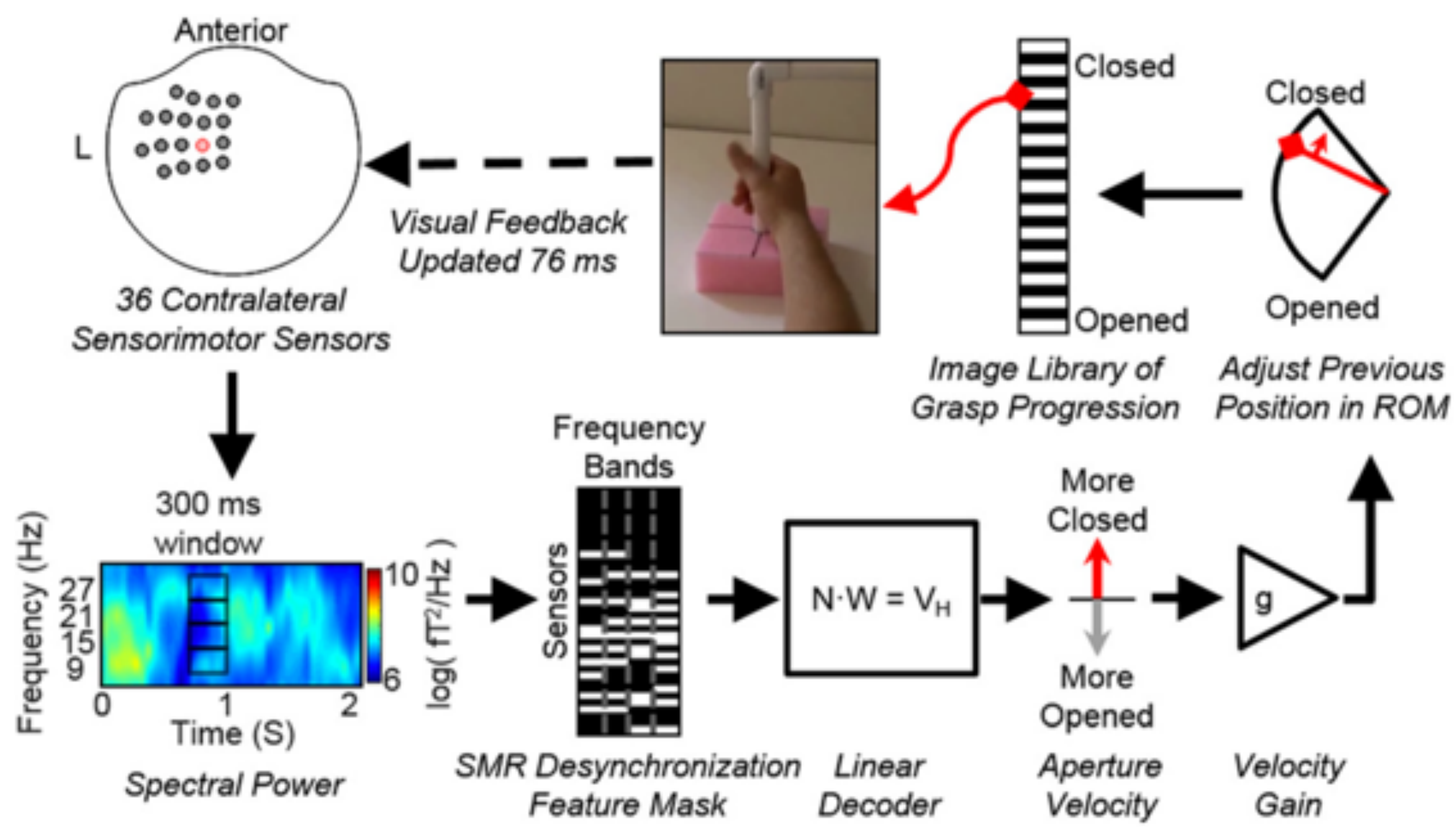
- **Consequence**

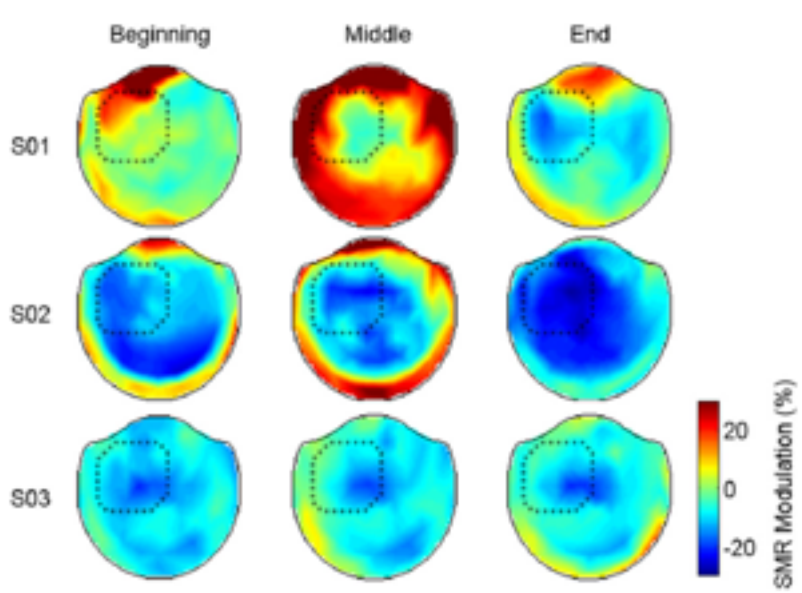
promote therapeutic neuroplasticity?

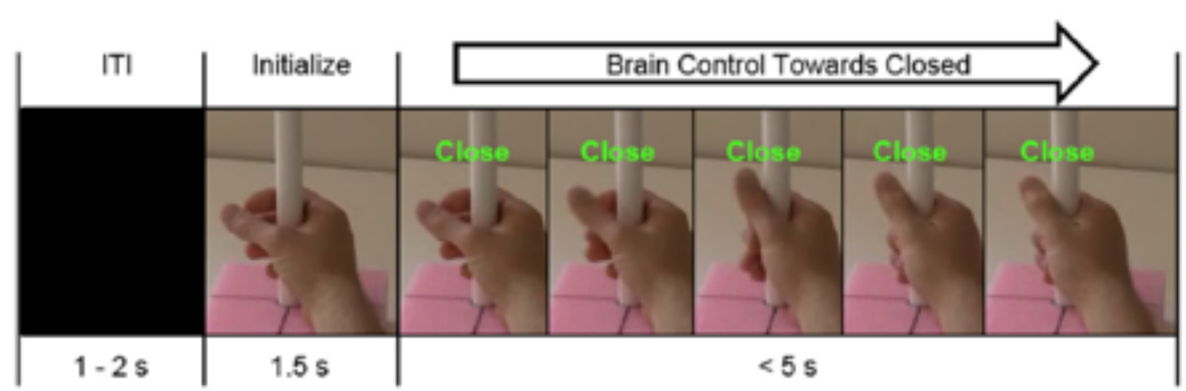
BCI/BMI AND NEUROFEEDBACK

Training of sensorimotor rhythms

e.g. translation of SMR into proportional control grasping







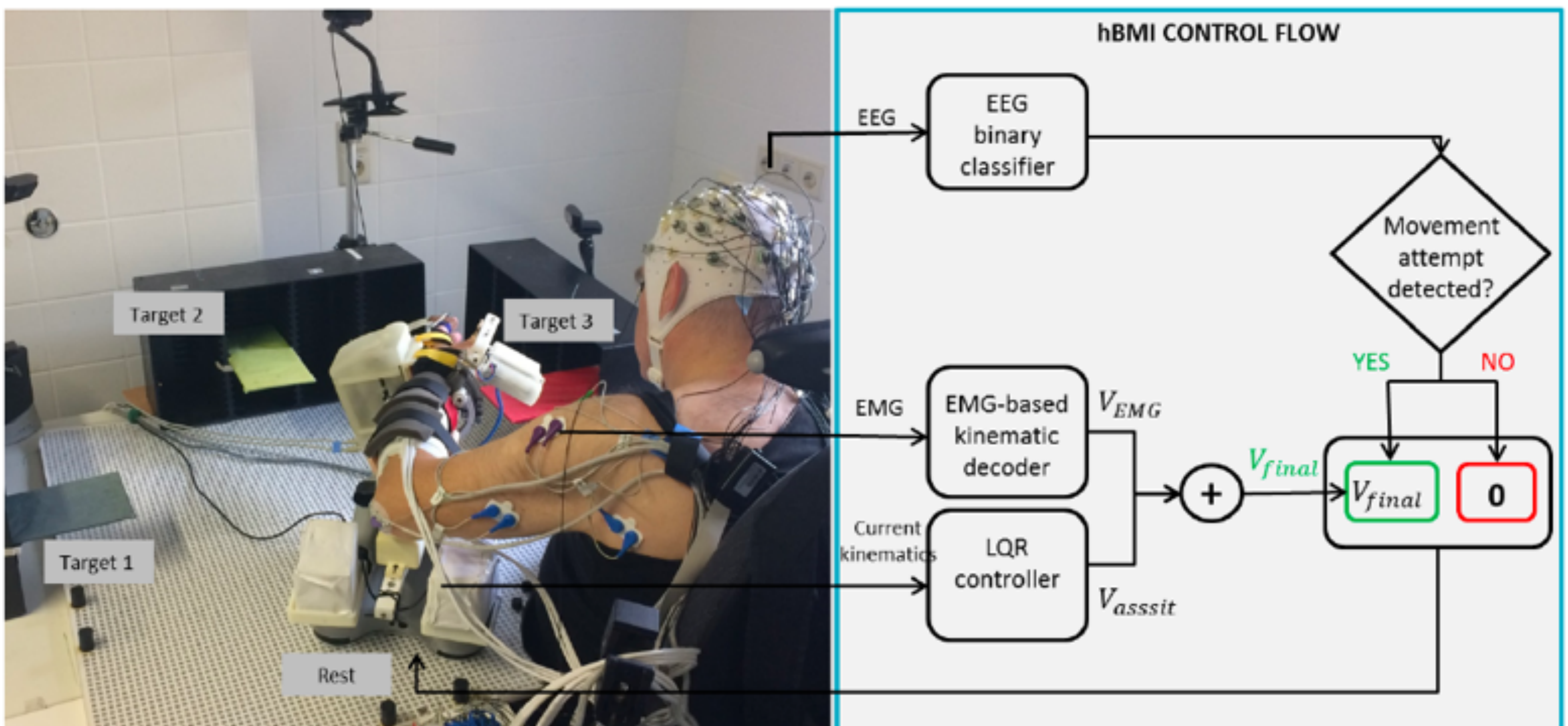
— Foldes et al., 2015, *J Neuroeng Rehabil* 12:85

BCI/BMI AND STROKE

BCI-based motor imagery decoding

as an integrative therapy

`EEG-gated EMG control – the EEG decoder detects a user intention – the exoskeleton provides assistance to the movement based on EMG`



— Sarasola-Sanz et al., 2017, *IEEE Int Conf Rehabil Robot* 2017:895

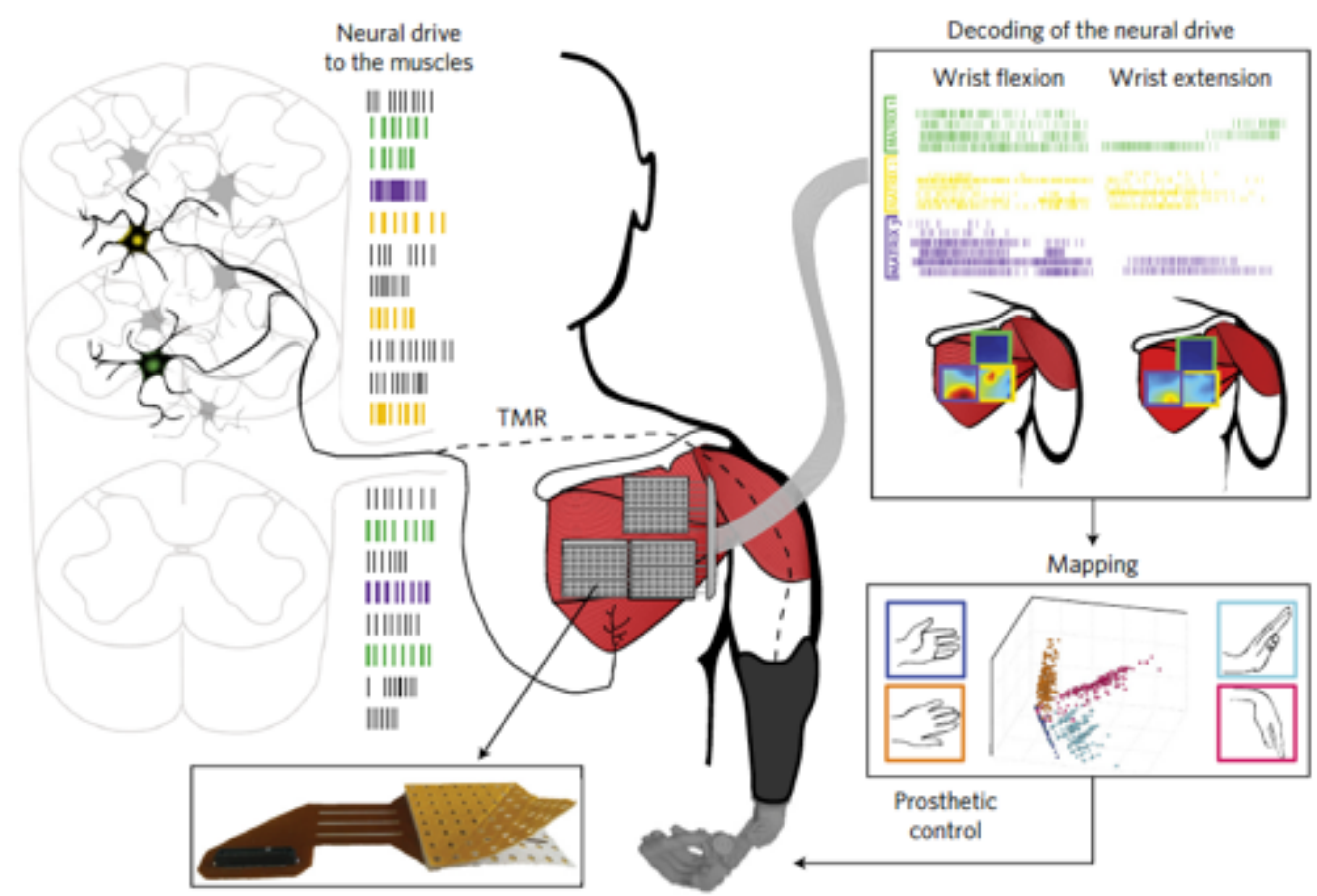
BCI/BMI AND AMPUTATION

Interfacing spinal motor neurons

— nerves are surgically redirected to innervate accessory muscles

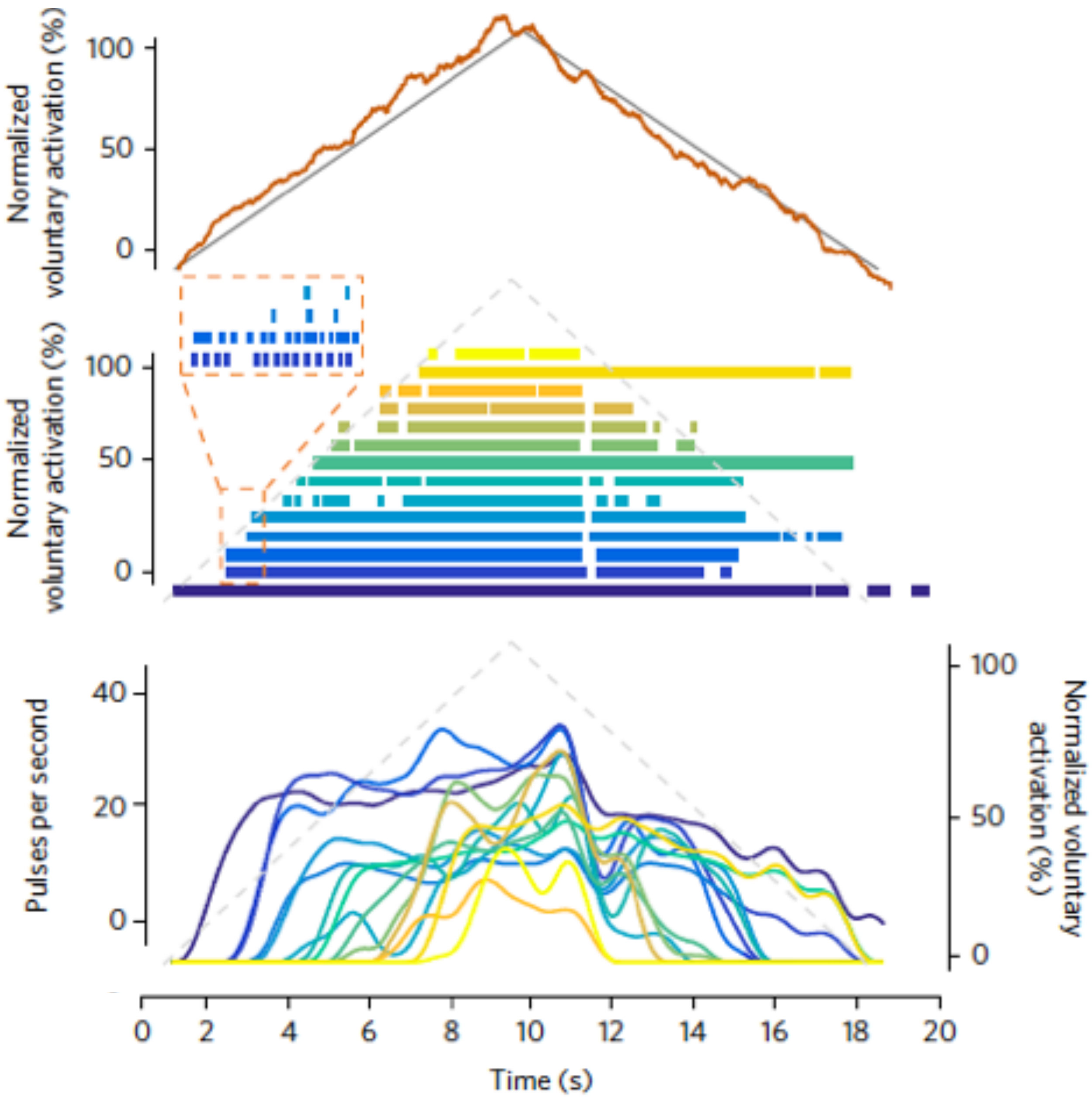
— the discharge timings of the innervating motor neurons are decoded by deconvolution of the EMG signals

— the series of discharge timings are then mapped into degrees of freedom of the prosthesis

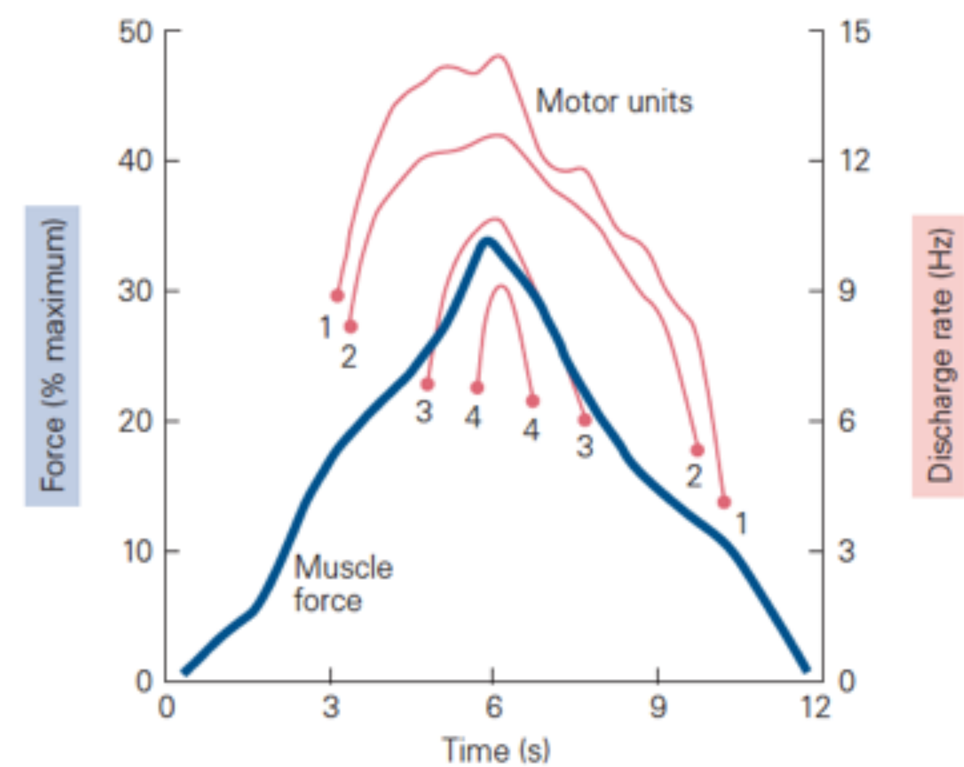


— Farina et al., 2017, *Nat Biomed Eng* 1:0025

BCI/BMI AND AMPUTATION



task – increase and decrease the intensity of muscle activity of the missing limb



— Farina et al., 2017, *Nat Biomed Eng* 1:0025

— Person and Kudina, 1972, *Electroencephalogr Clin Neurophysiol* 32:471

BMI/BCI IN MONKEYS

Self-feeding task

transform neural activity into control signals for 5-dof robot arm

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endpoint velocity and gripper command
extracted from the instantaneous
firing rates of simultaneously
recorded neurons in M1 in real-time
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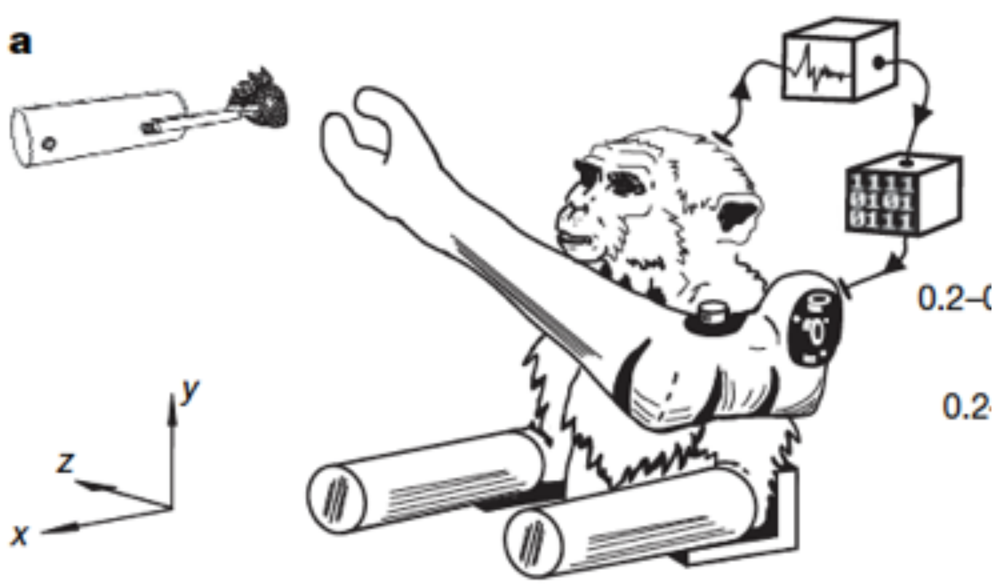
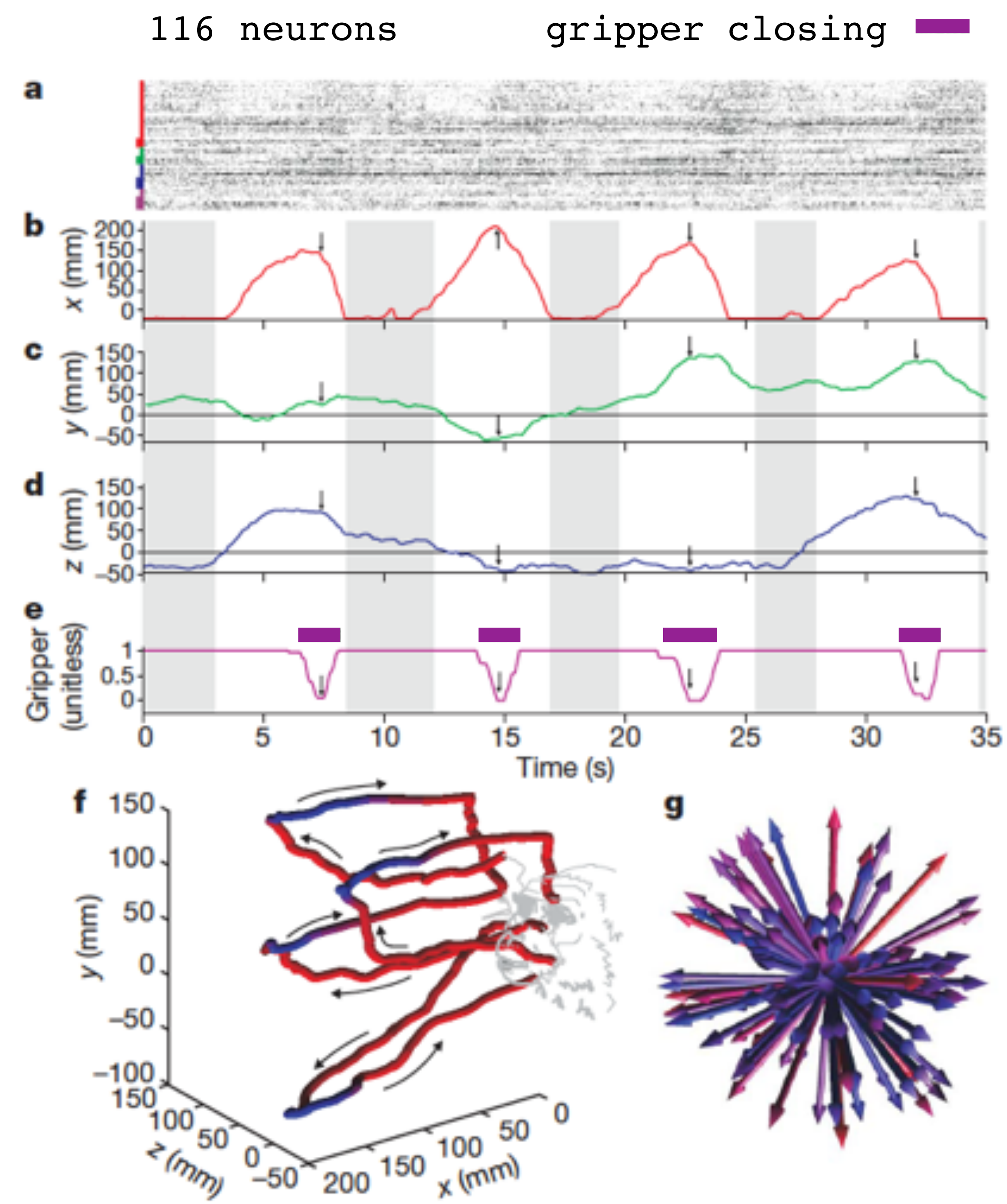




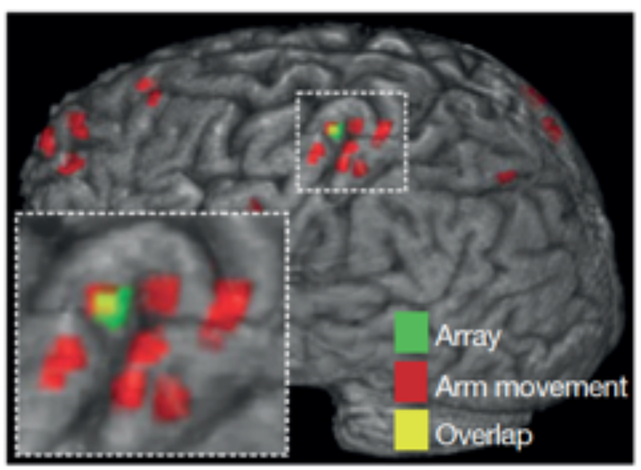
—Velliste et al., 2008, *Nature* 453:1098

BCI/BMI AND PARALYSIS

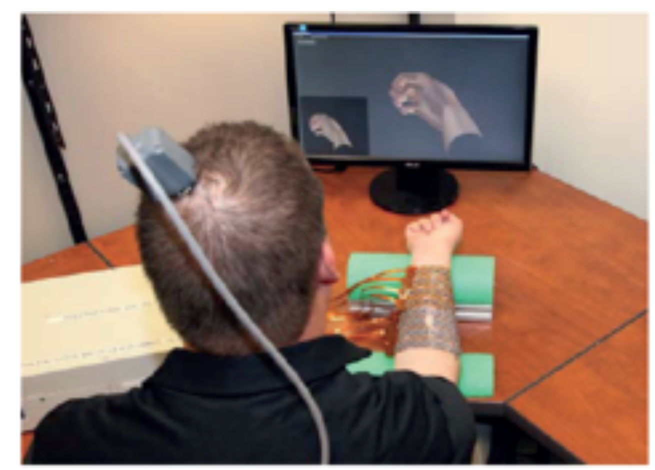
Neural Bypass System (NBS) in a patient with SCI

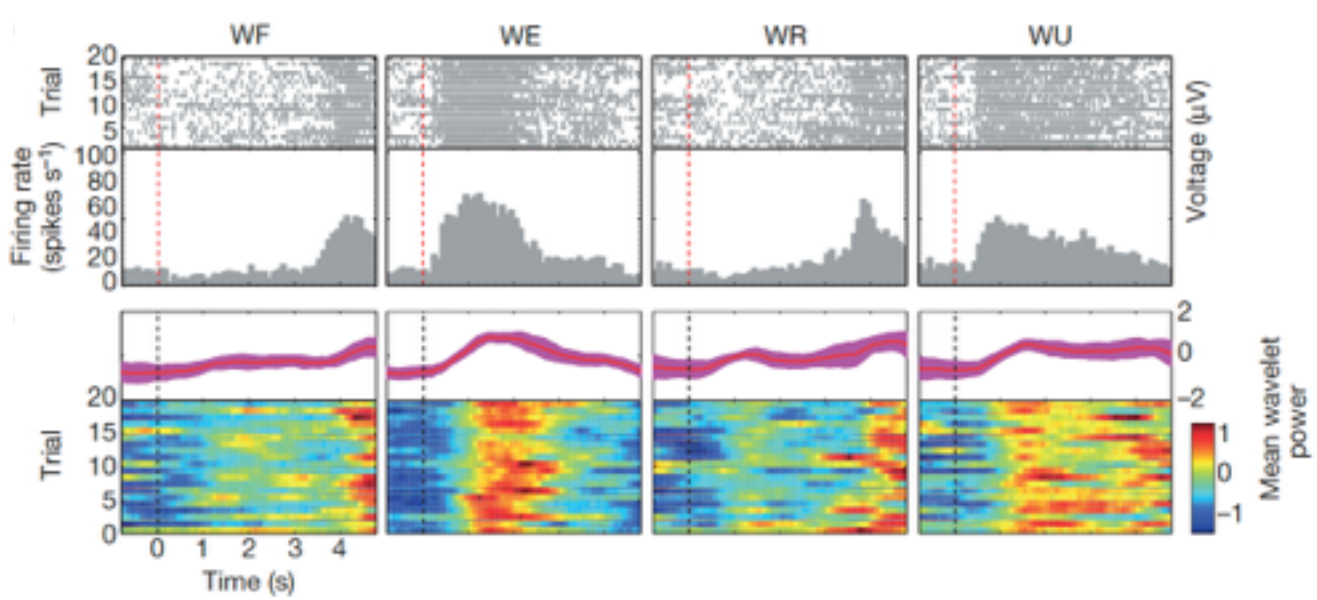
training to use cortical motor activity to control
a neuromuscular electrical stimulator

Utah microelectrode array

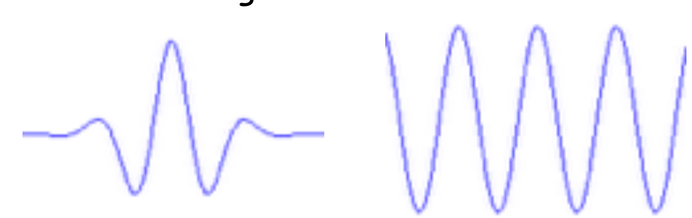


NMES



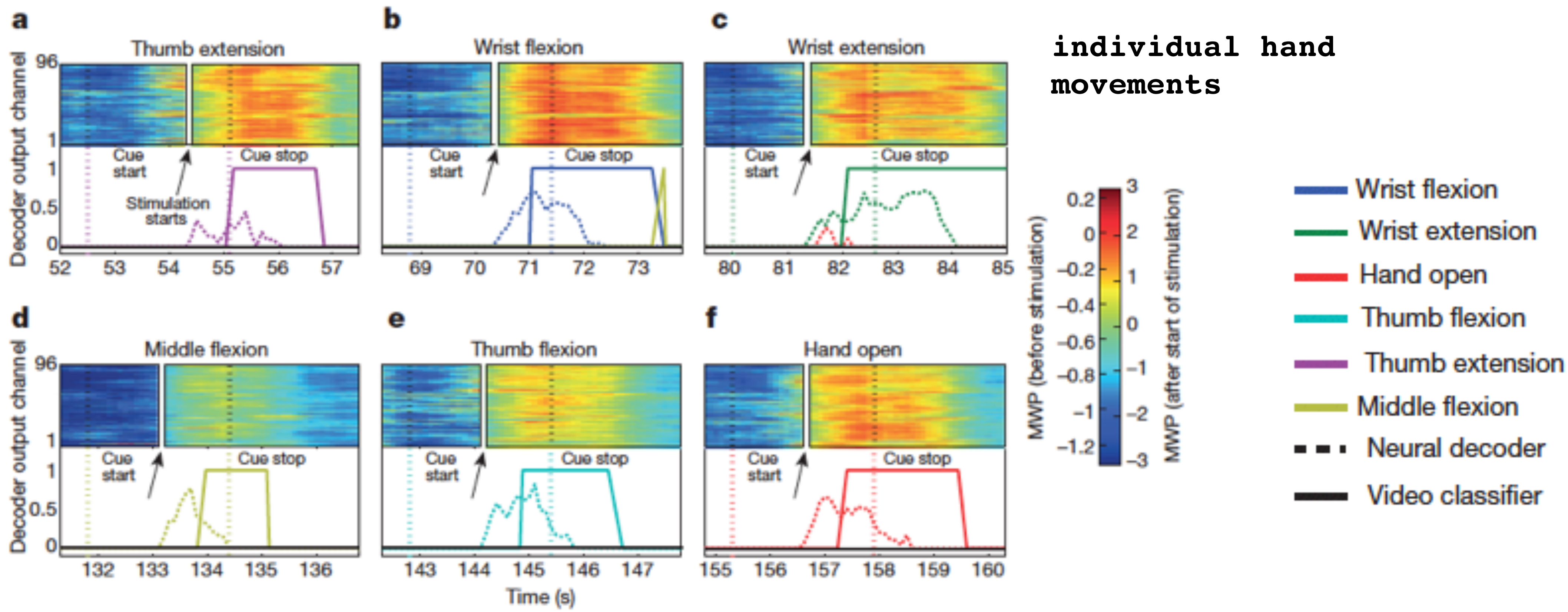


wavelet decomposition
➜ mean wavelet power
➜ decoding

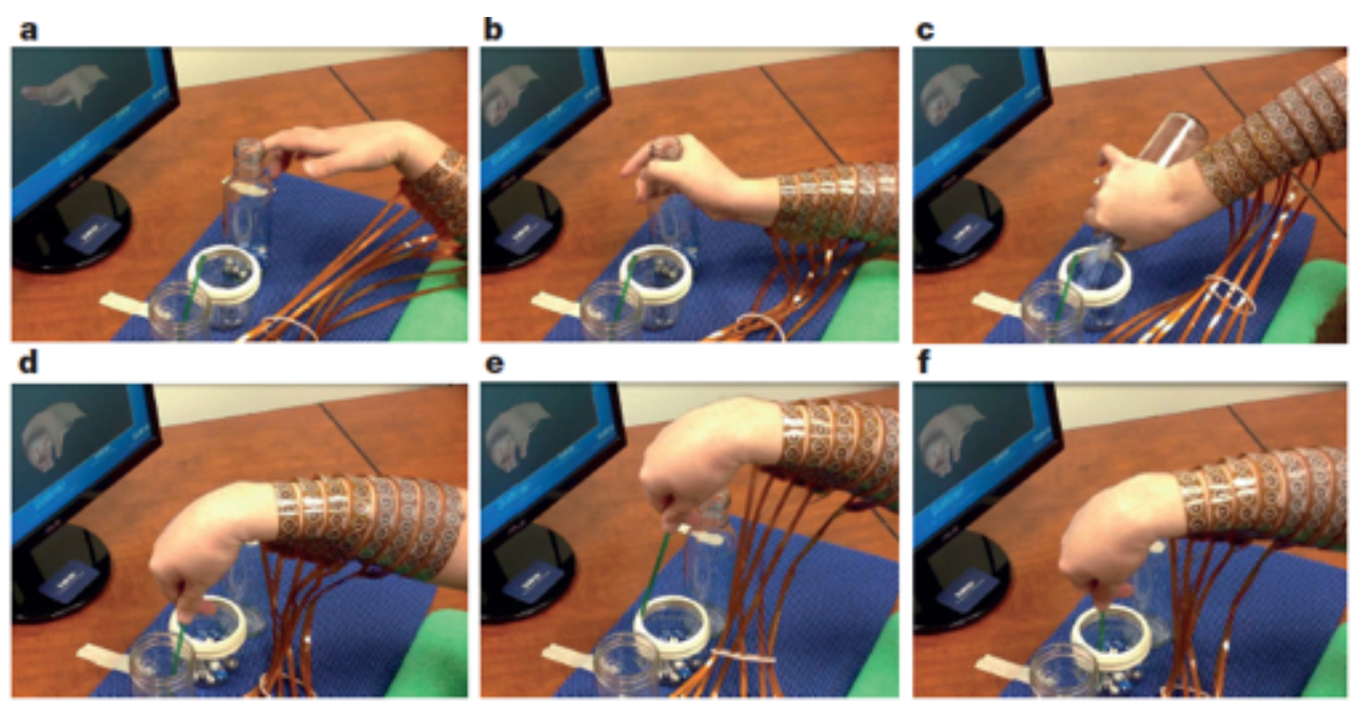


— Bouton et al., 2016, *Nature* 533:247

BCI/BMI AND PARALYSIS



individual hand movements



grasp-pour-and-stir functional movement task