A study of human locomotor trajectories

Phạm Quang Cường

December 11, 2009

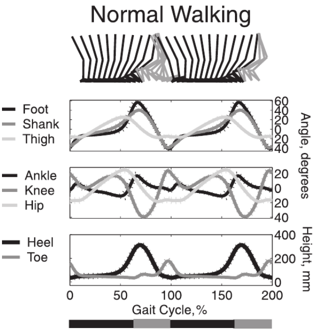
Thèse réalisée sous la direction de P^r Alain Berthoz,
au Laboratoire de Physiologie de la Perception et de l'Action
Collège de France, Paris, France

Outline

Outline

Locomotion: mutiple levels of description

Stepping pattern

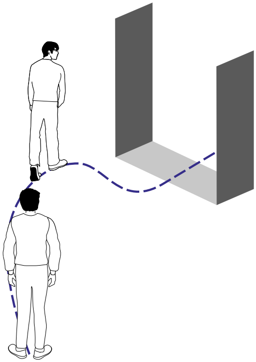


Hicheur et al, *J Neurophysiol*, 2006

Postural control

Berthoz, *Le sens du mouvement*, 1997

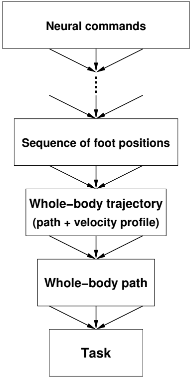
Trajectory formation

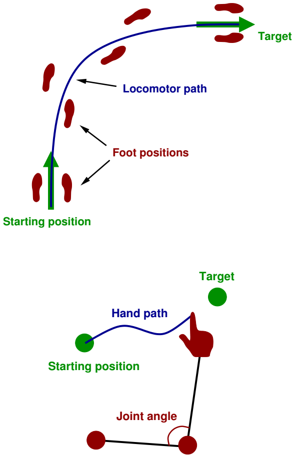


We focus here on the formation of whole-body trajectories in space

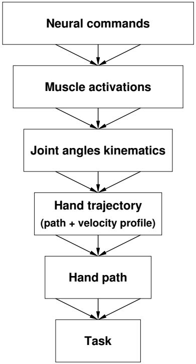
The redundancy problem

Redundancy in the formation of locomotor trajectories





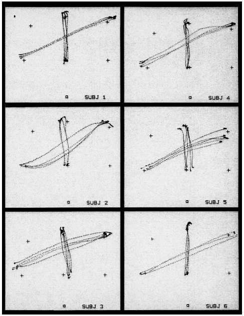
Redundancy in the control of arm movements



Jordan and Wolpert, in *The Cognitive Neuroscience*, 1999

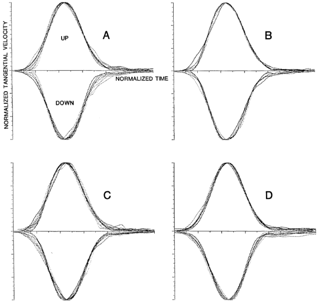
Spatial control of arm movements

Straight hand paths



Morasso, *Exp Brain Res*, 1981

Bell-shaped velocity profiles

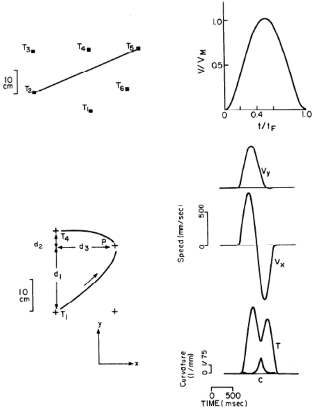


Atkeson and Hollerbach, *J Neurosci*, 1985

- Stereotypy observed only for hand trajectories in Cartesian coordinates
- Control in terms of Cartesian coordinates of the hand, not in terms of e.g. joint angles or muscle activity

Optimal control of arm movements

- Humans may select the hand trajectories that minimize a certain cost
- One popular model is the minimum jerk model developped by Flash and Hogan



Flash and Hogan, *J Neurosci*, 1985

$$\min_{x,y} \int_0^1 \left(\left(\frac{\mathrm{d}^3 x}{\mathrm{d}t^3} \right)^2 + \left(\frac{\mathrm{d}^3 y}{\mathrm{d}t^3} \right)^2 \right) \mathrm{d}t$$

Typical features:

- Straight, smooth, hand paths
- Bell-shaped velocity profiles
- Inverse relationship between velocity and curvature (via-points)

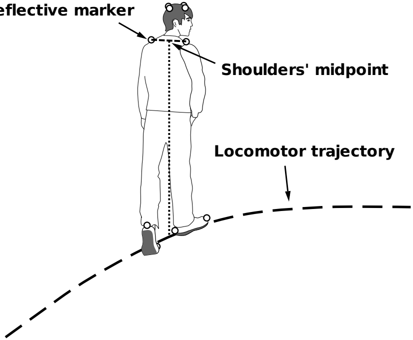
Our approach

- Take inspiration from the litterature on arm movements control (the "principle of motor equivalence", see Bernstein, *The co-ordination and regulation of movement*, 1967 and Berthoz, *Le sens du mouvement*, 1997)
  - Formation of locomotor trajectories (Vieilledent et al, *Neurosci Lett*, 2001; Hicheur et al, *Exp Brain Res*, 2005)
  - Optimal control principles
- Integrative view
- Combination of experimental and modeling studies

Outline

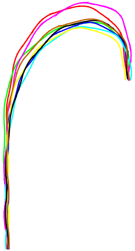
General experimental methods

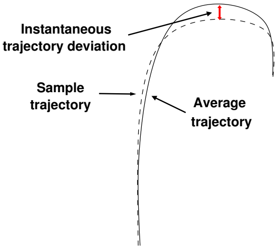
- Motion capture system: infrared cameras + light reflective markers
- Body position defined by shoulders' midpoint

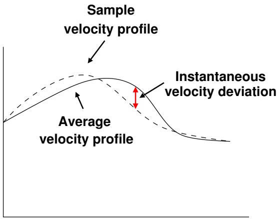


Average trajectories and variabilities

- Time rescaling so that $t_0 = 0$ and $t_1 = 1$
- Definition of average trajectories and variabilities







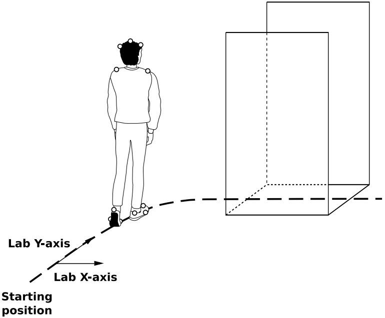
Outline

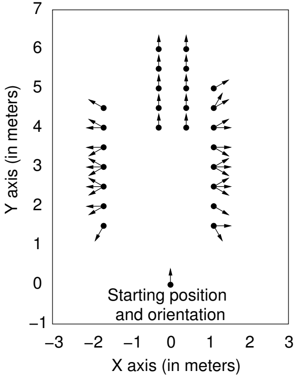
Experiment 1: stereotypy of locomotor trajectories

- Reminder: control of arm movements in terms of Cartesian coordinates of the hand
- What is planned and controlled in goal-oriented locomotion?
  - Step-level: plan and execute sequences of precise foot positions (FP), resulting in a whole-body trajectory
  - Trajectory-level: plan a whole-body trajectory (in Cartesian space) and implement it by appropriate sequences of foot positions
- Variability of the sequences of FP versus variability of whole-body trajectories

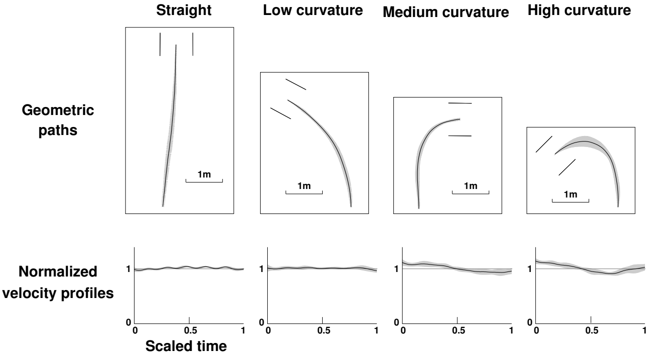
Experiment 1: methods

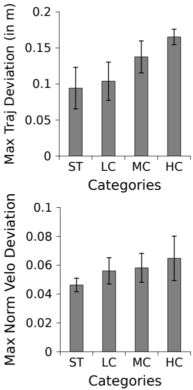
- Protocol: walking towards and through a distant doorway (Arechavaleta et al, 2006)
- Constraints on Initial and final positions and walking directions
- 40 targets (a target = position × orientation)
- 6 subjects × 40 targets × 3 repetitions = 720 trajectories





Experiment 1: results (trajectory stereotypy)

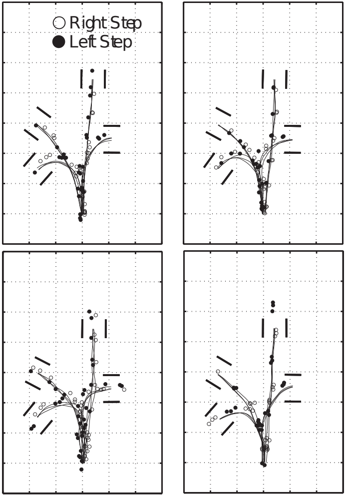


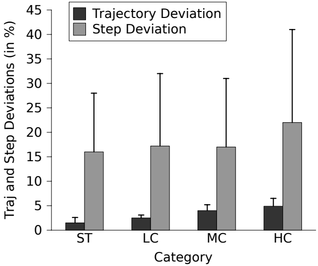


Hicheur, Pham et al, *Eur J Neurosci*, 2007

Even for HC, maximum variability was $\leq$ 17cm

Experiment 1: results (foot positions variability)





Hicheur, Pham et al, *Eur J Neurosci*, 2007

- variability of the sequences of FP ($\geq$20% of step length)
- variability of whole-body trajectories ($\leq$5% of trajectory length)

Experiment 1: conclusions

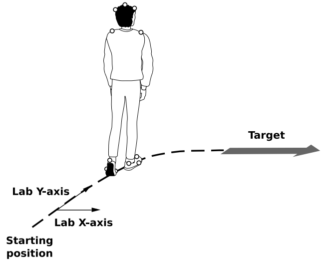
- Goal-oriented locomotion is not planned and controlled as a sequence of precise "foot pointings"
- Rather, it is likely planned and controlled at the level of whole-body trajectories
- This is reminiscent of the concept of spatial control of hand movements (Morasso, *Exp Brain Res*, 1981)

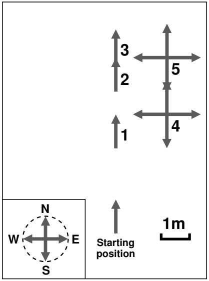
Experiment 2: influence of vision and of gait direction

- How whole-body trajectories are affected by changes in motor and sensory conditions?
- We varied the motor (walking forward or backward) and sensory (walking with or without vision) conditions

Experiment 2: methods

- Protocol: same as in Exp 1 with the door replaced by an arrow
- 4 conditions:
  - **Visual Forward (VF)**
  - **Nonvisual Forward (NF)**
  - **Visual Backward (VB)**
  - **Nonvisual Backward (NB)**
- 14 subjects $\times$ 4 conditions $\times$ 11 targets $\times$ 3 repetitions

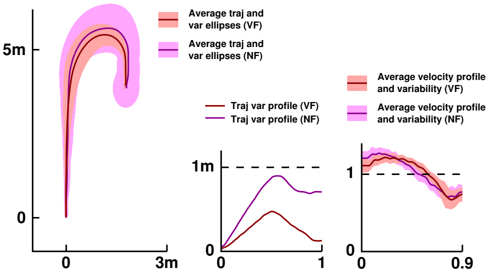


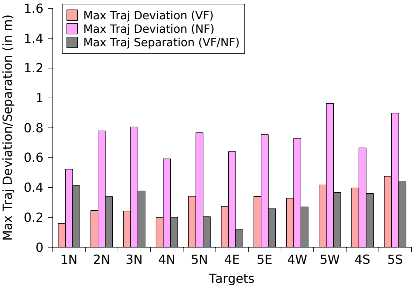


Experiment 2: results (effect of vision I)

Visual Forward (VF) vs Nonvisual Forward (NF)

- Small differences in average trajectories (MTS=**30cm** on average)
- Large differences in variability profiles (**31cm** for **VF** vs **74cm** for **NF**)



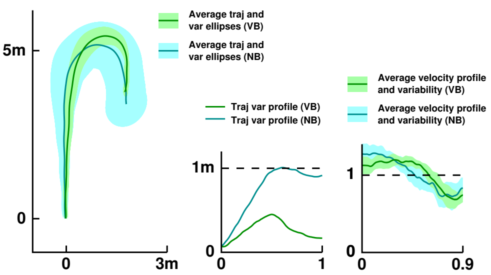


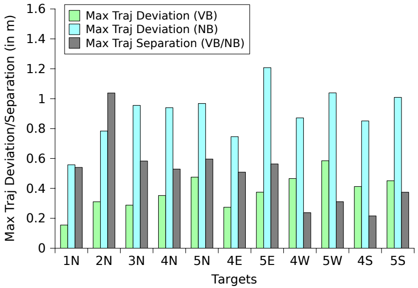
Pham and Hicheur, *J Neurophysiol*, 2009

Experiment 2: results (effect of vision II)

Visual Backward (VB) vs **Nonvisual Backward (NB)**
Same observations as in the comparison **VF**/**NF**:

- Relatively small differences in average trajectories (**50cm**)
- Large differences in variability profiles (**38cm** for **VB** vs **90cm** for **NB**)



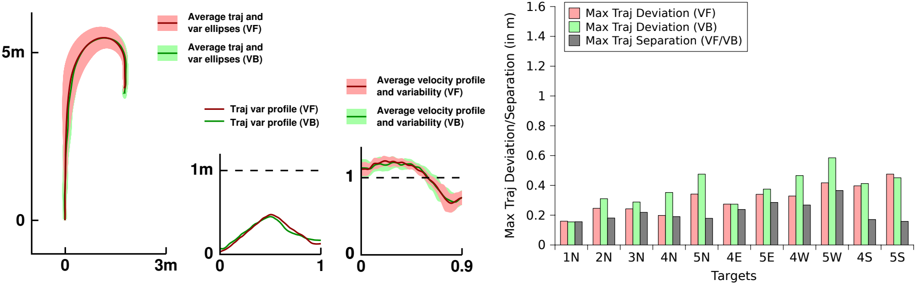


Pham et al, in preparation

Experiment 2: results (effect of gait direction I)

Visual Forward (VF) vs **Visual Backward (VB)**

- Small differences in average trajectories (**22cm**)
- Small differences in variability profiles (**31cm** vs **38cm**)

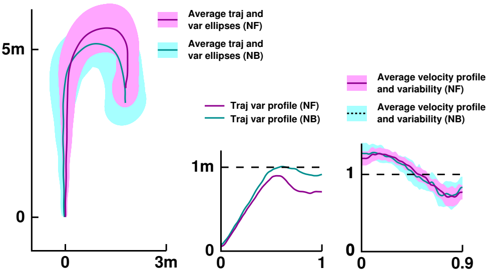


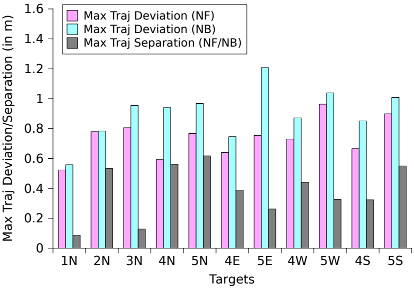
Pham et al, in preparation

Experiment 2: results (effect of gait direction II)

Nonvisual Forward (NF) vs **Nonvisual Backward (NB)**
Same observations as in the comparison **VF**/**VB**:

- Relatively small differences in average trajectories (**38cm**)
- Small differences in variability profiles (**74cm** vs **90cm**)





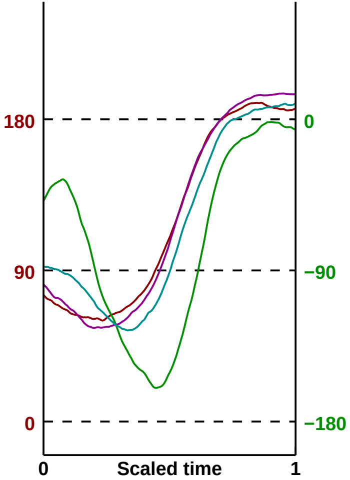
Pham et al, in preparation

Experiment 2: conclusions

- Average trajectories: similar across **visual** and **gait** direction conditions
  ⇒ trajectories are planned and controlled, to some extent, independently of **sensory** and **motor** conditions
- Gait direction does not affect the variability profiles
- Vision does affect the variability profiles
  ⇒ **Same open-loop processes** governing visual and nonvisual locomotion
  ⇒ Existence of **vision-dependent feedback processes**

Experiment 2: head/trunk coordination

We also studied the head/trunk coordination during steering, in the four conditions **VF**, **VB**, **NF**, **NB** (not shown here, can be discussed later)

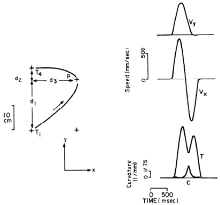


Pham et al, in preparation

Outline

Context

- Reminder: minimum jerk model for hand trajectories



- Common features of hand and locomotor trajectories:
  - smoothness
  - straightness for locomotor "reaching"
  - inverse relationship between velocity and curvature
- Can the minimum jerk model also simulate locomotor trajectories?

Minimum Square Derivative models

- Minimize

$$\min_{x,y} \int_0^1 \left(\frac{d^n x}{dt^n}\right)^2 + \left(\frac{d^n t}{dt^n}\right)^2 dt$$

for $n = 1, 2, 3, 4$ (min velocity, min acceleration, min jerk, mini snap)

- subject to the constraints (initial and final conditions)

$$\begin{array}{ll} x(0) = x_0, & x(1) = x_1 \\ y(0) = y_0, & y(1) = y_1 \\ \dot{x}(0) = v_0^x, & \dot{y}(0) = v_0^y \\ \dot{x}(1) = v_1^x, & \dot{y}(1) = v_1^y \\ \ddot{x}(0) = a_0^x, & \ddot{y}(0) = a_0^y \\ \ddot{x}(1) = a_1^x, & \ddot{y}(1) = a_1^y \end{array}$$

where the x_0, x_1, y_0, $v_0^x, \ldots$ are extracted from the experimental data

- For $n = 3$ (min jerk), the optimal trajectory is made of 5th-order polynomials

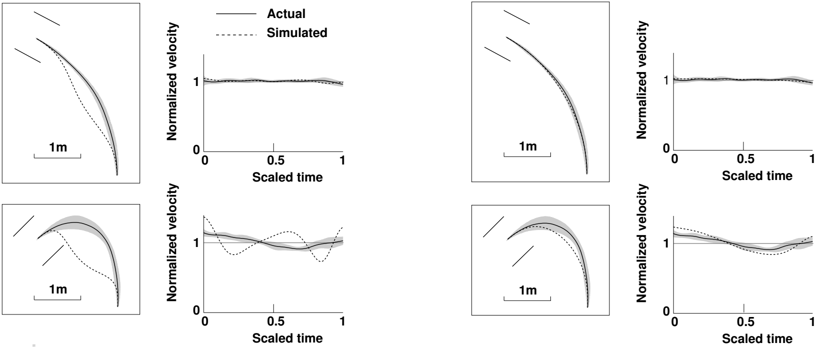
$$x(t) = c_5 x^5 + c_4 x^4 + c_3 x^3 + c_2 x^2 + c_1 x + c_0$$

$$y(t) = d_5 y^5 + d_4 y^4 + d_3 y^3 + d_2 y^2 + d_1 y + d_0$$

Results: minimum velocity and minimum acceleration

Minimum velocity

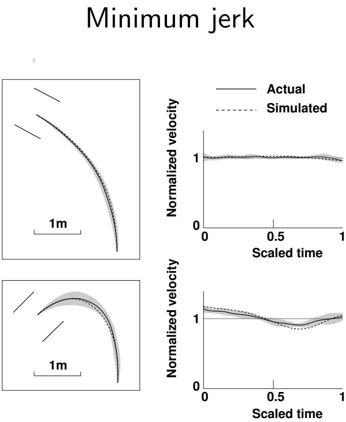
Minimum acceleration

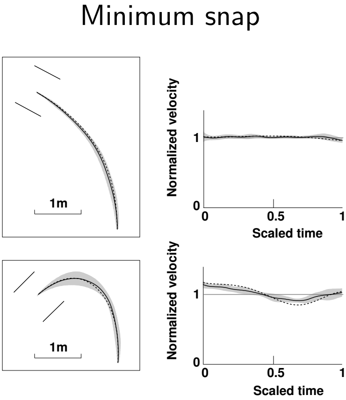


Pham et al, *Eur J Neurosci*, 2007

⇒ These models cannot simulate trajectories with large curvature

Results: minimum jerk and minimum snap



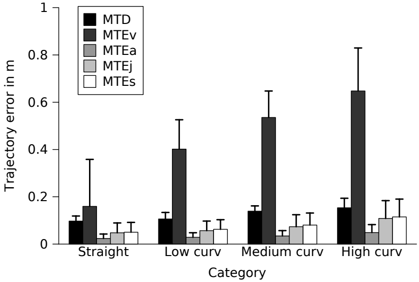


Pham et al, *Eur J Neurosci*, 2007

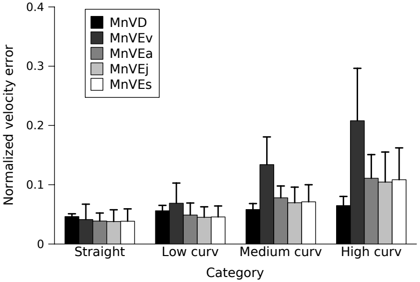
⇒ Good simulations for all categories: the simulated trajectory always lie within the variance ellipses

Results: quantitative comparisons

Max trajectory simulation error



Max velocity profile simulation error



Pham et al, *Eur J Neurosci*, 2007

- MTS $\leq$13cm for min jerk and min snap, that is $\leq$4% of trajectory length
- This is also smaller than the experimental variability (5%)

Conclusions

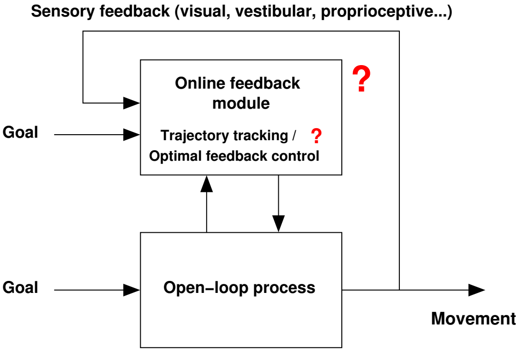
- The minimum jerk model (and also the minimum snap model) can accurately predict the average locomotor trajectories
- The formation of hand and locomotor trajectories thus may obey the same organizing principles
- This strengthens the "motor equivalence principle" hypothesis: "*at the higher levels of the motor system, there may exist kinematic representations of movements that are independent of the nature of the actual effector*" (Bernstein, *The co-ordination and regulation of movement*, 1967)

Outline

Main assumption

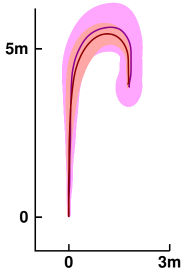
Two main issues (indicated by the question marks in the classical diagram)

- Existence of online feedback control in **visual** and **nonvisual** locomotion?
- Nature of the online feedback control?



Experiment 3: influence of vision on the variability profiles

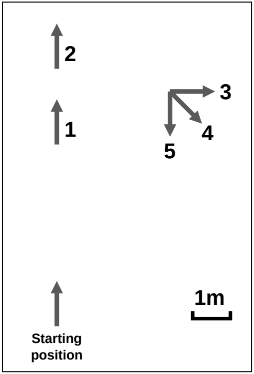
- Reminder: vision does not affect average trajectories



- How vision affects the variability profiles?
- Variability profiles in conditions **VF** vs **NF**

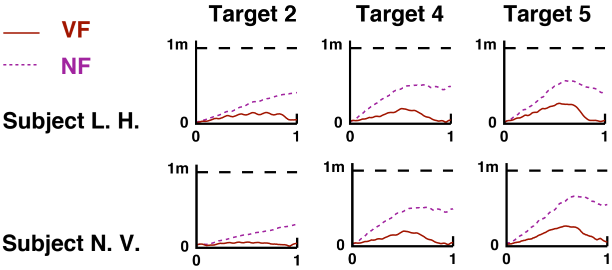
Experiment 3: methods

- Same protocol as in Exp 2
- 5 subjects × 2 conditions (**VF**/**NF**) × 5 targets × 8 repetitions
- Straight targets: 1, 2 ; Angled targets: 3, 4 , 5
- Intra-subject analysis



Experiment 3: results

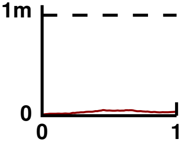
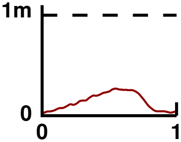
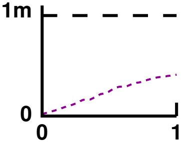
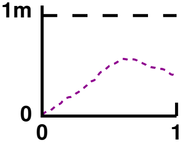
Variability profiles in conditions **VF** and **NF**



Pham and Hicheur, *J Neurophysiol*, 2009

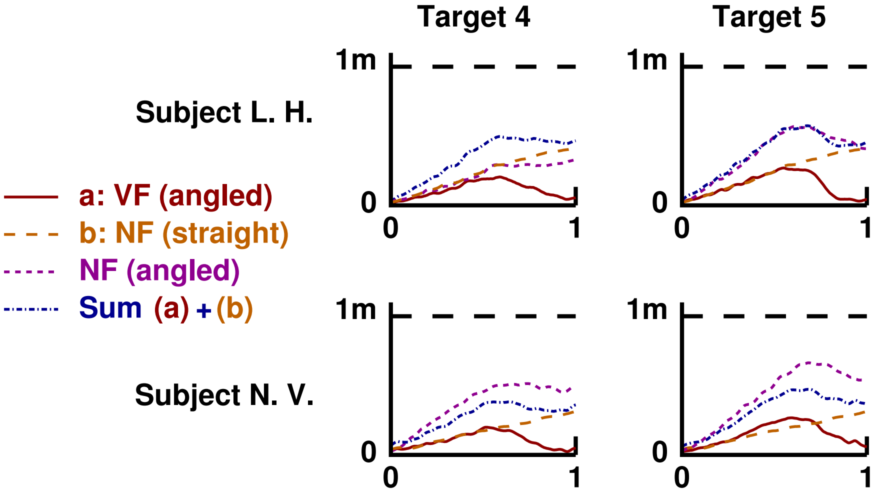
- Larger variability in NF than in VF
- VF: zero variability in straight targets, bump-shape in angled targets
- NF: linearly increasing in straight targets, non-monotonic in angled targets

Experiment 3: two-sources hypothesis

	Straight (targets 1 and 2)	Angled (targets 4 and 5)
VF	0 + 0 	0 + **Bump** 
NF	**Line** + 0 	**Line** + **Bump ??** 

- Bump: motor-complexity-dependent, vision-independent
- Line: motor-complexity-independent, vision-dependent

Experiment 3: two-sources hypothesis, verification



Pham and Hicheur, *J Neurophysiol*, 2009

Experiment 3: conclusions

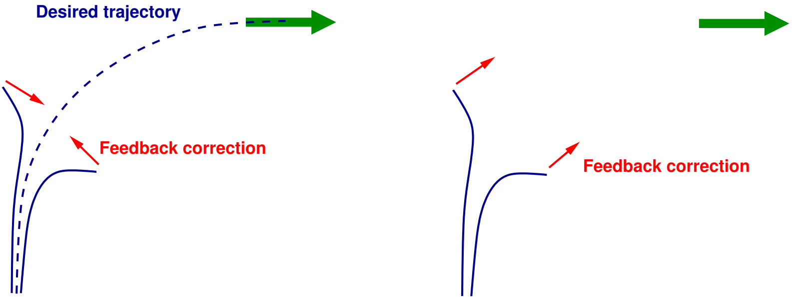
- Non-monotonic profiles $\Rightarrow$ existence of online feedback control
- Two-sources hypothesis $\Rightarrow$ the control mechanism in condition **NF** can be decomposed into:
  - a vision-independent component (bump)
  - a vision-dependent component (line)
- Bump-shape profile: interplay between execution noise and feedback control

Experiments 4 and 5

- What determines the amplitude of the variability in condition **VF**?
- Experiment 4: influence of the kinematic and geometric parameters of the trajectories on the variability (not shown here, can be discussed later)
- What is the nature of the online feedback?
  - "Desired-trajectory" tracking
  - optimal feedback control (see Todorov and Jordan, *Nat Neurosci*, 2002)
- Experiment 5 (not shown here, can be discussed later)

"Desired-trajectory" versus optimal feedback control

- "Desired-trajectory" tracking operates in two steps
  1. Compute an optimal trajectory according to some cost
  2. Track this trajectory (correct any perturbations back to the desired trajectory)
- Optimal feedback control: no intermediate representation, optimally correct perturbations with respect to the task



Outline

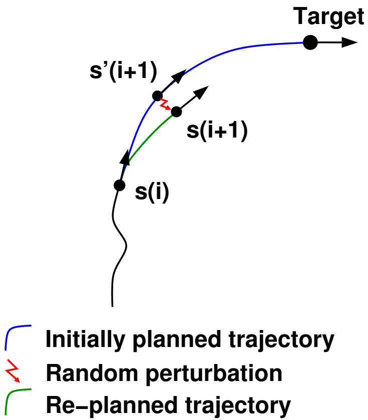
Context

- Deterministic models cannot explain variability profiles
- Here: stochastic models, more precisely some simplified optimal feedback control models (Hoff and Arbib, *J Mot Behav*, 1993; Todorov and Jordan, *Nat Neurosci*, 2002)
- Clarify the relationship between the control mechanisms in visual and nonvisual locomotion

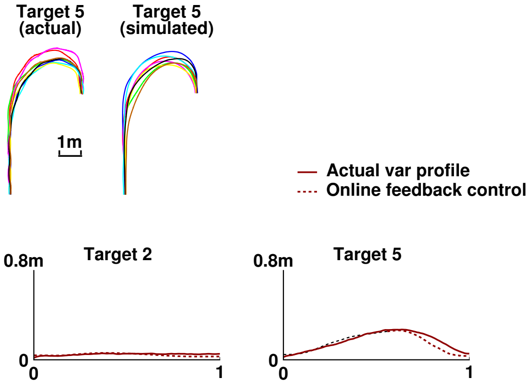
Visual condition: description of the model

Basic idea of optimal feedback control:
"goal-directed corrections"

1. Discretize the movement into n steps
2. At step i, compute first a minimimum jerk trajectory
3. Add some "signal-dependent" random perturbations to the provisional state $s'(i+1)$
4. Smoothly interpolate a new trajectory between the previous state $s(i)$ and the new perturbed state $s(i+1)$



Visual condition: results



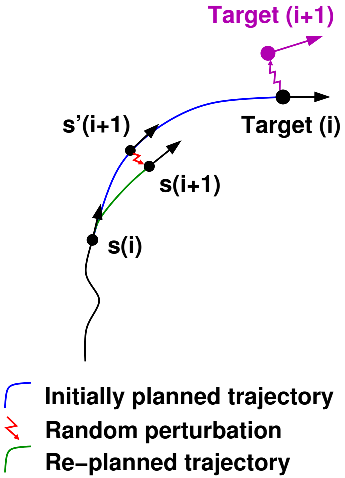
Pham and Hicheur,
J Neurophysiol, 2009

⇒ This model can simulate both the trajectories and the variability profiles:

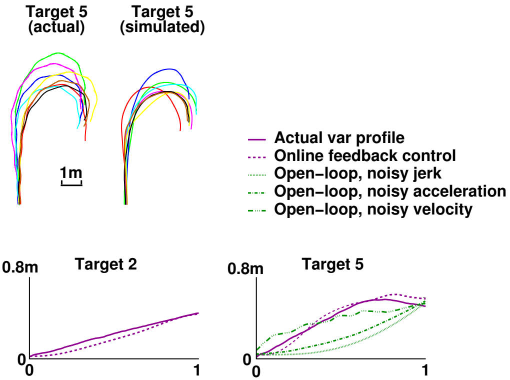
- almost zero in "straight" targets
- bump-shaped in "angled" targets

Nonvisual condition: online feedback model

- "Two-sources" hypothesis
- The first component can be simulated by the same algorithm as in condition **VI**
- The second component is related to state estimation and can be rendered by perturbing the target (can be discussed later)



Nonvisual condition: results



Pham and Hicheur,
J Neurophysiol, 2009

⇒ This model can simulate the variability profiles:

- linearly increasing in "straight" targets
- non-monotonic in "angled" targets

Open-loop models cannot reproduce the non-monotonic behavior

Stochastic models: conclusions

- Existence of online feedback control in **nonvisual locomotion** confirmed
- Two-sources hypothesis confirmed
- In particular: visual and nonvisual locomotion not only share the same open-loop processes but also the same feedback processes
- In nonvisual locomotion, same control mechanisms as in visual, but with respect to a corrupted target position

Outline

Summary of the results

- Locomotor trajectories are stereotyped. Goal-oriented locomotion is likely planned and controlled at the level of whole-body trajectories in space
- Locomotor trajectories are planned and controlled at a high cognitive level and, to some extent, independently of the sensory and motor conditions of locomotion
- Similar principles seem to underlie the formation of locomotor and hand trajectories
- A combination of optimal open-loop and feedback processes governs the formation of locomotor trajectories. The open-loop process is likely based on minimum jerk principle, the feedback process on optimal feedback control

Perspectives

- Developmental and clinical aspects: how the previous properties are acquired in children and how are they affected by motor and cognitive deficits (joint work with D^r Belmonti)
- Locomotion and navigation in animals: availability of electrophysiological data (rats) or of transgenic subjects with specific spatial cognition deficits (mice)
- Humanoid robotics: how our understanding of human locomotion can help building more efficient walking and navigating robots?

Remerciements

Je souhaiterais remercier

- MM. Alain Berthoz et Halim Hicheur
- MM. les membres du jury
- l'ensemble des collègues du LPPA et d'ailleurs
- l'ensemble du personnel du LPPA
- ma famille et mes amis