

Better understand and improve accuracy control : from fundamental to applied point of view

Laure Fernandez

Institut Sciences du mouvement

Marseille

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DES SCIENCES ETIENNE
DU MOUVEMENT JULES
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(Aix*Marseille
université
Initiative d'excellence



Laure Fernandez
Maître de Conférence
Recherche : UMR 7287 Institut Sciences du
Mouvement Humain
Equipe : Performance motrice et Modélisation multi-
échelles
Enseignement: Faculté des Sciences du Sport,
Marseille

PhD en Sciences du Mouvement
Post-doc Institut Scientifique Santa Lucia, Dpt
Physiologie motrice, Rome, Italie

LES ÉQUIPES DE RECHERCHE

- [PSNM : Plasticité des Systèmes Nerveux et Musculaire](#)
- [AdapJuste : Adaptations et ajustements aux contraintes externes et internes](#)
- [DCI : Dynamique Comportementale et Immersion](#)
- [ICS : Interactions Cognition Sensorimotricité](#)
- [CMC : Contextes, Motivation et Comportements](#)
- [P3M : Performance Motrice et Modélisation Multi-échelles](#)
- [BIOROB : Biorobotique](#)
- [GIBOC : Groupe Interdisciplinaire en Biomécanique Ostéoarticulaire](#)
- [CBI : Conception bio-inspirée](#)

Accuracy Control

How can I ensure task success whatever the accuracy requirement?



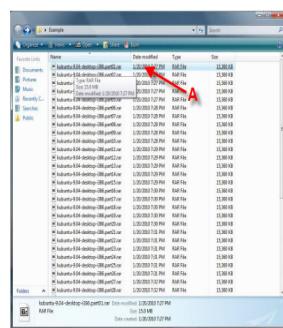
Direct control



Indirect control



Populations



Speed-accuracy trade off

THE Psychological Review

J. MARK BALDWIN
PRINCETON UNIVERSITY

EDITED BY

J. MCKERN CATTELL,
COLUMBIA UNIVERSITY

WITH THE CO-OPERATION OF
ALFRED BINET, BOUÉ, DE MARETTE, D'ALEXANDER, JOHN LEWIS, H. H. MCKALLI-
SON, UNIVERSITY OF CHICAGO; G. S. FULLERTON, UNIVERSITY OF PENNSYLVANIA;
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UNIVERSITY COLLEGE, LONDON.

Series of Monograph Supplements,
Vol. III., No. 2 (Whole No. 13), July, 1899.

The Accuracy of Voluntary Movement

BY
R. S. WOODWORTH.

[Submitted as a thesis for the Degree of Doctor of Philosophy in the Faculty of Philosophy, Co-
lumbia University, and being Vol. V., No. 4, of Columbia University Contributions to Philosophy,
Psychology and Education.]

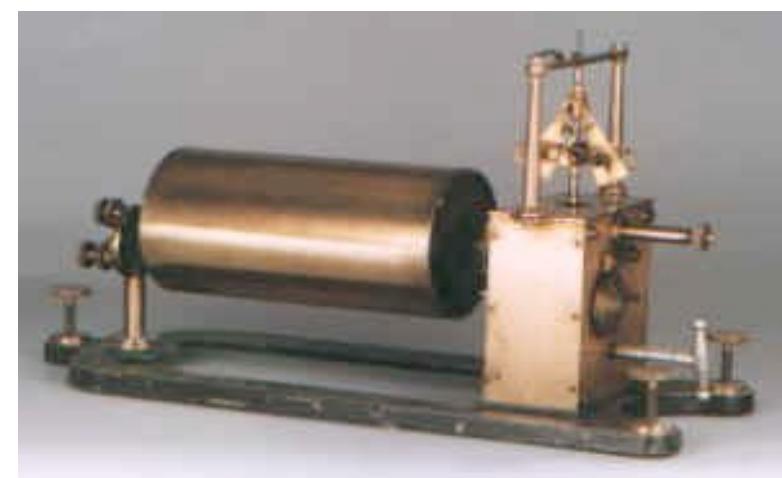
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Accuracy of Voluntary Movement
Psychological Review, 13, 1899

Woodworth (1899)



ROBERT S. WOODWORTH



Speed-accuracy trade off

Psychol.

J. MARK BALDWIN,
Professor of Psychology
ALFRED BUNNELL, Econ.
SON, University of
G. H. HOWES, M.D.,
UNIVERSITY OF WISCONSIN,
COLLEGE OF MEDICINE,
STUDENTS

Series
Vol. III,

THE

ERROR

mm.

4-

2-

0-

20 40 60 80 100 120 140 160 180 200

SPEED

FIG. 2.

Accuracy of Voluntary Movement

Submitted as thesis
University, and "A
Psychology and Education"

TT

66 FEET

ERROR

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20 40 60 80 100 120 140 160 180 200

SPEED

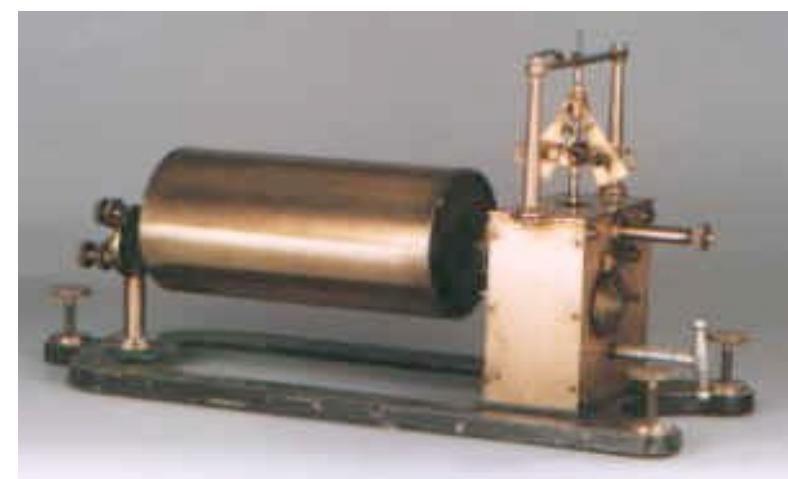
FIG. 3. Relation of accuracy to speed. Right hand.

Accuracy
Psychol.

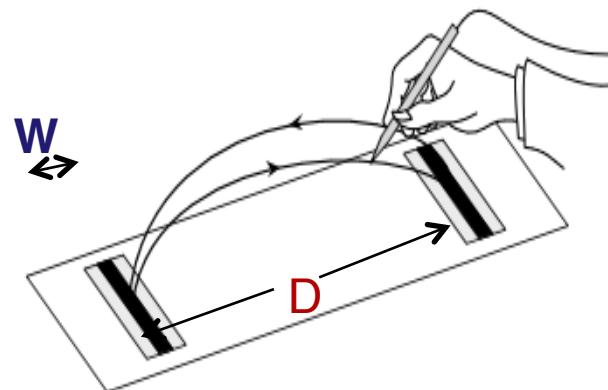
Woodworth (1899)



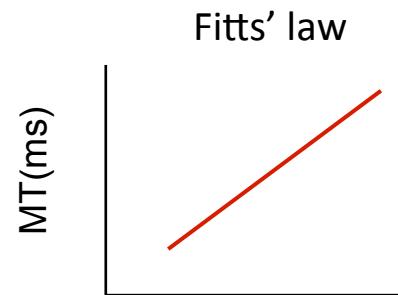
ROBERT S. WOODWORTH



General problem : Why we move the way we do ?



Index of Difficulty
 $ID = \log_2 (2D / W)$
(Fitts, 1954)



- Information processing capabilities
- Despite the multiple **biomechanical degrees of freedom** and **variability** of movements, humans move in a highly **stereotyped** way.

A central problem in motor control: **why?**

Accuracy Control

- Where does come from the speed-accuracy trade-off ?
- Where does come from this optimal movement in response to the task and/or organism constraints ?
- What does the subject try to minimize in a movement constrained in speed and accuracy ?

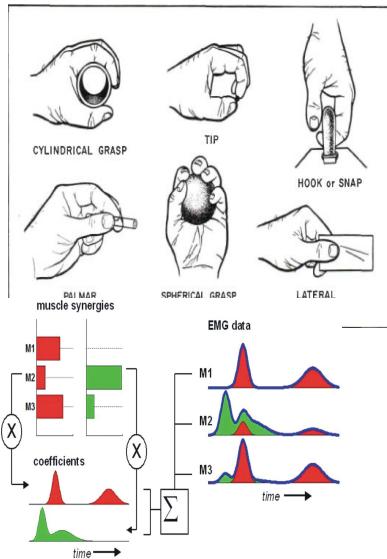
- Is it purely **motor**
- Is it purely **informational** ?
- Which degradation in case of **fatigue**

Fundamental

Applications

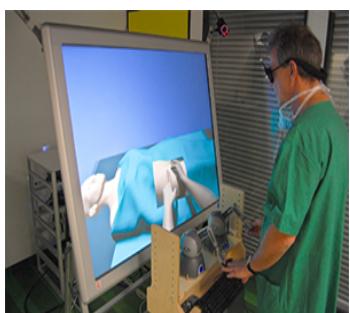
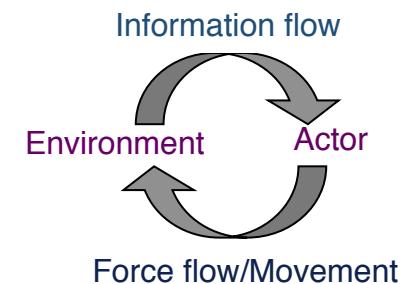
Accuracy control

- Accuracy control: **multi-levels**



End-point level

- End-point kinematics
- Task performance analysis
- Actor/Environment Interaction



Effector level

- Muscular Coordination
- Haptic Interaction
- Grip force / prehension



Applications : Why do we need to understand accuracy control?

- To improve performance in accuracy control situations

Human Movement Interface

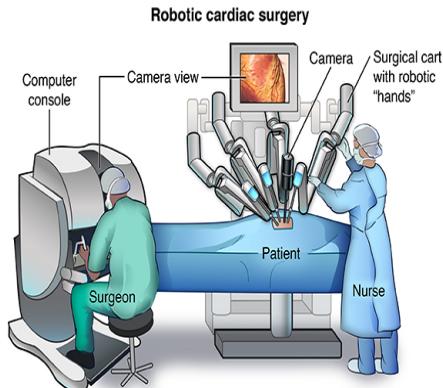


Ergonomics



Musculoskeletal disorders

Telesurgery
Motor Space / Task Space



Pathology
Parkinson disease



Arthrosis
Loss of articular mobility

Rehabilittaion protocol
Occupational therapy

Accuracy Control – Main results

- Where does come from the speed-accuracy trade-off ?

Study 1

- Is it purely **motor**
 - Cocontraction improves performance → energetic consideration
 - **Speed modulation comes first**

Study 2

- Is it purely **informational** ?
 - Fast time scale of the perceptual-motor calibration process
- Which degradation in case of **fatigue** ?

Question

- What does the subject try to minimize in a movement constrained in speed and accuracy ?

Study 1

- Is it purely **motor**
- Is it purely **informational** ?

Neuroscience 197 (2011) 233–241

MOVING FASTER WHILE PRESERVING ACCURACY

O. MISSENARD* AND L. FERNANDEZ

Aix-Marseille University, UMR 6233 Human Movement Sciences Institute, 163 Avenue de Luminy, 13288 Marseille Cedex 09, France

evolutionary advantageous to the organism. In other words, we move the way we do because movements are planned and executed in a fashion that is close to optimal (Todorov, 2004; Diedrichsen et al., 2010). This is to say

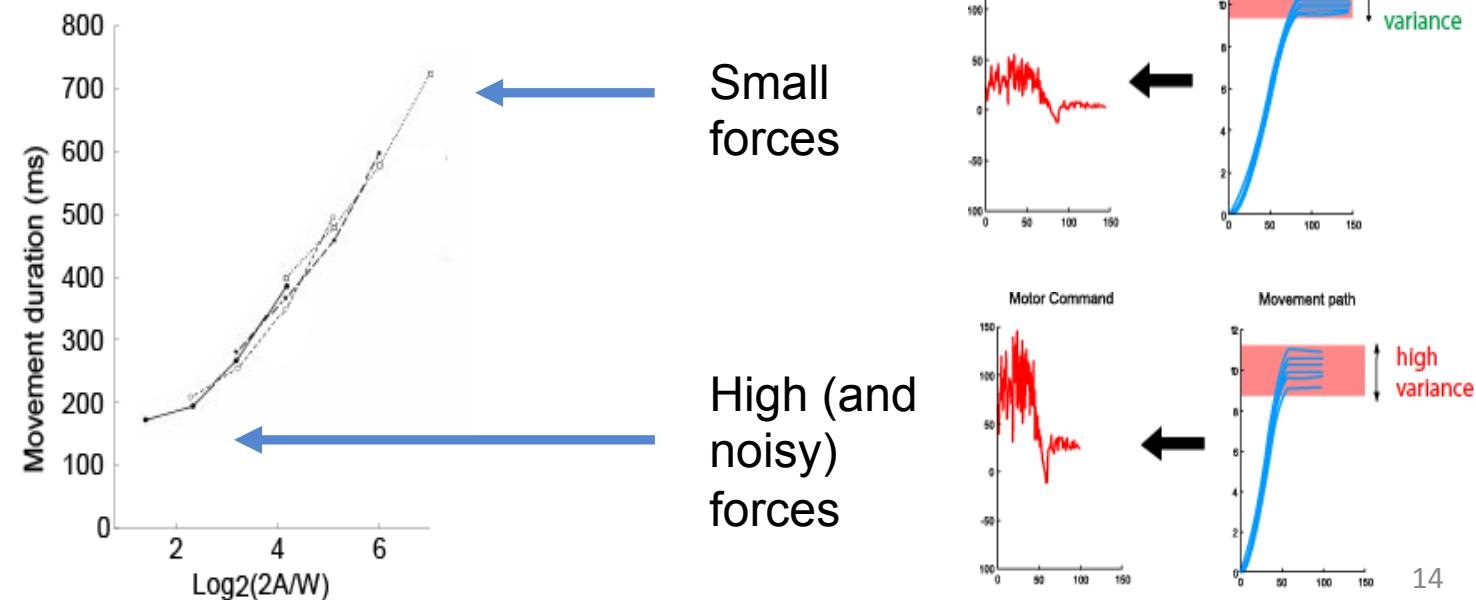
Cost function for accuracy control

- How can I ensure task success whatever the accuracy requirement?
 - 1/ Movement time modulation
 - 2/ Impedance modulation

Movement Time modulation

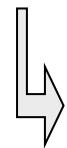
- Woodworth, Fitts
- Neuromuscular force production → signal dependent noise (Schmidt et al., 1979)

$$MT = a + b \cdot \log_2 \left(\frac{2A}{W} \right) = a + b \cdot ID$$



Movement time modulation

- Cost function includes: **movement time and movement accuracy error**



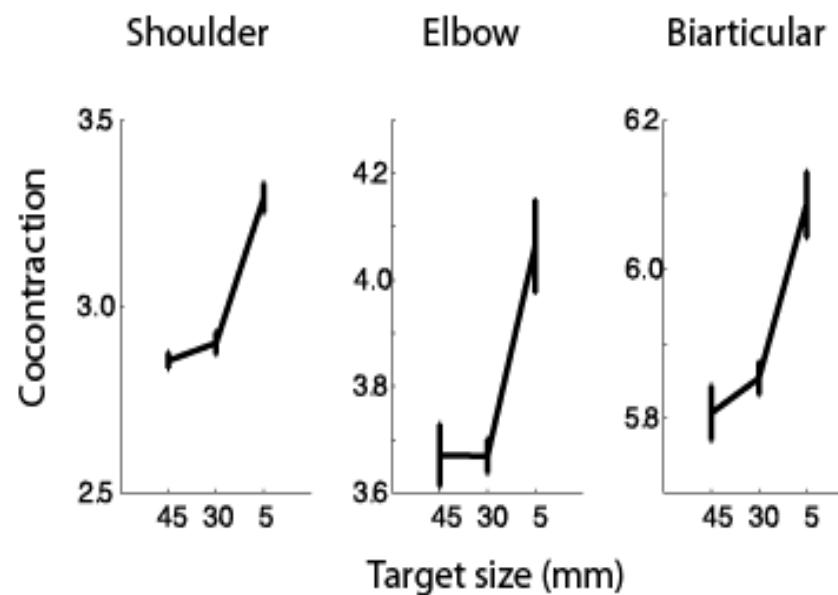
Compromise between speed and accuracy

Schmidt et al, *Psychol Rev* 1979
Meyer et al, *Psychol Rev* 1988
Harris & Wolpert, *Nature* 1998
Tanaka et al, *J Neurophysiol* 2006
Guigon et al, *Eur J Neurosci* 2008

Impedance modulation

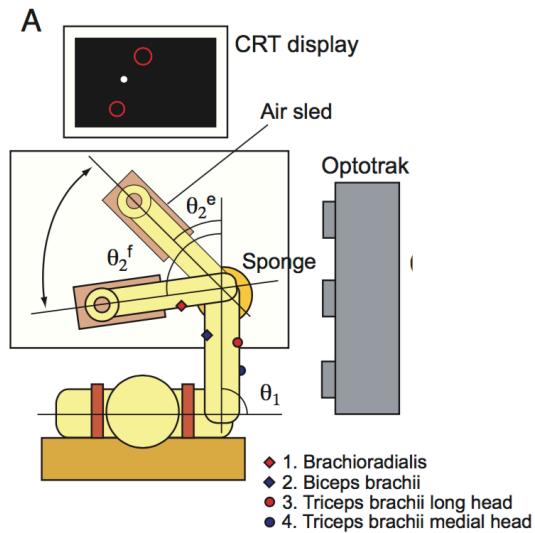
- The **mechanical impedance** of a point on a structure is the ratio of the force applied to the point to the resulting velocity at that point.
- Impedance can be voluntarily modulated by using **muscular cocontraction** (e.g. Osu et al, *J Neurophysiol* 2002).
- Cocontraction is a **metabolically costly** strategy.

Impedance modulation

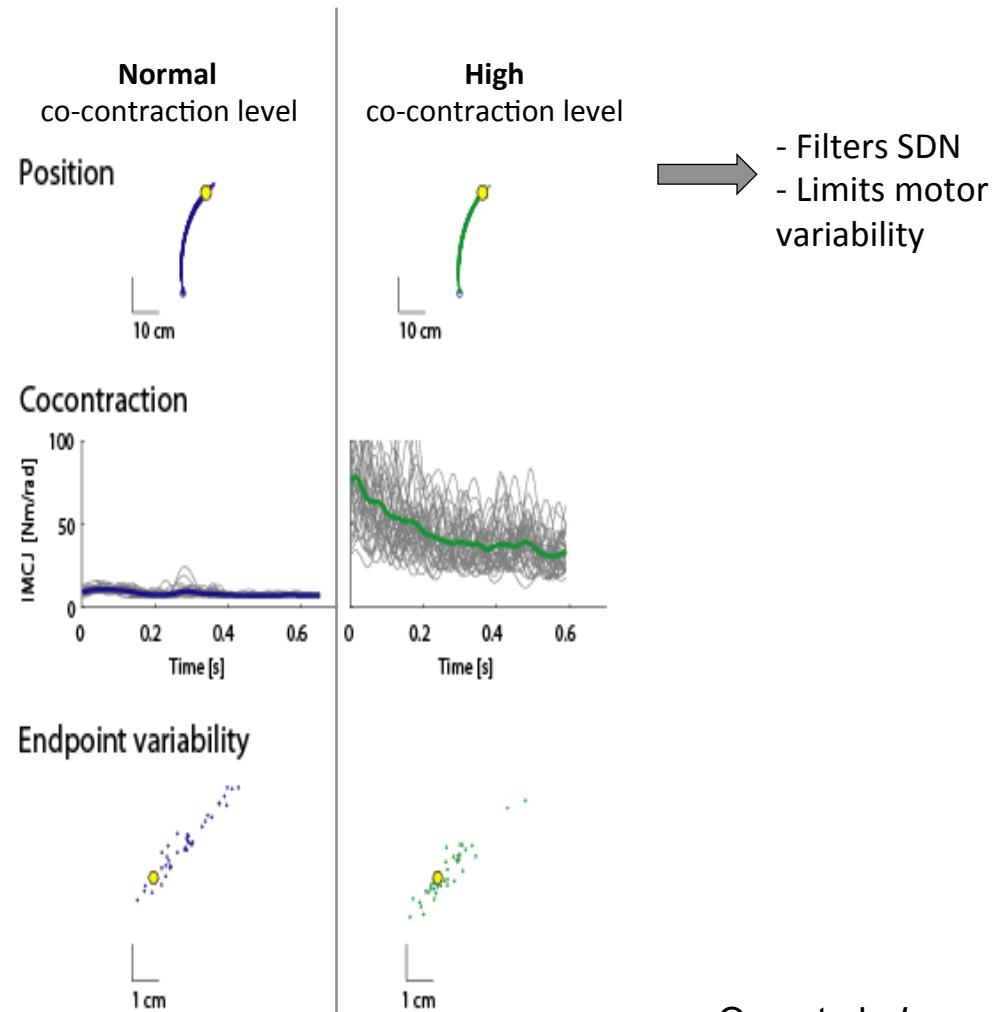


Gribble et al, *J
Neurophysiol* 2003

Impedance modulation



Fixed movement Speed



Osu et al, *J Neurophysiol* 2004

Aim

Fundamental

Determine if **cocontraction** enables humans to move faster while preserving **accuracy**
It is unknown how **movement time** modulation and **impedance modulation** coexist.

Applied

Trade-off between **performance** and **musculoskeletal disorders** using devices requiring fine motor skills (& overuse of these devices)



Experimental strategy

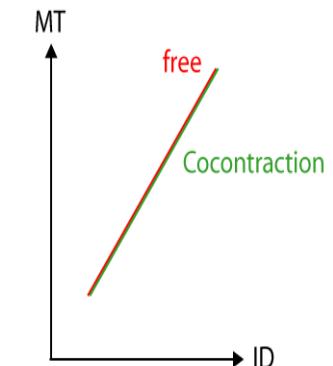
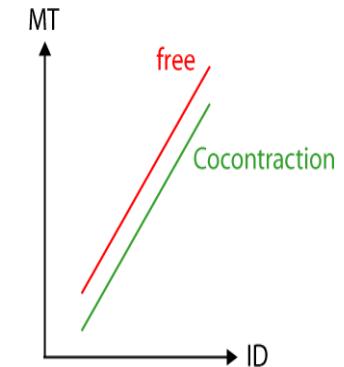
- Effect of **cocontraction on Fitts' law**
- We compared Fitts' law when subjects move:
 - With no particular instruction
 - With the instruction to use cocontraction

Important :

- Fitt's task: subjects receive **no particular instruction about energy economy**: one can imagine that subjects do not care about energy economy when asked to move as fast as possible.

Experimental strategy

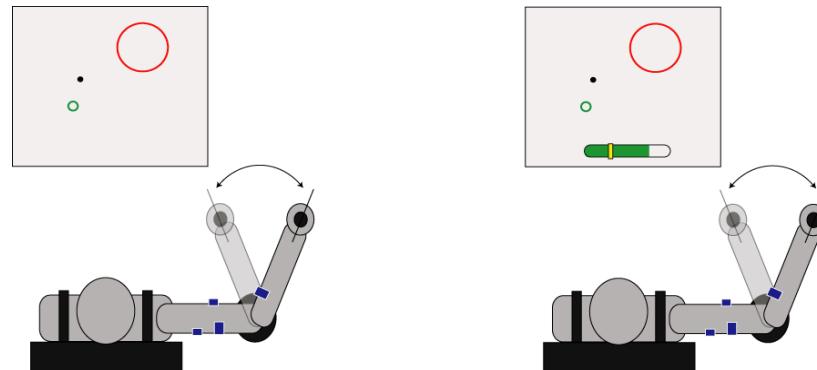
- We studied the **effect of cocontraction** on Fitts' law.
- Predictions:
 - Cocontraction improves Fitts' law
 - Reveals **metabolic considerations** in trajectory formation
 - Fitts' law is unchanged despite cocontraction
 - Suggests that subjects naturally use a strategy which is optimal in terms of **energy economy** and **accuracy control**...



Experimental protocol

- 10 subjects (2 females, 8 males)
- **Discrete aiming task:**
 - As fast and as accurate as possible (the smallest overshoot number as possible)
 - 5 ID by target width modulation (ID = 2; 3; 4; 5; 6) / Amplitude 40°

Free versus Cocontraction



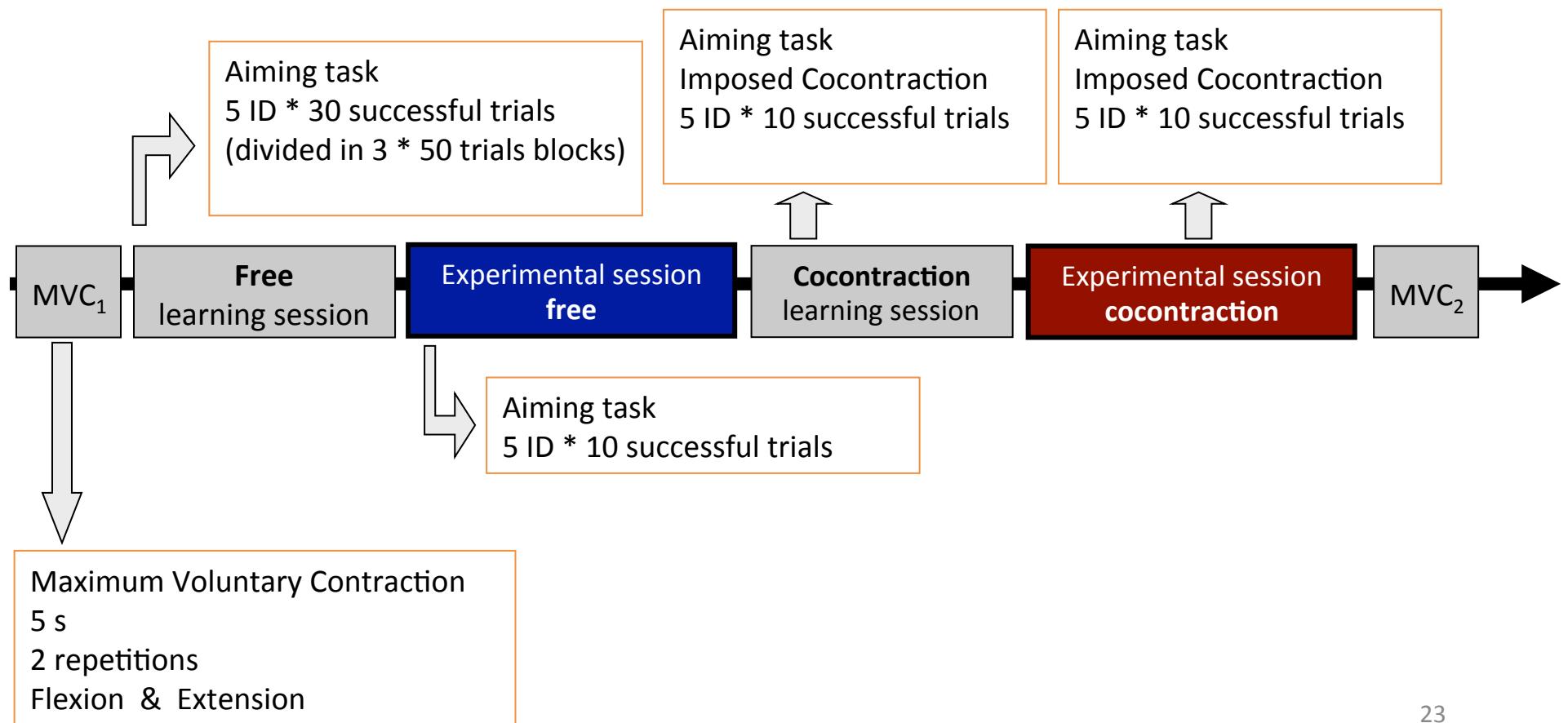
Dependent variables:

- Elbow angular position
- EMG (4 muscles: triceps long and lateral head / biceps / brachioradialis)

- EMG bio-Feedback:
sum of antagonists (i.e. the strongest group) normalized activity

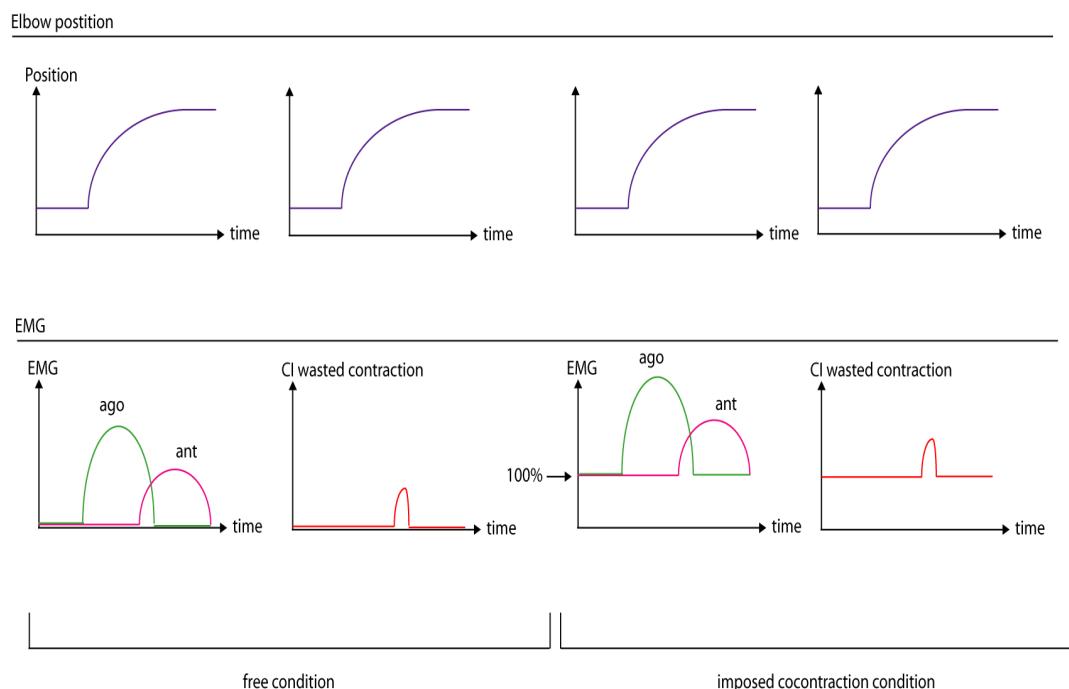
- a minimum of 6% EMGmax was imposed

Experimental protocol

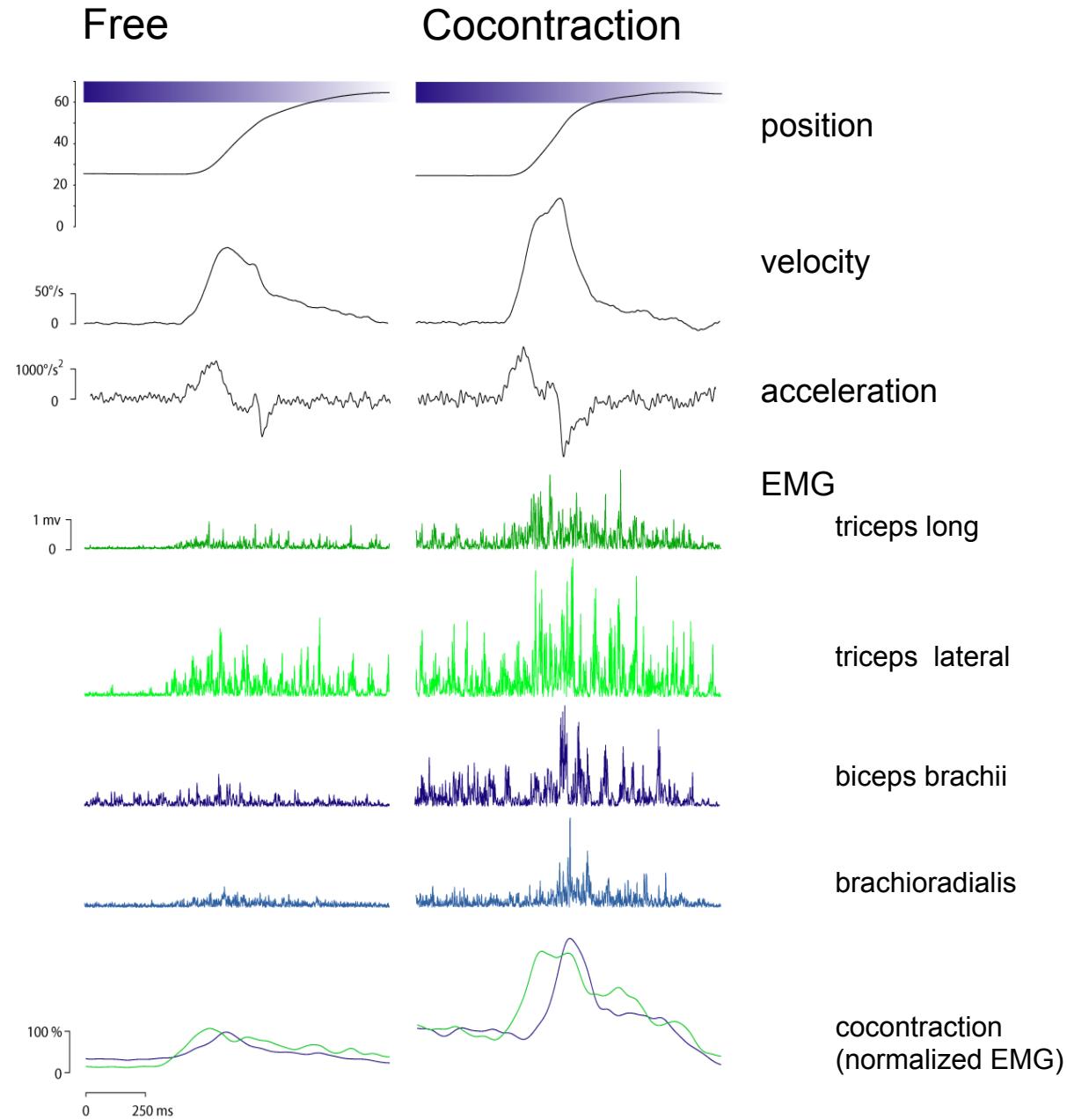


Experimental protocol

- **Cocontraction computation:**
 - *wasted contraction*: the minimum normalized muscle activity for each antagonist pair of muscles (Thoroughman & Shadmehr, *J Neurosci* 1999; Gribble et al, *J Neurophysiol* 2003)
 - normalization versus the pre-movement activity in the cocontraction condition (Darainy & Ostry, *Exp Brain Res* 2008)

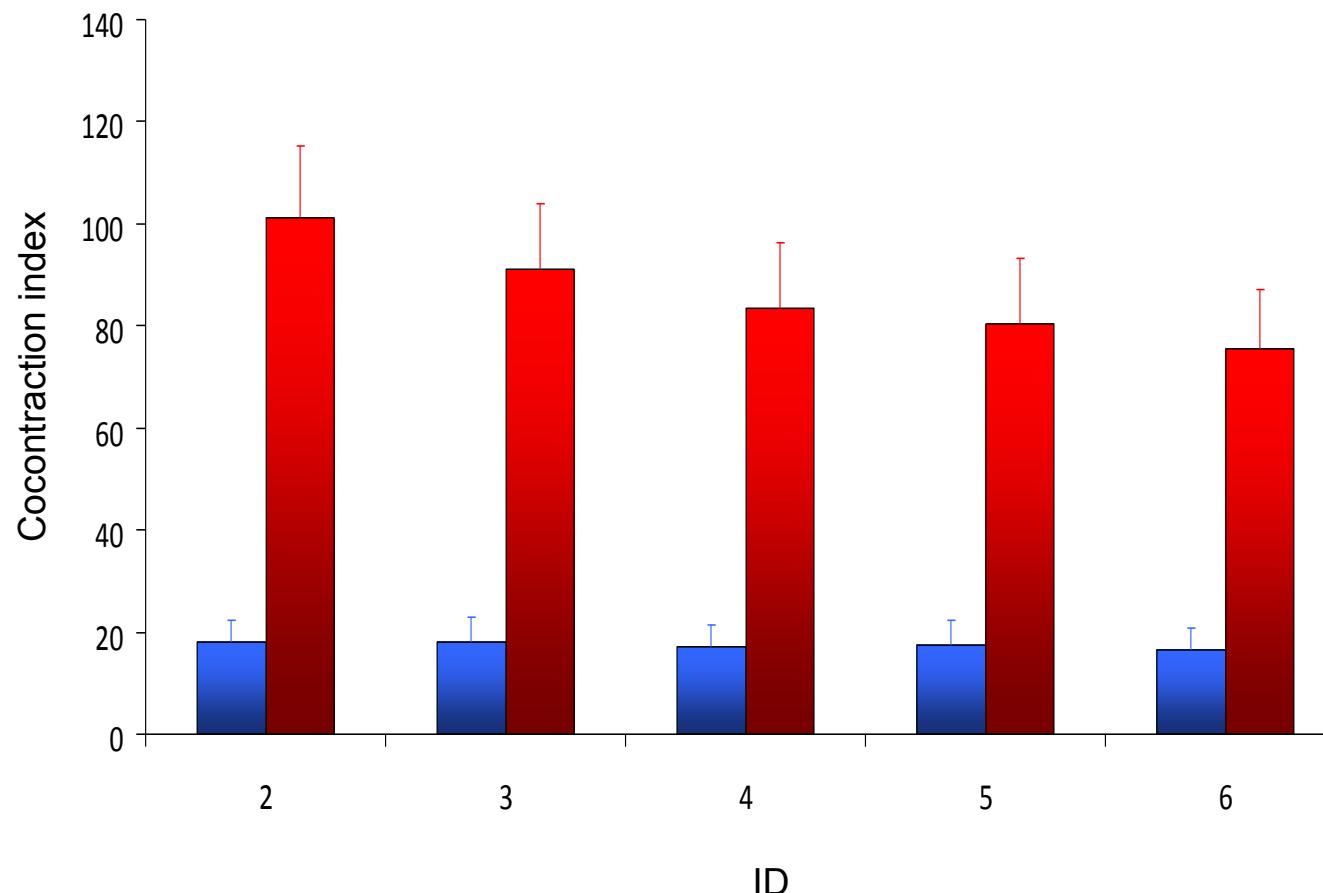


Results



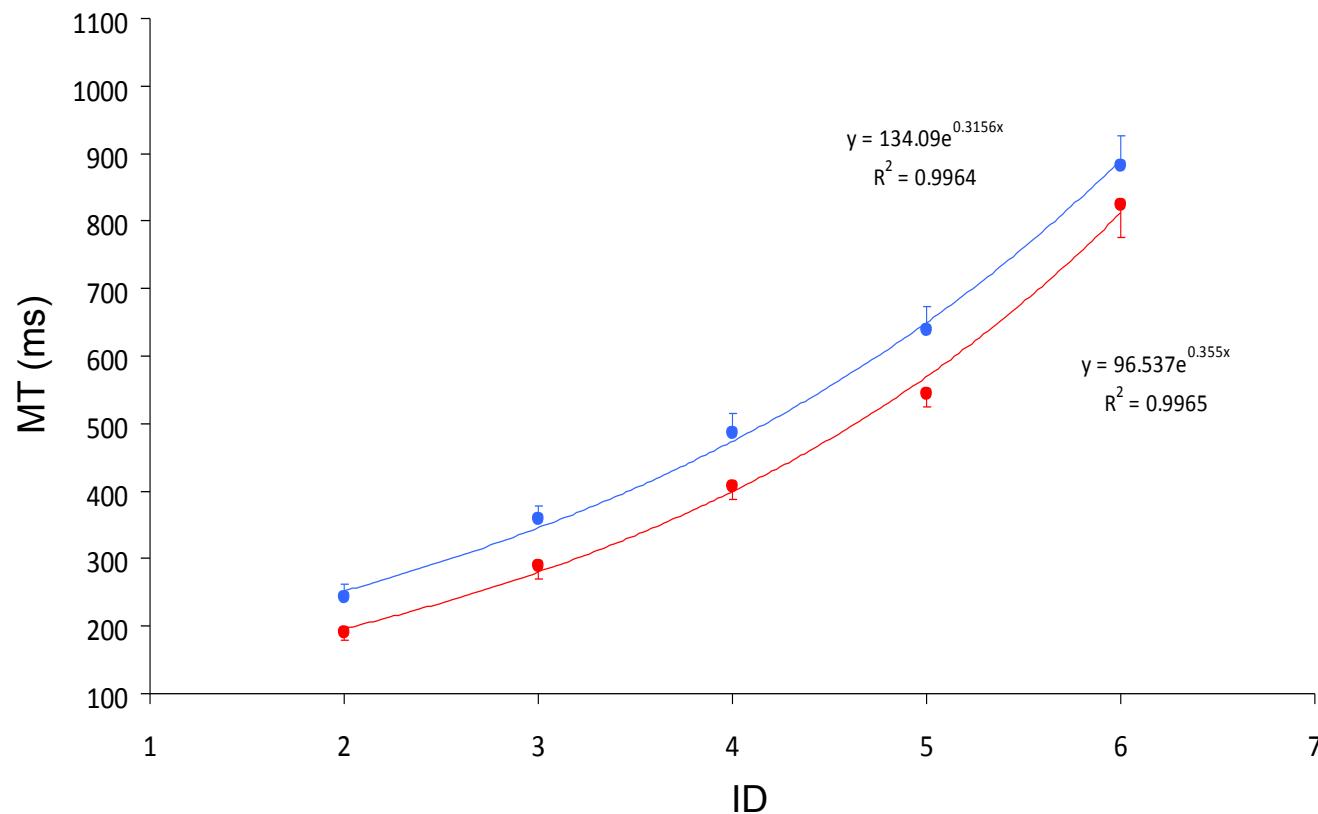
Results

- Cocontraction index: free vs. cocontraction (mean value during movement)



Results

- Fitts' law: free vs. cocontraction



No interaction.

Cocontraction effect ($p = 0.004$): MT significantly lower in the cocontraction condition, for each ²⁷ ID.

Results

- Summary
 - Although subjects were asked to move as fast as possible in both conditions... **MTs were lower when subjects used cocontraction**, whatever the ID.
 - Movement were **less symmetrical** in the cocontraction condition.
 - The learning sessions allowed the subjects to get a **stable performance level**.
 - A **similar (low) level of accuracy errors** was reached in the two compared conditions.

Discussion

Increased limb impedance allows to achieve a given required accuracy with shorter movement times.

- Why does **cocontraction** shorten movement times ?
 - Likely explanation :

because cocontraction filters the **variability** due to
neuromuscular noise...

... and thus improves **movement accuracy**

Selen et al, *Exp Brain Res* 2006
Gribble et al, *J Neurophysiol* 2003
Osu et al, *J Neurophysiol* 2004

Conclusion

- What do we learn about **mechanisms of accuracy control and execution** ?
 - **Speed modulation comes first** : Cocontraction mainly used when speed cannot be modulated (metabolic consideration)
 - Cocontraction = good strategy to optimize **task performance**, when **energy economy** is not a concern.

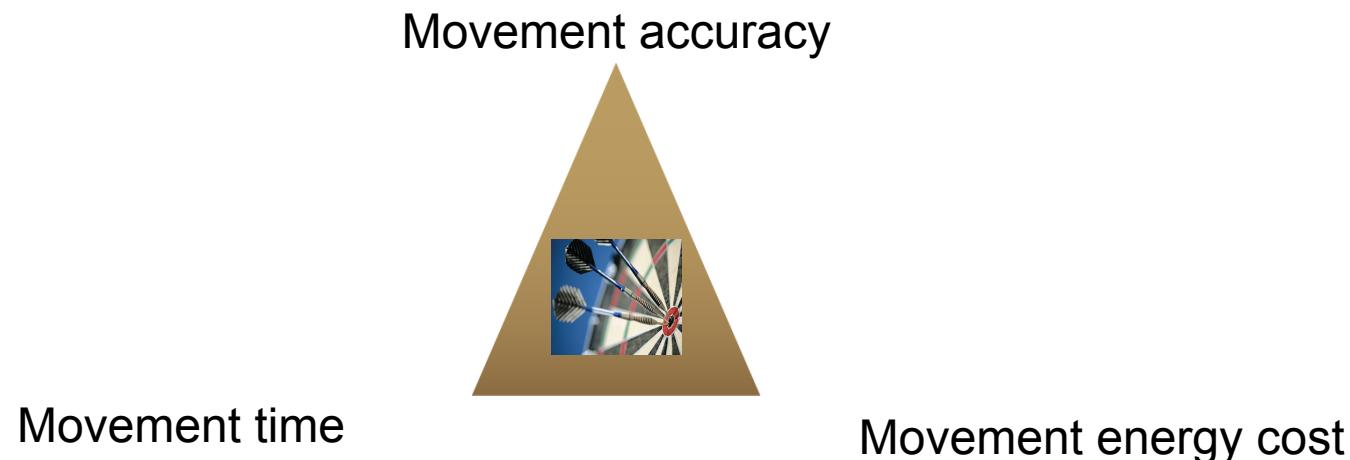
Conclusion

- What does the subject try to minimize in a movement constrained in speed and accuracy ?
 - Is it purely **motor** ?

Energy economy plays a fundamental role in movement accuracy control

→ Metabolic consideration

→ More complex speed-energy-accuracy trade-off



Question

- What does the subject try to minimize in a movement constrained in speed and accuracy ?
 - Is it purely **motor**
 - Is it purely **informational** ?

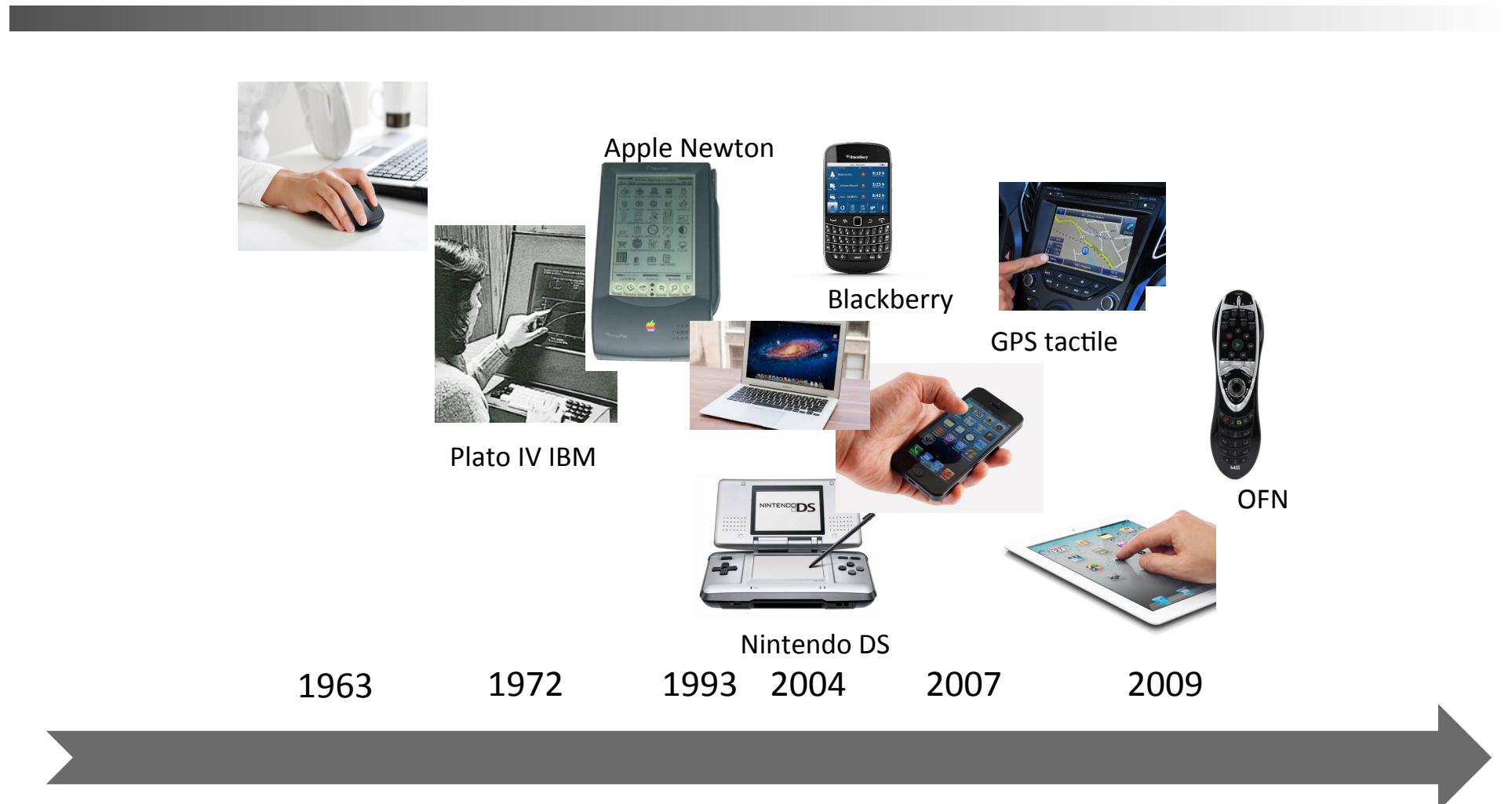
Study 2



Perceptual-motor calibration process to a non 1:1 mapping : the case of changes in visual display gain

Laure Fernandez, Gilles Montagne, Marie-Christine Roubaud, & Géry Casiez

Applied domain : Human Movement Interface



Applied domain : Human Movement Interface

Direct Interaction



Indirect Interaction



Task Space

Motor Space

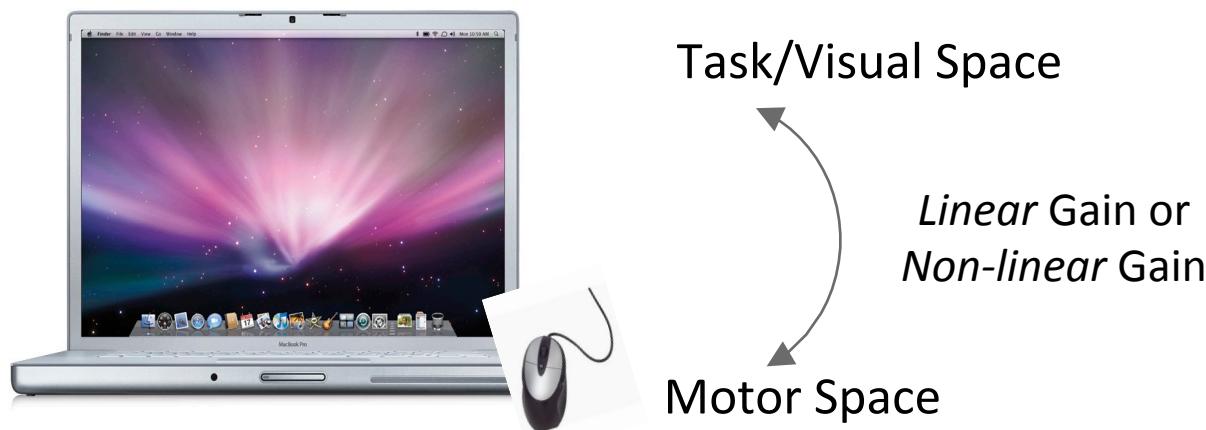
Applied domain : Human Movement Interface



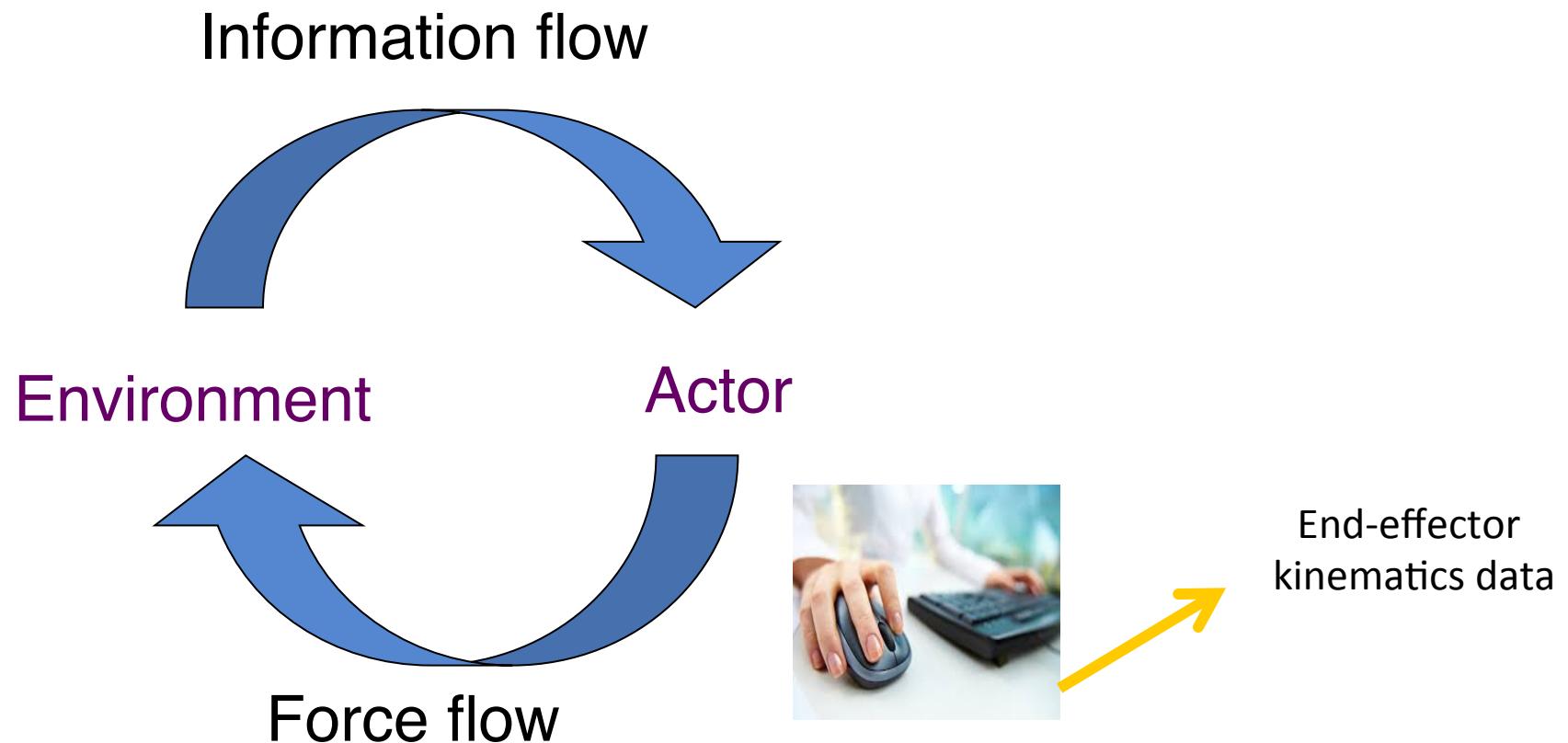
Human efficiency could be increased
improving Human-Machine interaction
But need to understand accuracy control

Context : gain manipulation in HMI

- Device as mouse/trackpad functionning
- Accurate movement realized from a **motor point of view** with the consequences observed in **visual space** (i.e. environment) (Casiez et al., 2008)



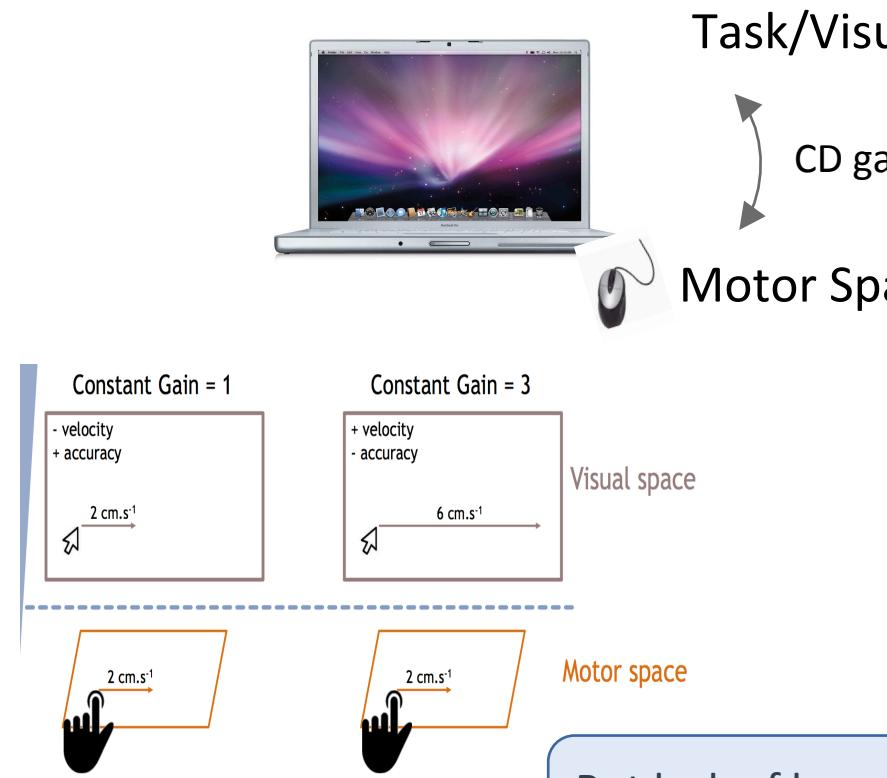
Theoretical context



Manipulation of coupling = skewed relationship between **motor space** and **environment** (visual space)
→ **calibration** to the perceptual consequences of its actions

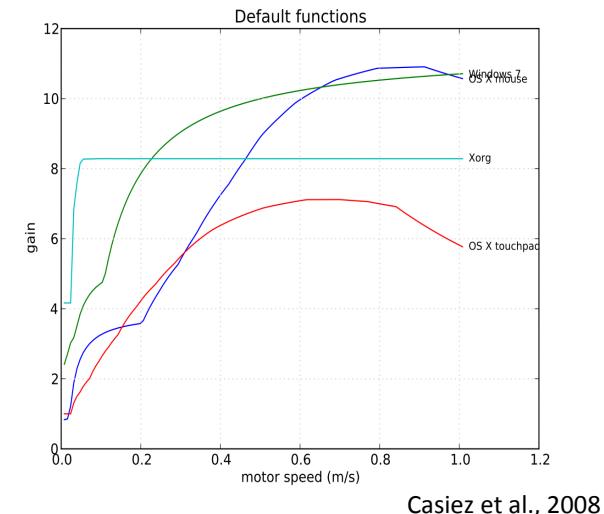
Context : gain manipulation in HMI

- Control Display Gain : algorithm transformation of raw user input for system use



Scotto et al., 2020

But lack of knowledges on **how do we adapt behavior to the gain manipulation ?**



38

Context : gain manipulation in HMI

Experimental Brain Research
<https://doi.org/10.1007/s00221-020-05856-1>

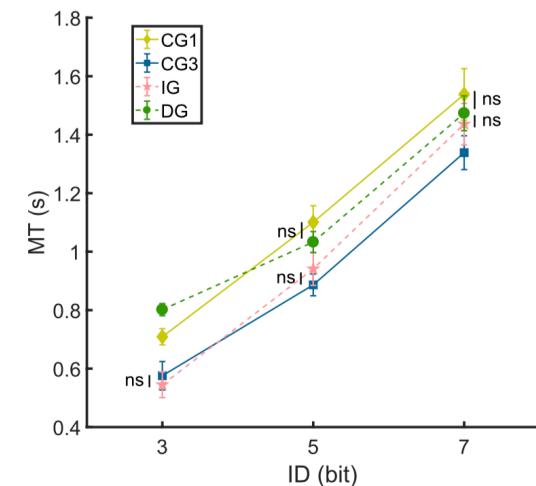
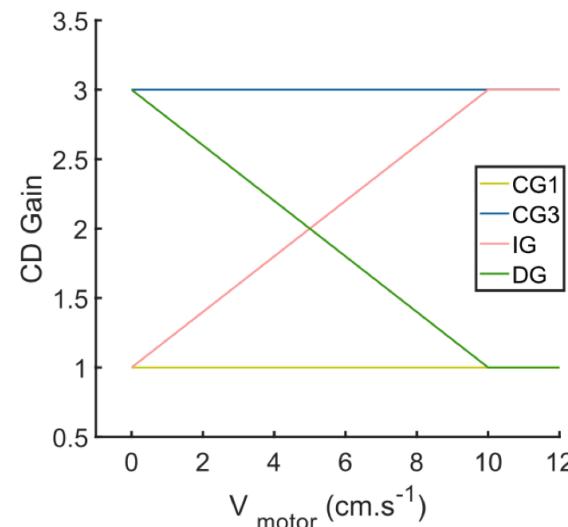
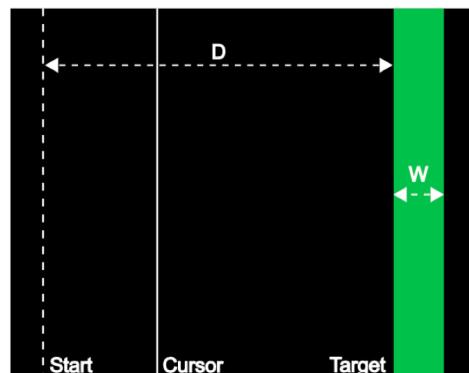
RESEARCH ARTICLE



Sensorimotor control and linear visuomotor gains

Cécile R. Scotto¹ · Van Hoan Vu² · Géry Casiez^{3,4} · Laure Fernandez²

Received: 7 February 2020 / Accepted: 11 June 2020
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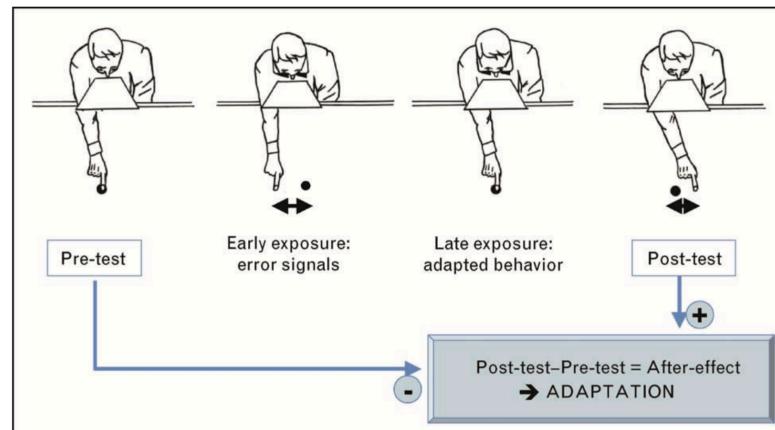


Performance increases with certain Control Display gain

How do we deal with a sudden change of a mapping between motor and visual space ?

Experimental strategy

- We studied the **perceptual-motor calibration process** while users face a sudden change in a **control display gain**
- Protocol: aiming task, speed-accuracy trade-off
- Identical to prism adaptation studies



Aim

Fundamental

Understand the **perceptual-motor calibration process** while users face a sudden change in *control display gain* (CD gain) when performing aiming tasks.

Applied

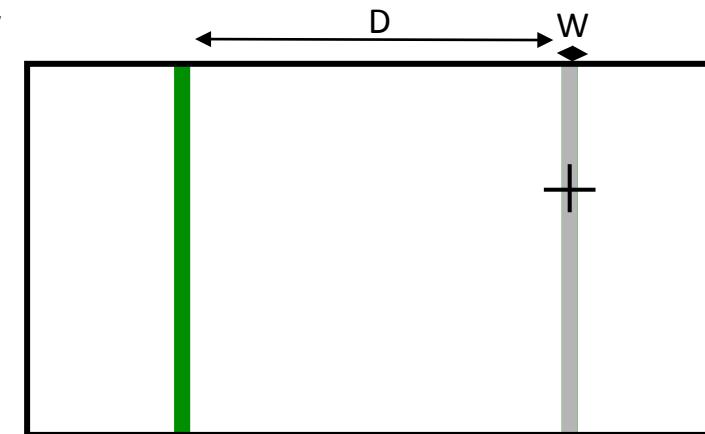
Improve **Human efficiency** when shifting from one device to another one (ex: telesurgery)

- Predictions:
 - Very fast recalibration → adaptative and flexible behavior even with movement accurately constrained
 - Changing CD gain abruptly → increase in movement time
 - Post-effect during the last phase of the movement in opposite direction in comparison to those observed following the first perturbation

Method



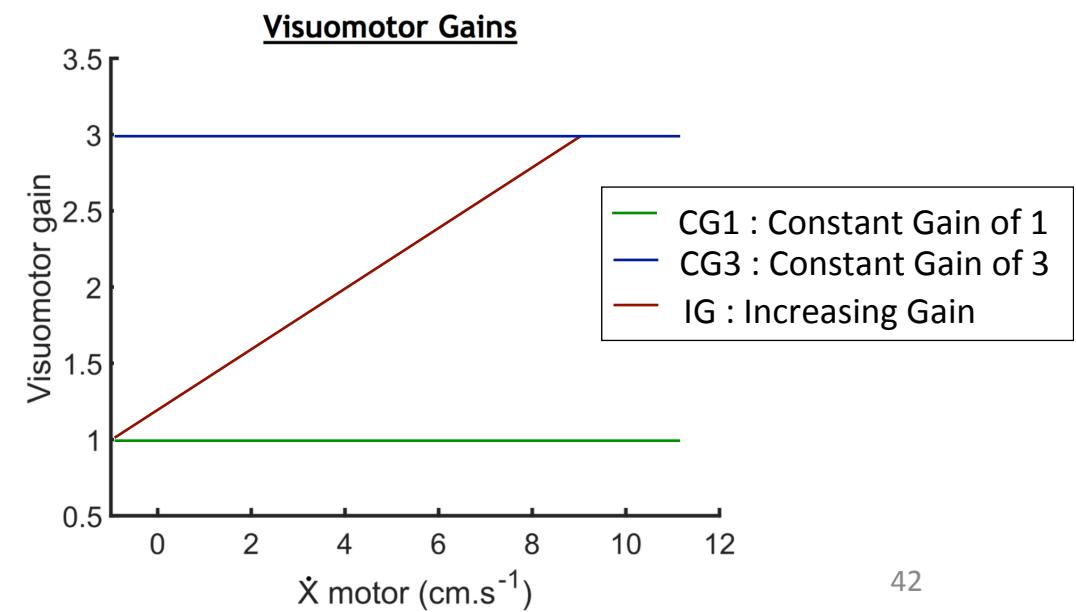
Control Display
Gain



Discrete aiming task
Move as fast and as accurate as
possible

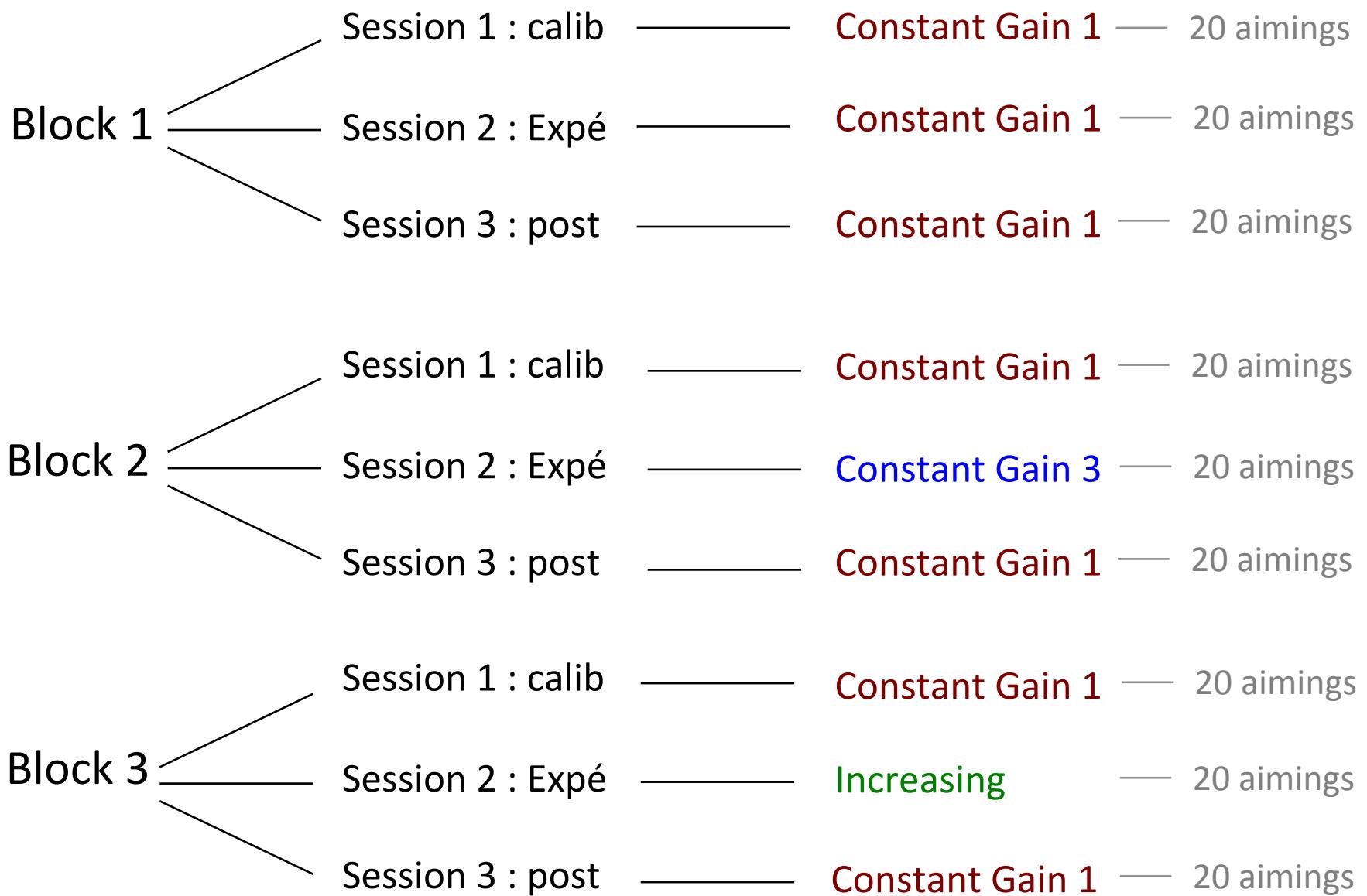
- Task Difficulty
 - Distance : 8 cm
 - Width : 2.5 cm

ID 6



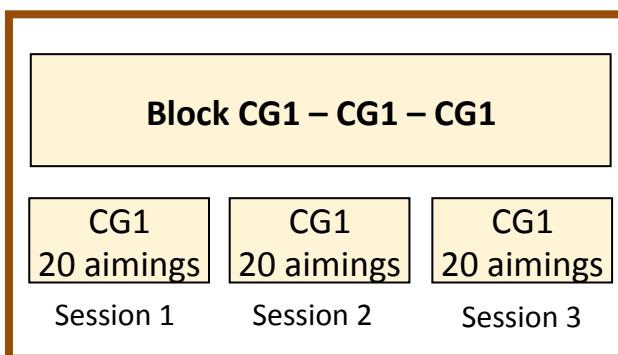
Experimental Design

- 3 blocks X 3 Sessions
 - 3 blocks
 - Constant Gain 1
 - Fonction Constante 3
 - Fonction Increasing
 - 3 Sessions
 - 1: Calibration
 - 2: Expérimentale (CG1, CG3, IC)
 - 3: Post Session
- 20 aimings/session

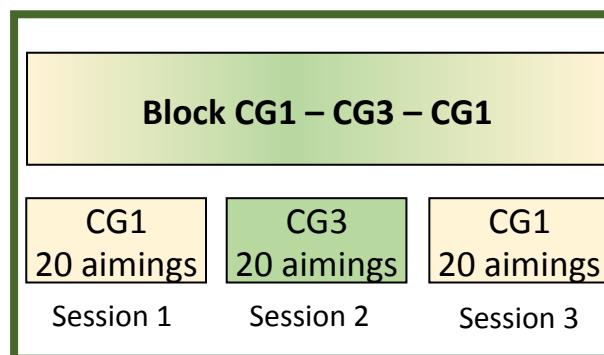


Experimental Design

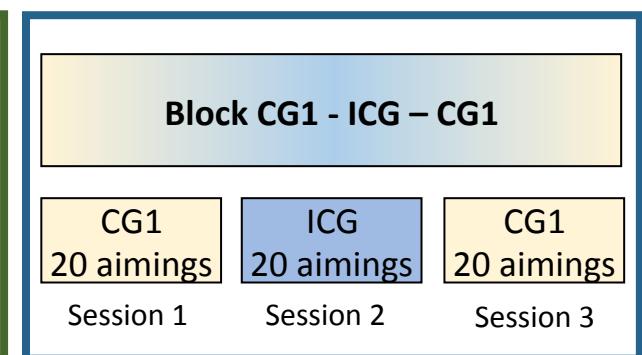
Block 1



Block 2



Block 3



Independent Variables

Discrete Aiming task

1 ID

3 Blocks * 3 Sessions

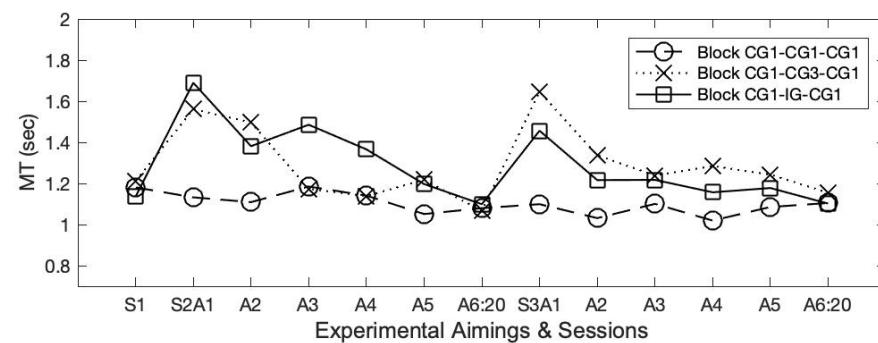
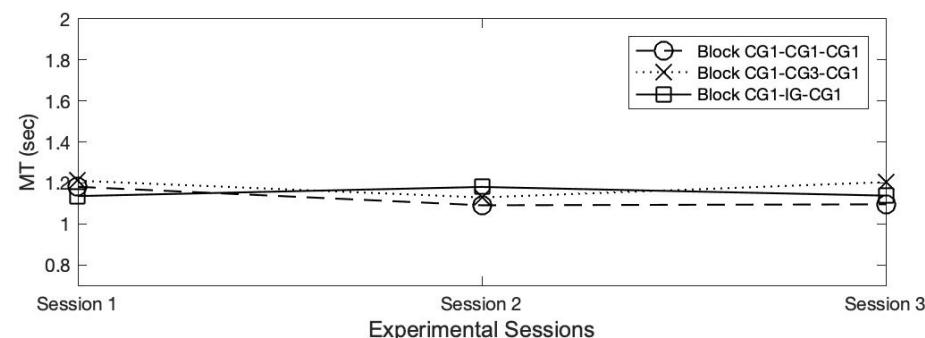
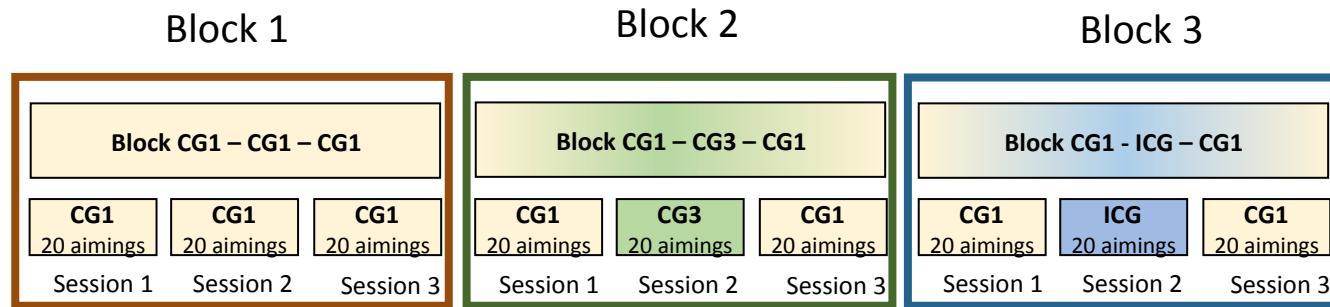
20 aimings / session

Dependent Variables

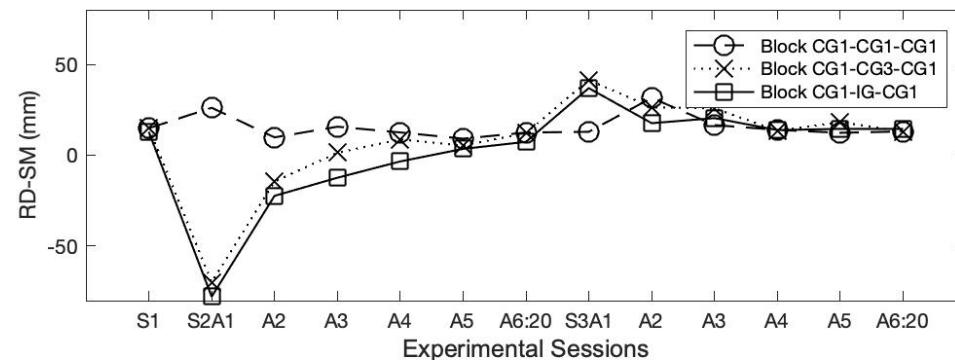
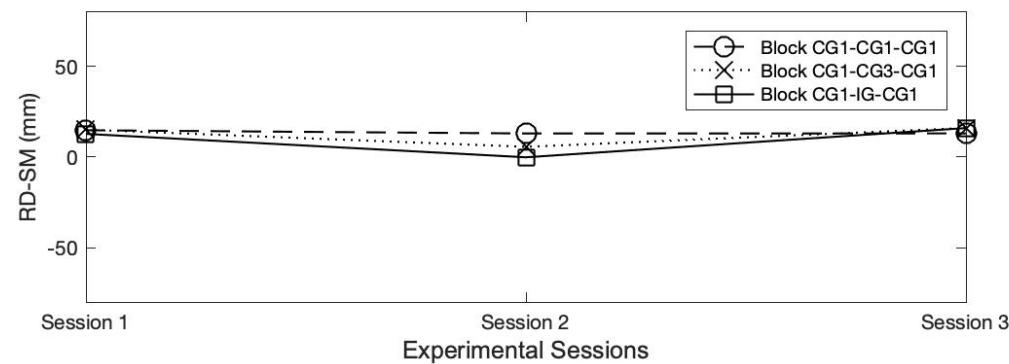
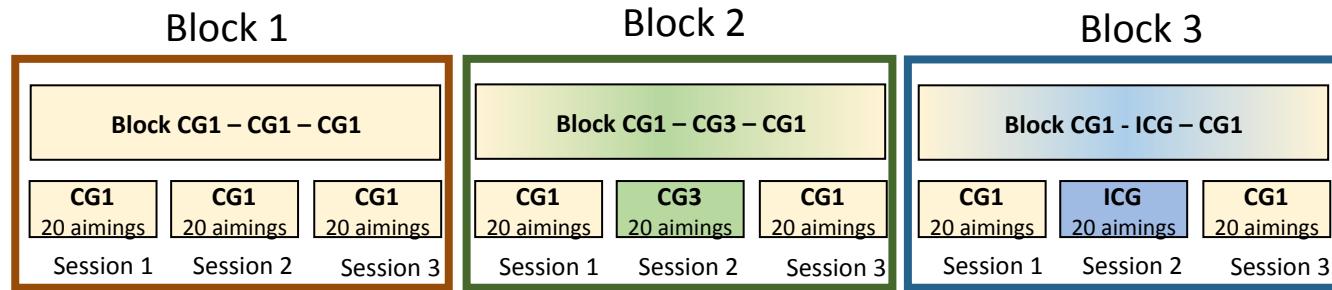
- Macroscopic variables
Temps de Mouvement

- Movement kinematics
Position at the end of the first sub-movement

Results



Results



Discussion

- We able to perform fast and accurate movement when the **perception-action coupling is perturbed**
- Very **fast time scale** of the perceptual-motor calibration process when a CD gain suddenly changed

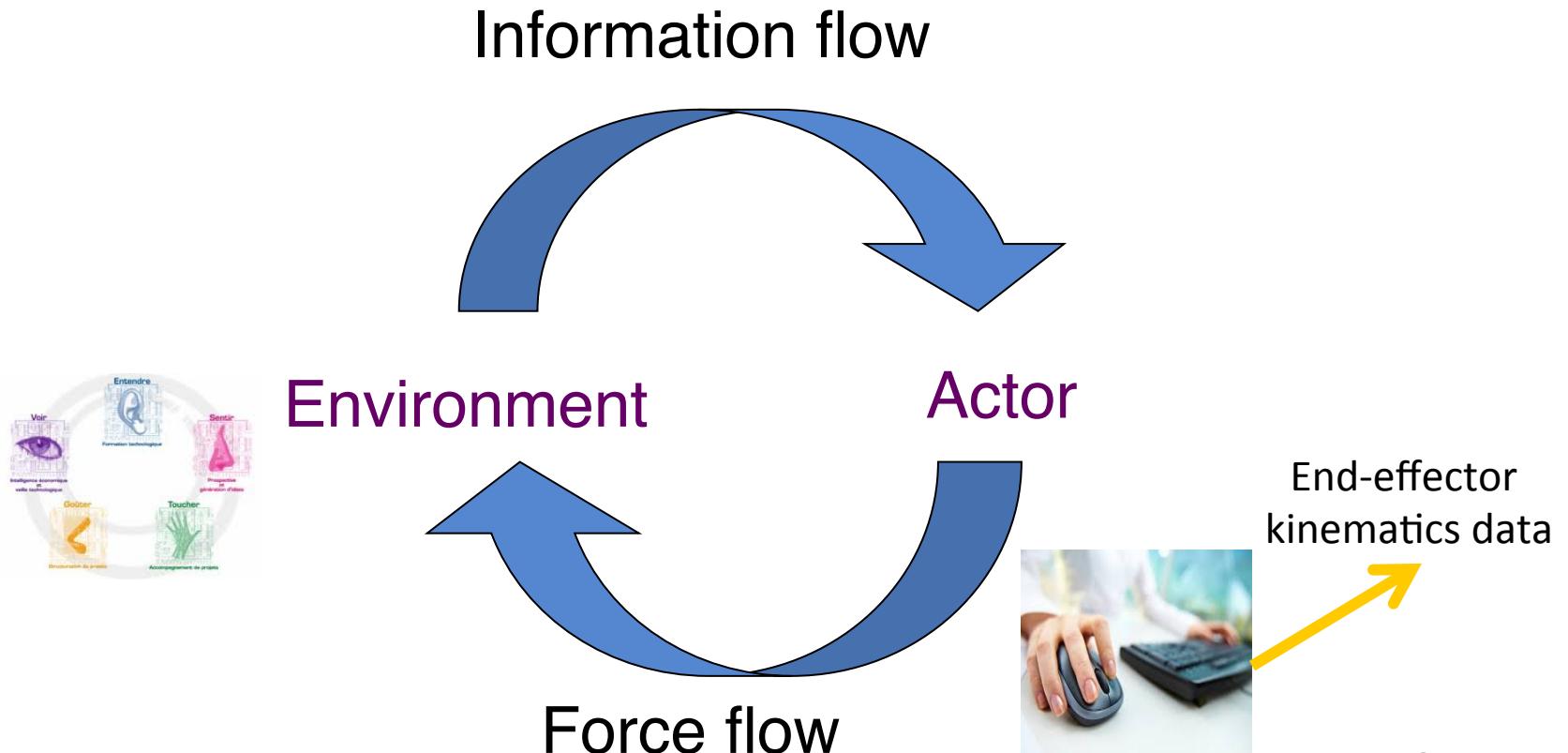
Implications / Applications

Improve Human efficiency when shifting from one device to another one (ex : telesurgery or HCI)



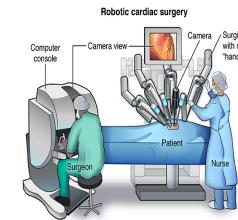
Theoretical conclusion

Perception-Action coupling process **highly and rapidly adaptable and flexible** according to the constraints



Perceptual-motor calibration: some examples

- Everyday life, variety of tools to interact with our environment



- As well as different external situations



→ we are able to ***calibrate perceptual-motor control*** to the ***kinetic*** and ***geometric properties*** of the particular tool being used or to different environmental situations

General conclusion / Implications

Fundamental

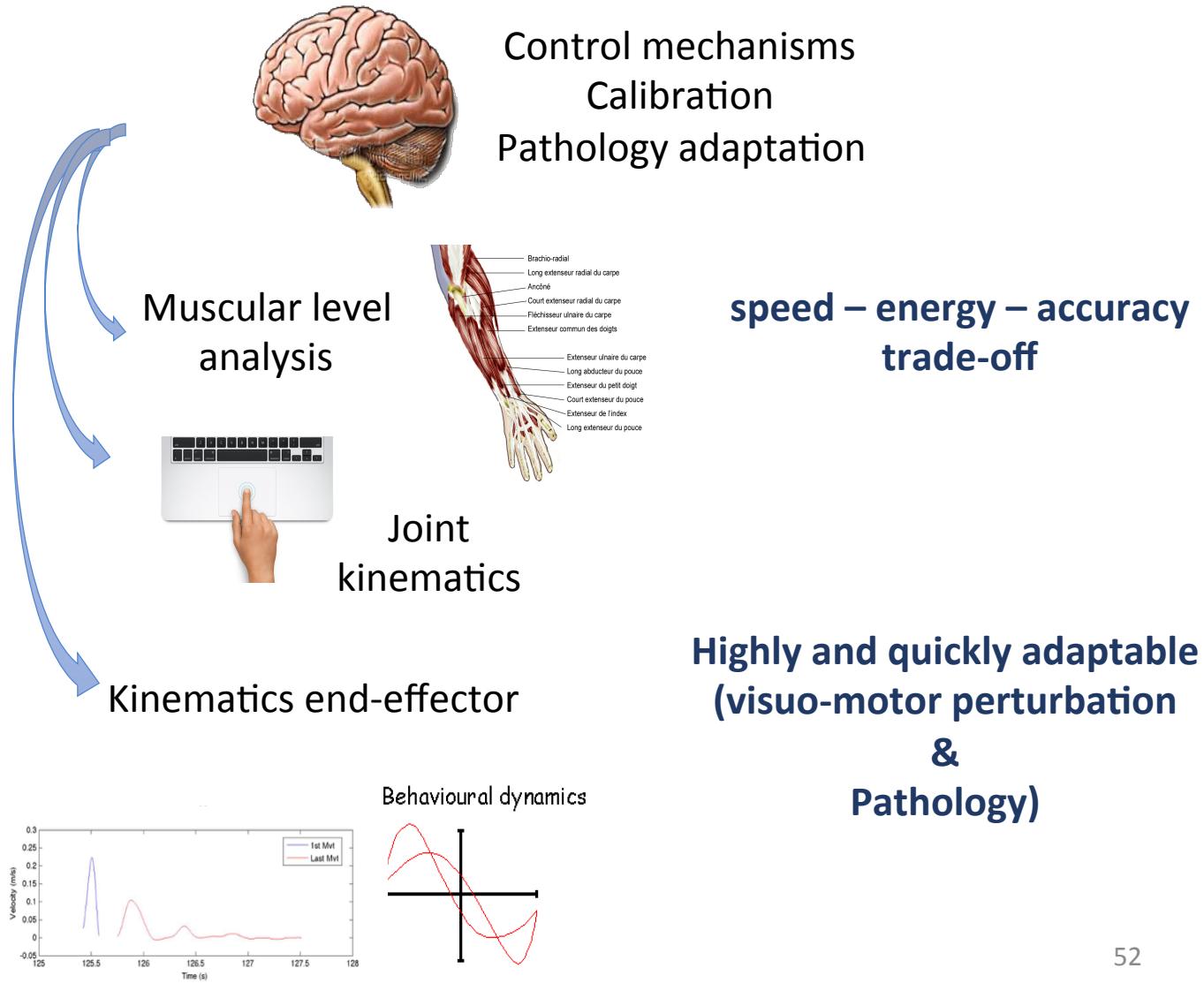
Better understanding of the **accuracy control** at different levels: neuromuscular, perceptivo-motor coupling

Applied

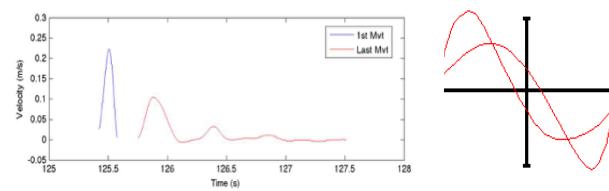
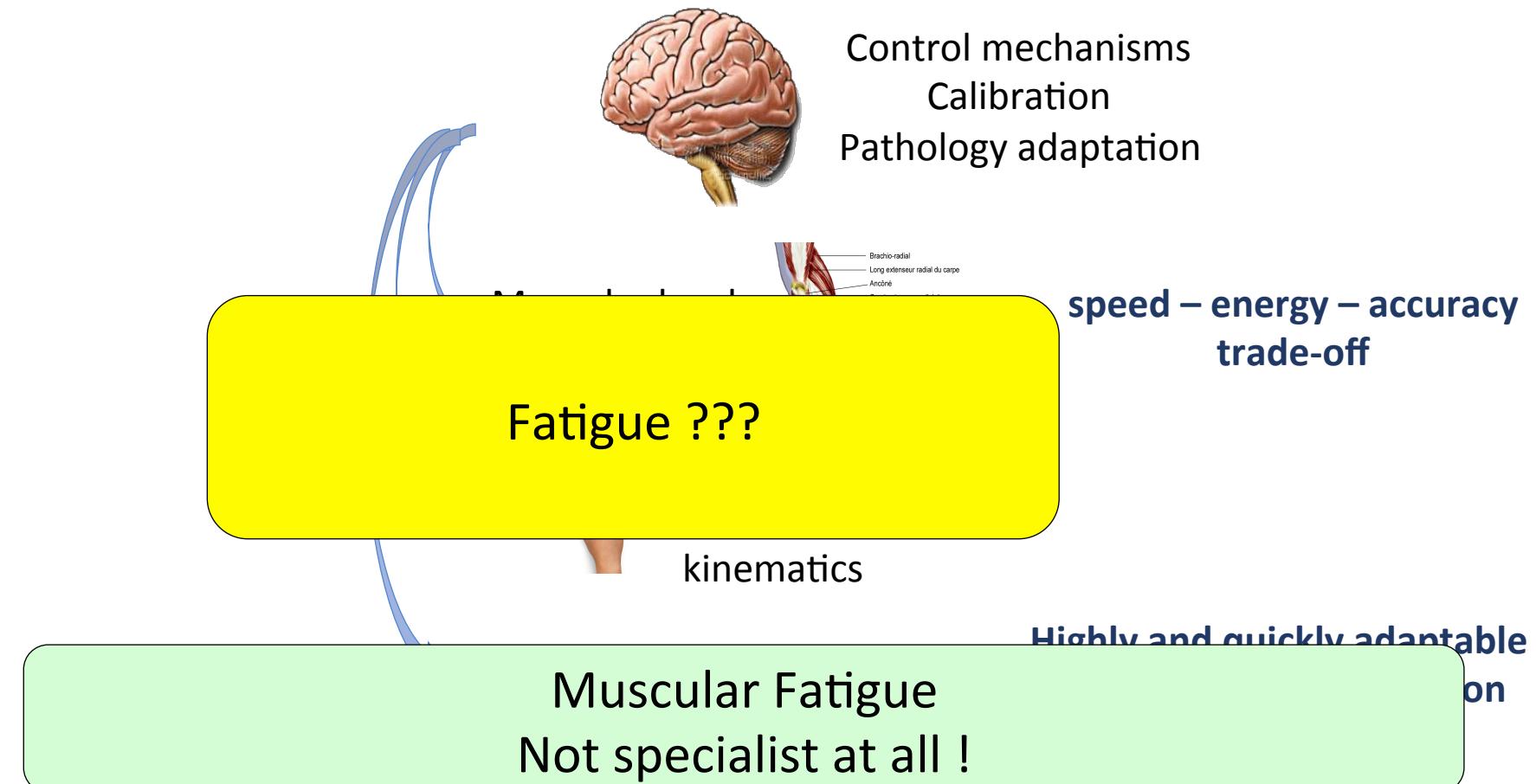
Improve Human efficiency at different levels : Human Movement Interface, Ergonomics, Rehabilitation protocol

+ adaptation to pathology

General conclusion : a Multi-scale analysis of accuracy control



General conclusion : a Multi-scale analysis of accuracy control

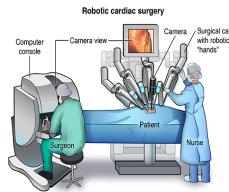


Question

- What does the subject try to minimize in a movement constrained in speed and accuracy ?
 - Is it purely **motor**
 - Is it purely **informational** ?
 - Which degradation in case of **fatigue** ?

(Accurate) Motor control & fatigue

- Muscular fatigue is experienced in many situations where movement control is crucial

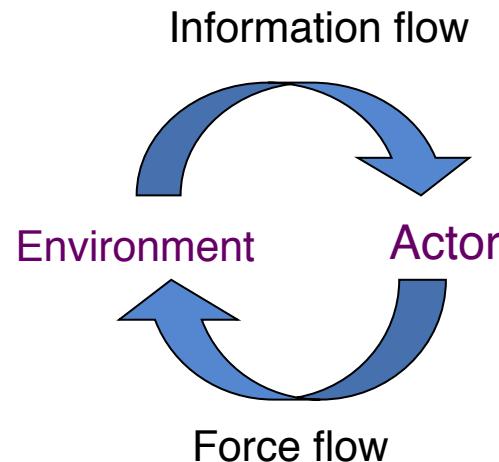


- Understand the **functional consequences of muscular fatigue**

Motor control & fatigue

- How can we consider fatigue ?
 - Internal perturbation that creates some impairment in the neuromuscular control
- Fatigue is classically defined as a loss of maximal available force (Edwards, 1981)
- This loss of available force affects motor control
 - Fatigue impairs movement accuracy even for movement requiring relatively small forces
- Task performance decreases with fatigue

Motor control & fatigue: Theory



Fatigue ?

Change in the Gain/mapping
Between command and force production

- If we consider fatigue as a perturbation, how do we calibrate perception-action coupling in fatigue condition ?
- What happens when we have to face to informational accuracy constraints and fatigue constraints ?

Fatigue & accuracy control

Fatigue and Cocontraction

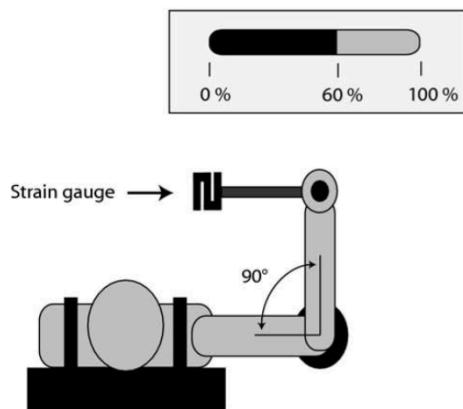
- **Cocontraction** increases **movement endpoint accuracy** (Gribble et al., 2003; Osu et al., 2004)
- **Cocontraction** increases **limb impedance** and thus limits **variability** induced by **neuromuscular noise** (Selen et al., 2007)
- What happens when we have to face to informational accuracy constraints and fatigue constraints (Selen et al., 2005)

Fundamental

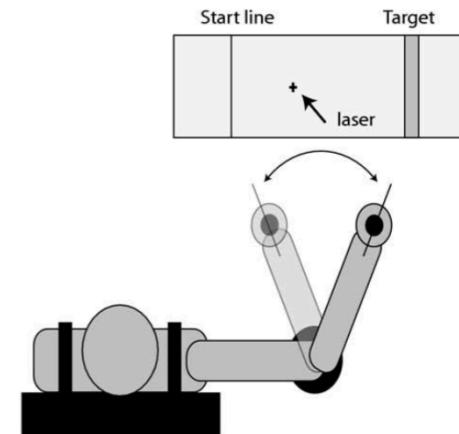
What happens when we have to face to **informational accuracy** constraints and **fatigue** constraints

Fatigue & accuracy control

A



B



VI

MT Imposed

VD

Endpoint variability

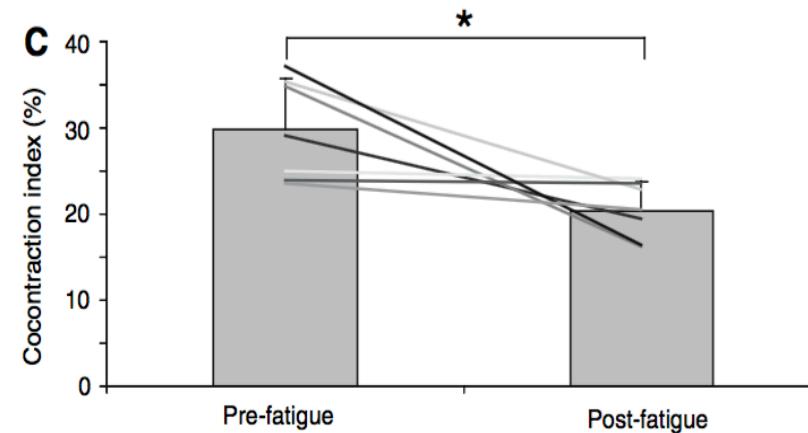
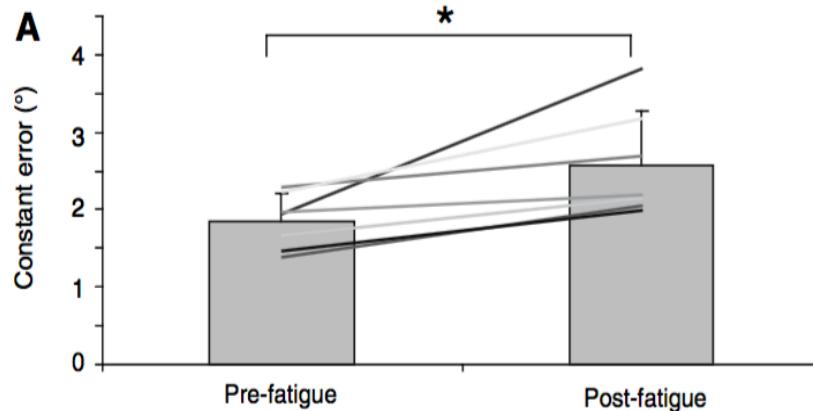
D



(Missenard et al., 2008)
59

Fatigue & accuracy control

Fatigue and Cocontraction



(Missenard et al., 2008)

- Ratio of required to available force is unchanged
- → impairment in movement accuracy
- Could not be explained by the lack of available force
- But due to a decrease in **muscular cocontraction**

Fatigue & accuracy control

- How does the CNS deal with the control of accuracy in fatigue condition ?
- During fatigue, the CNS accord more importance to energy expenditure minimization → decrease in accuracy

The CNS could have chosen to dedicate more importance to energy economy than to task performance

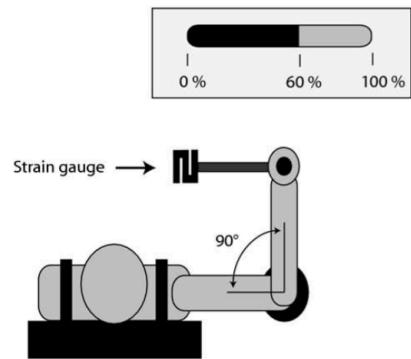
Fatigue & accuracy control

Effect of fatigue on Fitts' law

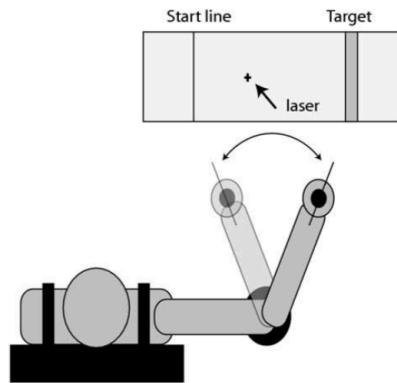
- How to preserve task success in the presence of changes in the neuromuscular system (i.e. with fatigue)?
- Fundamental problem for the CNS is to adapt motor planning and execution to fatigue
- Postulates
 - **Noise** in motor commands is **signal-dependent**
 - Fatigue affects 3 aspects of the production of muscular force :
 - Fatigue increases **force variability**
 - Prolongs **contraction** and **relaxation times**
 - Reduces the **gain** between a given **muscular activation** and the **force** it produces

Fatigue & accuracy control

A



B



VI

Index of Difficulty
Fatigue

VD

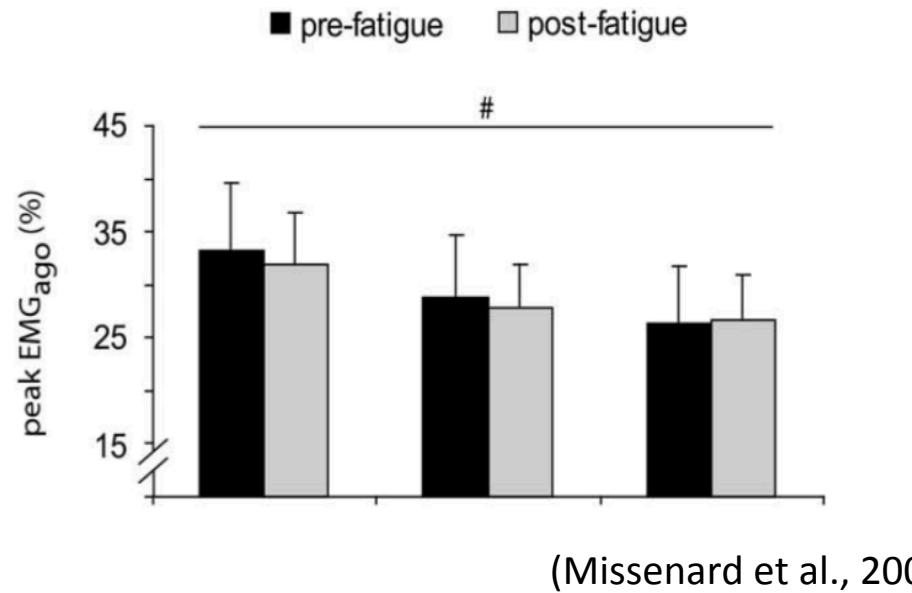
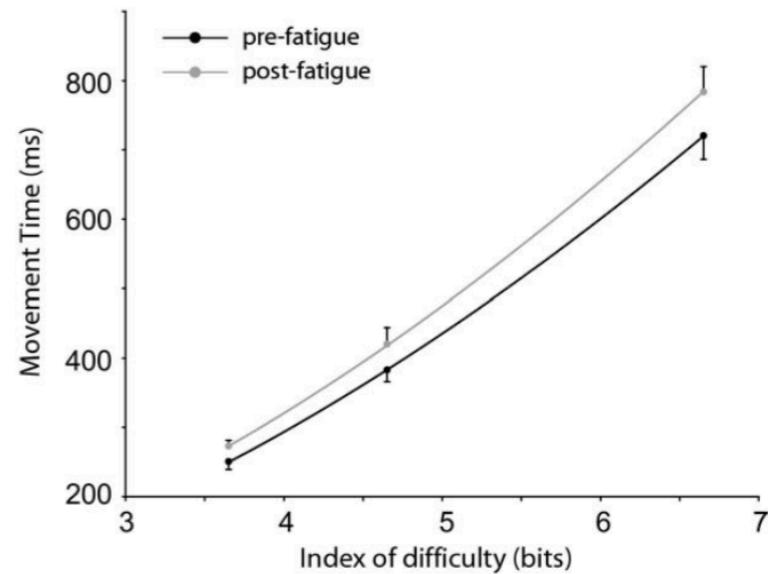
Movement Time
Kinematics profiles
EMG

D



(Missenard et al., 2009)
65

Fatigue & accuracy control



- Fatigue → decreases movement time, but Fitts law still holds
- Fatigue → quantitative but not qualitative change on movement kinematics
- EMG activities → No change between pre and post fatigue conditions

Fatigue & accuracy control

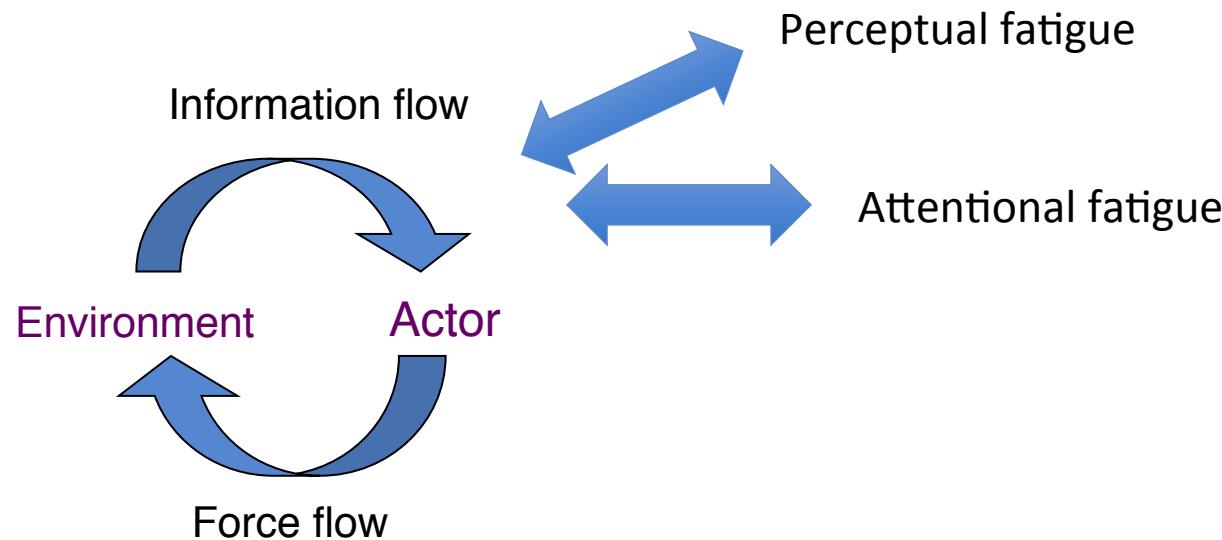
- Discussion

- Increase in **force variability** with **fatigue** was proportional to **force level**, fatigue increases the strength of SDN
- Fatigue prolongs **muscle contraction** and **relaxation**
- Fatigue affects **relation between EMG and force output** : slower movements are observed during fatigue whereas muscle activation magnitude is unchanged

Humans' motor system adapts motor planning and execution to fatigue in order to preserve task success

Conclusion

- What about cognitive fatigue



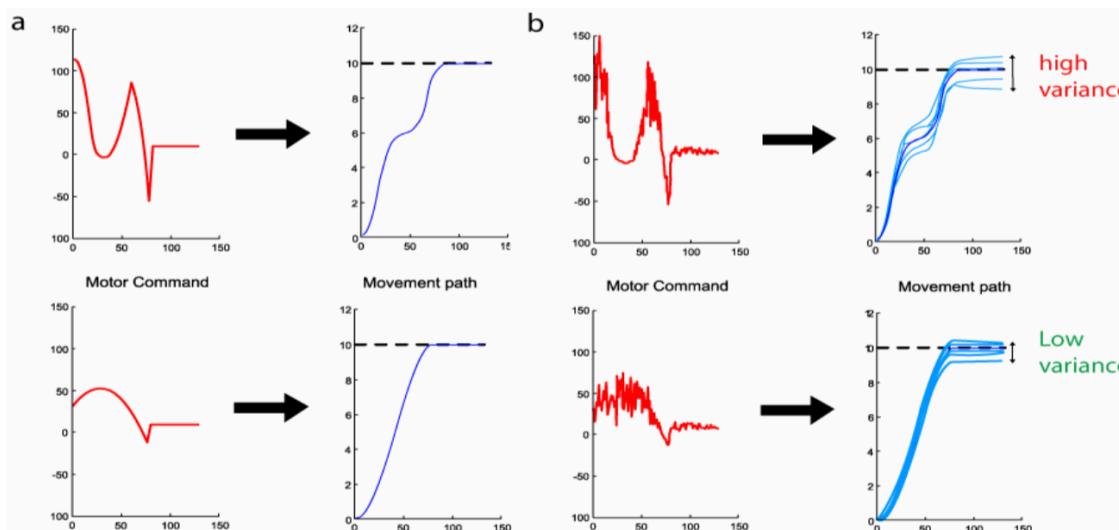


Merci pour votre attention



Motor control & fatigue

- Fatigue consequence on motor noise ?



- With fatigue : SDN gain increases
 - Decrease of accuracy
 - & change on movement trajectory

Harris & Wolpert (1998)

General problem: why we move the way we do?

Computational motor control: because we move in an **optimal** way

Principle:

1. An objective is defined (e.g. reach a target).
2. A **cost function** is defined that describes how good the solution is.
What is the cost???
3. By combining the objective and the **constraints**, it is possible to derive the best possible solution to the problem, usually using computer simulations.
4. If the prediction of the model is matched by biology, it is concluded that, indeed, we have understood the purpose of a system (**the “why” question**).

General problem: why we move the way we do?

Most of the computational models are successful...

(reviews in: Todorov, *Nature Neurosci* 2004; Bays & Wolpert, *J physiol* 2007; Kording, *Science* 2007)

... but there is no consensus on the cost function.

Minimize jerk? (Flash & Hogan, *J Neurosci* 1985)

Minimize torque? (Uno et al, *Biol Cybern* 1989)

Minimize energy economy? (Anderson & Pandy *J Biomech Eng* 2001)

Minimize movement time? (Tanaka et al, *J Neurophysiol* 2006)

Minimize endpoint errors variation? (Harris & Wolpert,

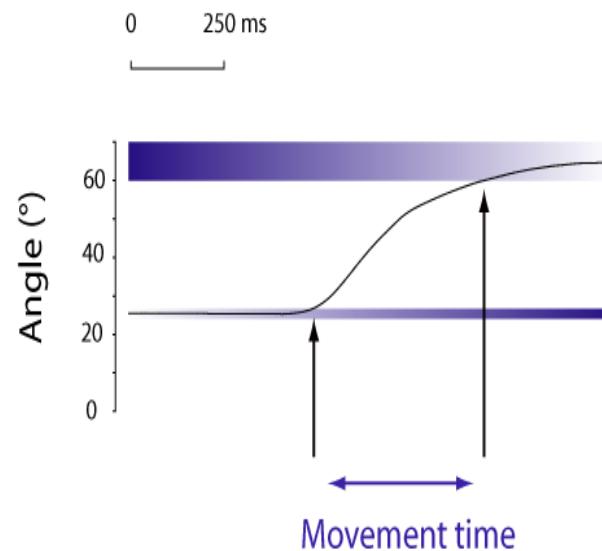
Nature 1998, Todorov & Jordan, *Nature Neurosci* 2002)
... probably because cost functions depend on the task and the context.

Liu & Todorov, *J Neurosci* 2007

Experimental protocol

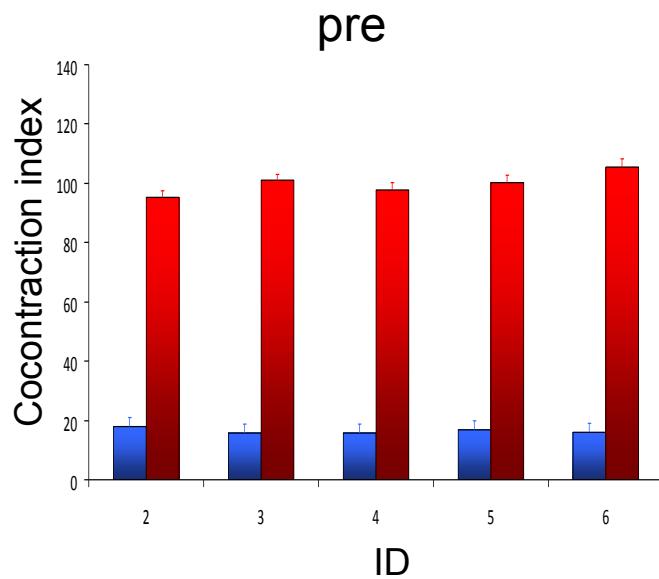
- **Movement time computation:**

time interval between the moment when the cursor exists the start target and enters the arrival target for the last time

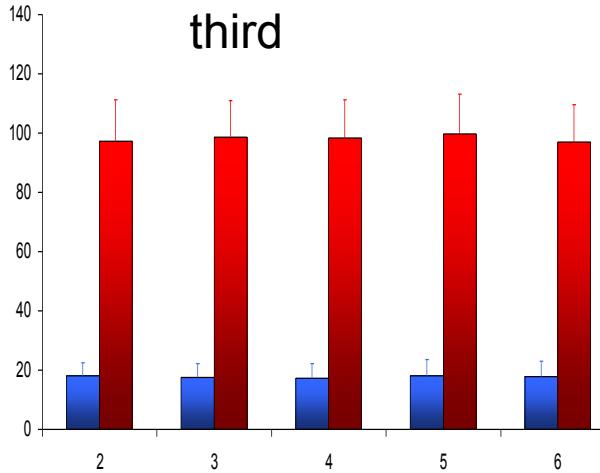


Results

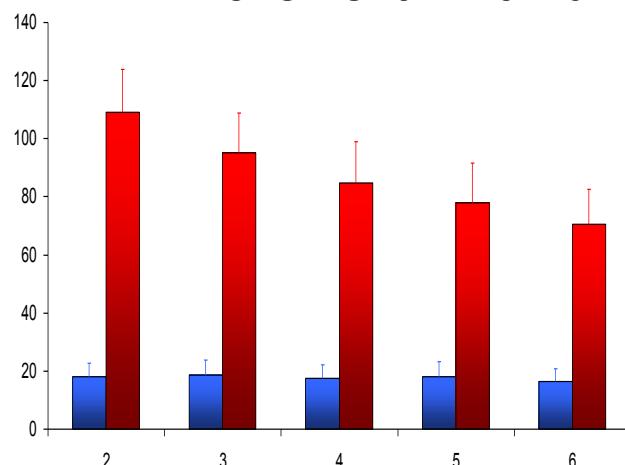
Cocontraction index: free vs. cocontraction (more detailed)



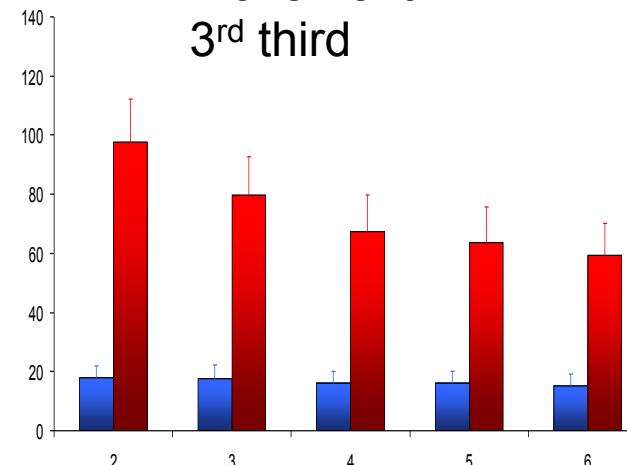
Movement 1st
third



Movement 2nd third

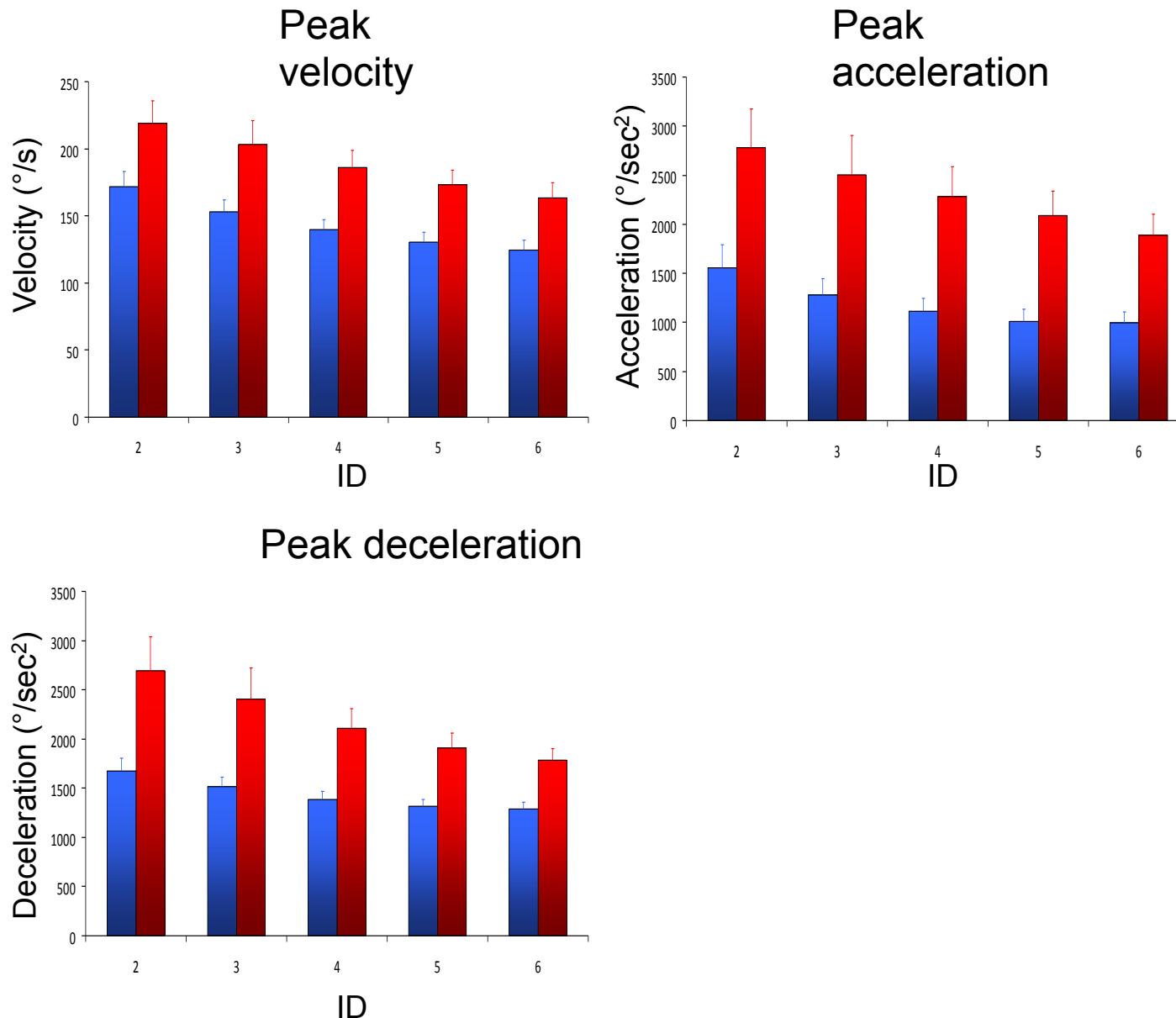


Movement
3rd third



Results

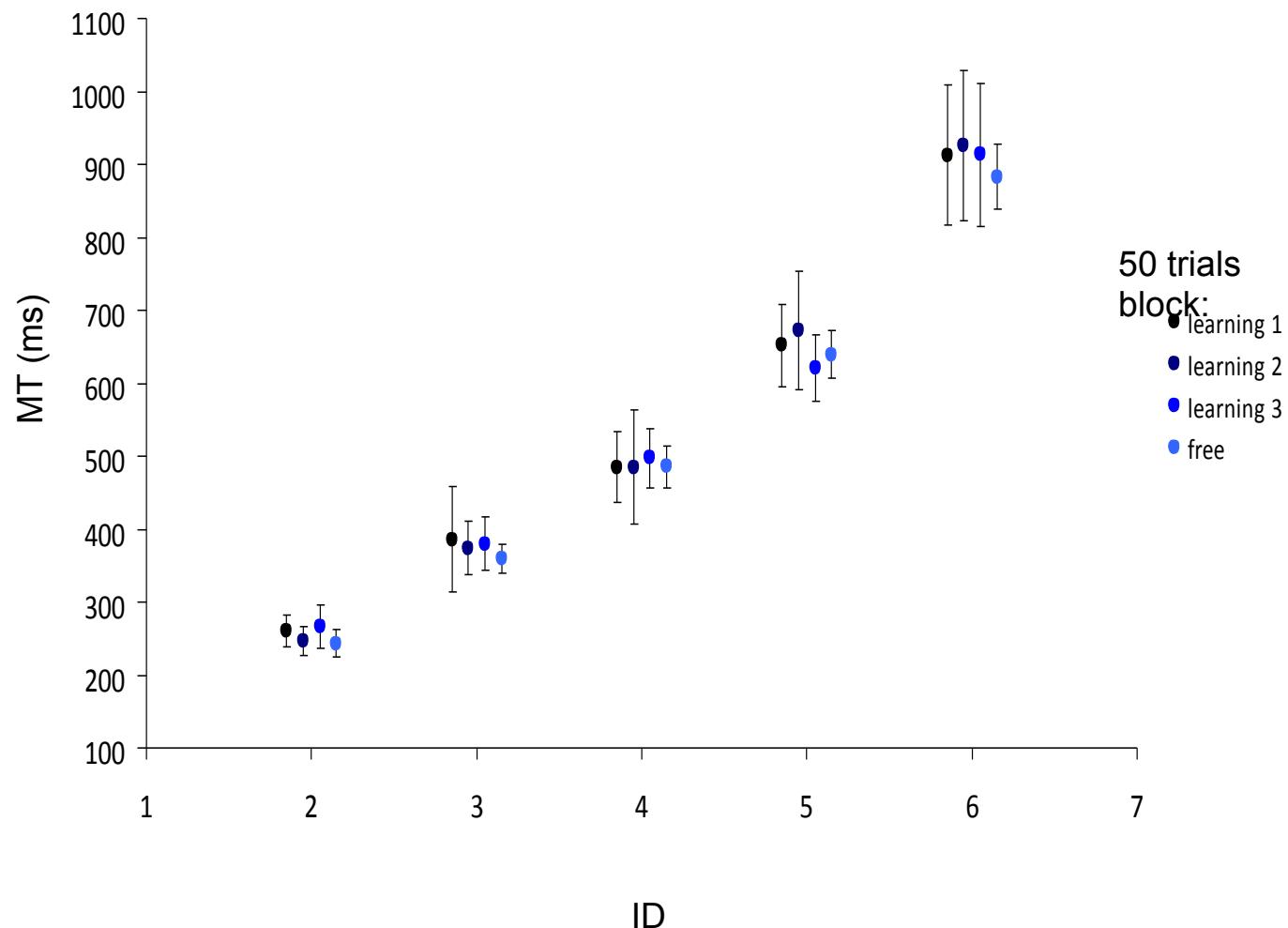
kinematics: free vs. cocontraction peak values



Results

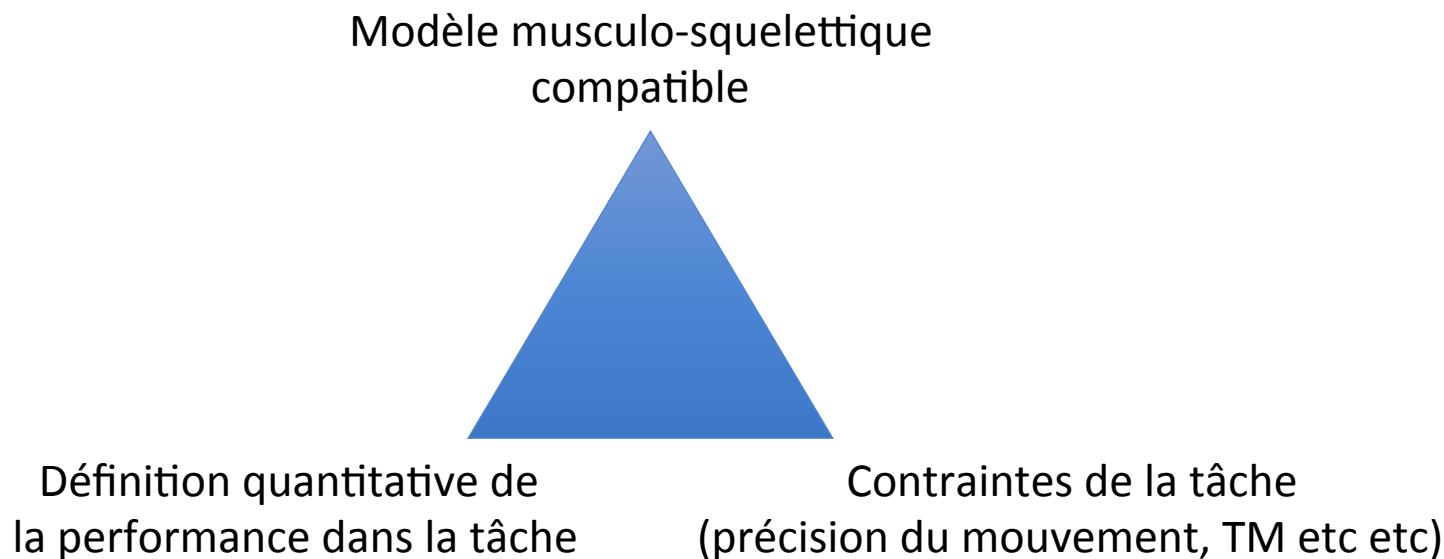
Learning : Fitts' law

- Not revealed in MTs: for a given ID, MT are statistically unchanged

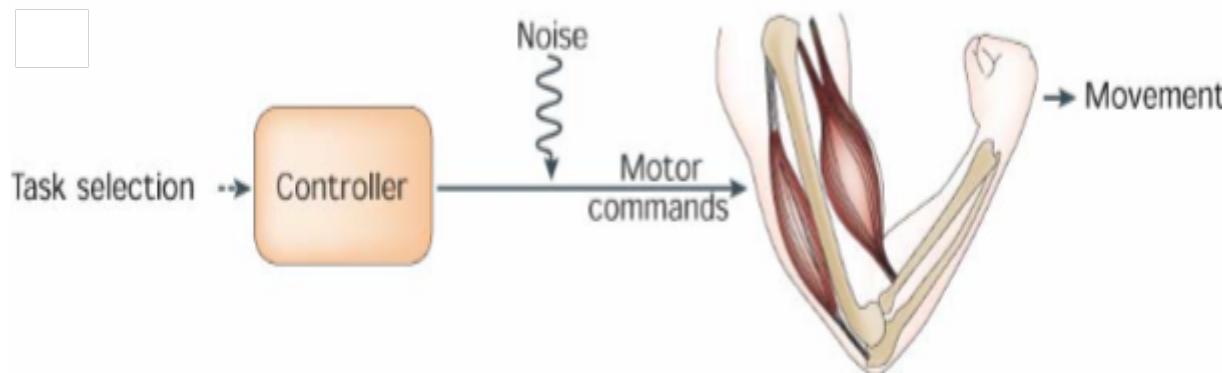


Optimal control theory

- Pour résoudre un problème de contrôle optimal, 3 points doivent être spécifiés



Notion de contrôleur



→ calcule un signal de contrôle (= commandes motrices) approprié pour une tâche et un critère de performance donné

→ Transmis au système musculo-squelettique

- Critère de perf : quantité à minimiser
- Le **coût** peut dépendre du **signal de contrôle** et/ou de **variables** décrivant l'état du système musculo-squelettique (e.g. vitesse, position etc)

Optimal control theory

- Nous bougeons de façon **optimale**
 - Un **objectif** est défini (atteindre une cible)
 - Une **fonction de coût** est définie qui décrit comment la solution est satisfaisante (e.g. vitesse et précision)

Quel est le coût ???

vitesse et la précision), il est possible de trouver la meilleure solution possible au problème en utilisant des simulations

- Si la prédiction du modèle matche avec les résultats, alors nous pourrons affirmer que nous avons compris d'où vient le **conflit vitesse-précision**

Optimal control theory

- Critère de perf : quantité à minimiser et combinaison de deux
 - Exemple :
 - Jerk / Energie / Force end-effector / effort musculaire

Optimal control theory

- Manque de consensus sur la fonction de coût.
- Coût à minimiser était :
 - le **jerk**? (Flash & Hogan, 1985)
 - le **torque**? (Uno et al, 1989)
 - L'**énergie dépensée** (Nelson, 1983)
 - Le **temps de mouvement**? (Tanaka et al, 2006)

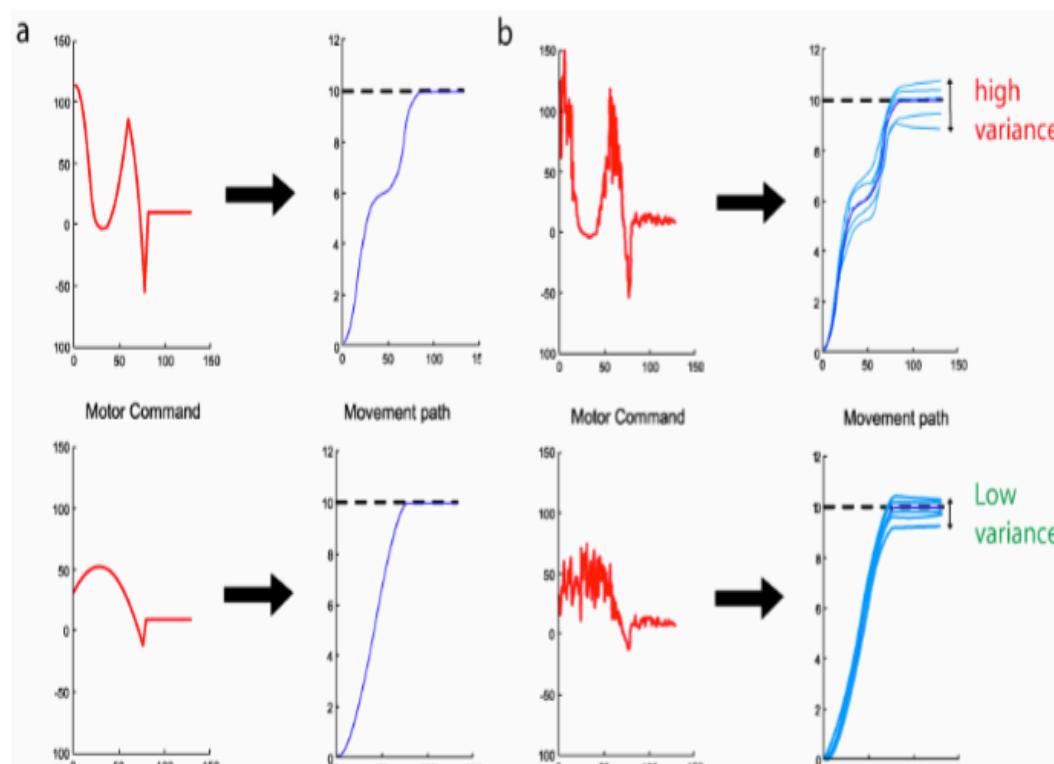
... probablement parce que la fonction de coût dépend de la tâche et du contexte (ex : sauter le plus haut possible)
• **la variance du end-point**? (Harris & Wolpert 1998, Todorov & Jordan, 2002)

Qu'en est-il donc quand il faut être rapide et précis à la fois ?

Liu & Todorov, *J Neurosci* 2007

Fonction de coût pour le contrôle des mouvements précis

- Movement time modulation



(Adapté de Harris & Wolpert, 1998)

Cost function pour le contrôle de la précision

Modulation du temps de mouvement

La fonction coût inclue : le **Temps de mouvement** et la **précision finale**



Compromis entre la vitesse et la précision

Schmidt et al, *Psychol Rev* 1979

Meyer et al, *Psychol Rev* 1988

Harris & Wolpert, *Nature* 1998

Tanaka et al, *J Neurophysiol* 2006

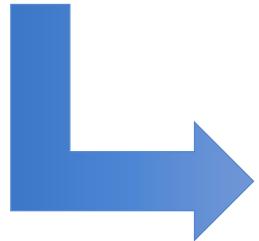
Guigou et al, *Eur J Neurosci* 2008

→ Mais l'énergie joue également une rôle fondamental dans le contrôle des mouvements précis (cf Missenard & Fernandez, 2013).

Optimal control theory

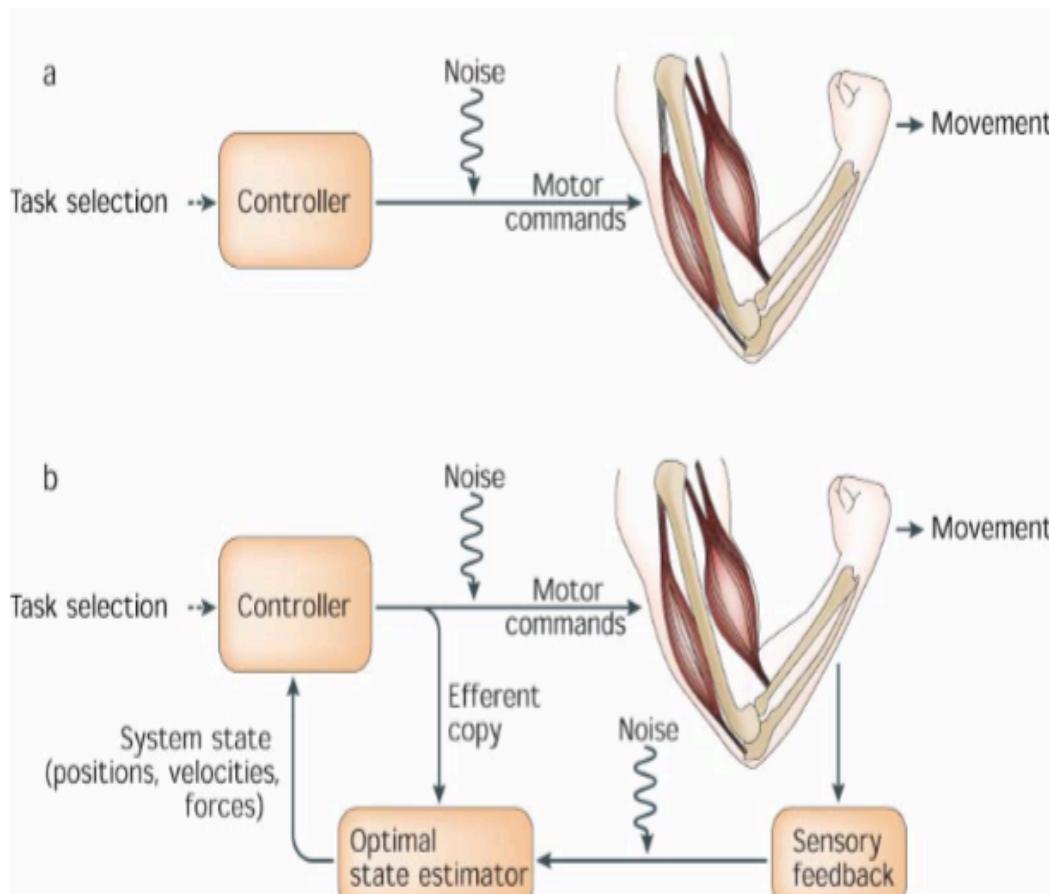
- Limites :

- Le SNC ne peut ignorer les infos sensorielles disponibles pendant le mouvement
- Ces modèles ne peuvent prédire les conséquences d'une perturbation en cours de mouvement



Notion de Modèle en **Boucle ouverte** vs **Boucle fermée**

Optimal control theory



Adapté de Scott (2004) & Todorov (2004)⁸³