Neuromechanics of Human Motion

Optimal Feedback Control

Joshua Cashaback, Ph.D.

Human Behaviour — Recap

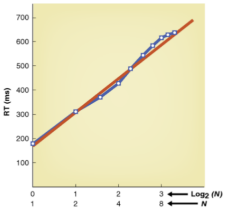
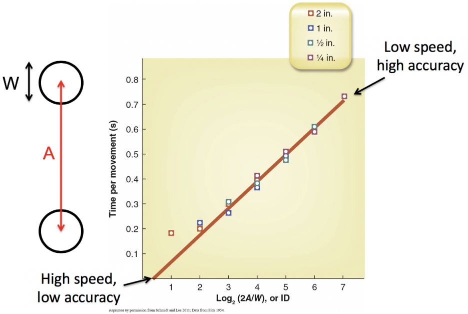


FIGURE 2.7 Hick's Law: The relation between choice RT and number of S-R alternatives (*N*) is replotted using Merkel's data from figure 2.6, with choice RT as a function of $\text{Log}_2(N)$.

Reprinted by permission from Schmidt and Lee 2011; Data from Merkel 1885.



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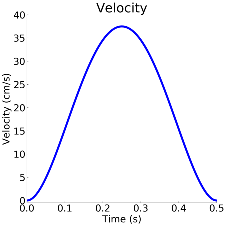
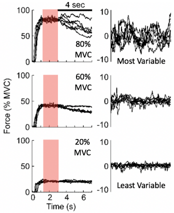
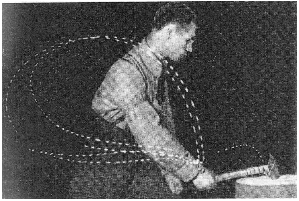
Human Behaviour — Recap

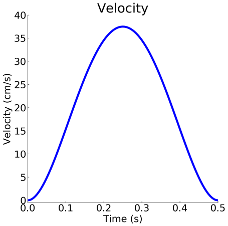




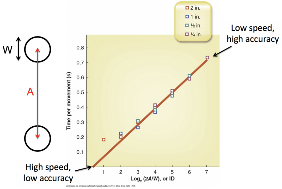


Human Behaviour — Recap

min(jerk); min(joint moment rate); min(sdn)



min(sdn)



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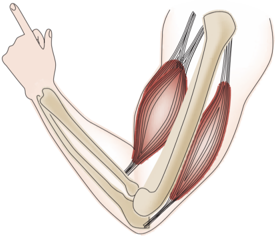
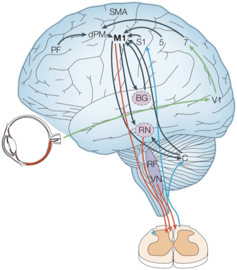
Lecture Objectives

1. General Concepts of Optimal Feedback Control (OFC)
2. Stereotypical Features of Human Motion
   a. Fitt's Law
   b. Bell-shaped Velocity Profiles
   c. Behaviour of Redundant Systems — Task-relavance
3. Probing Feedback Gains
   a. short-latency
   b. long-latency
4. Neural Basis of OFC

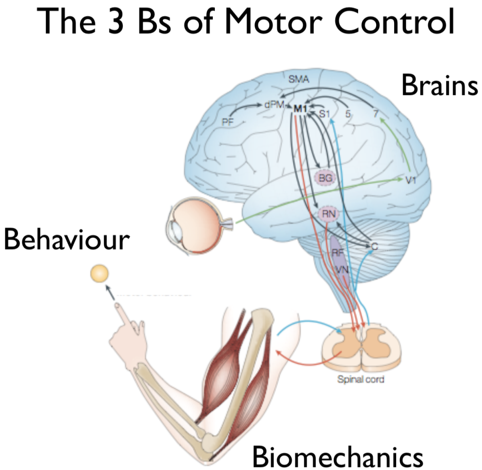
Biomechanics and Brain



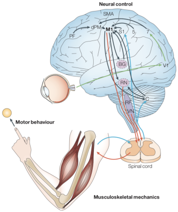
Equally
Important
&
Intimately
Linked



The Three B's of Human Movement

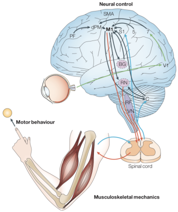


Optimal Feedback Control

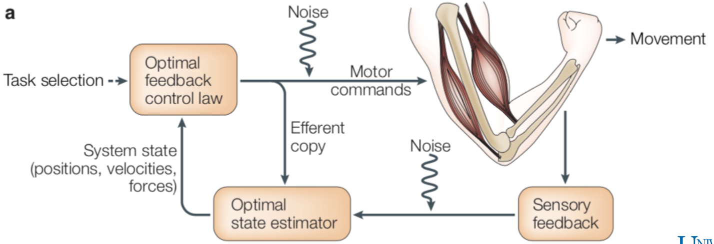


(Todorov and Jordan, 2002; Scott, 2004)

Optimal Feedback Control



(Todorov and Jordan, 2002; Scott, 2004)



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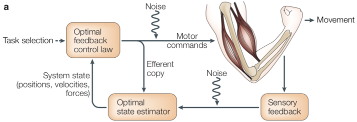
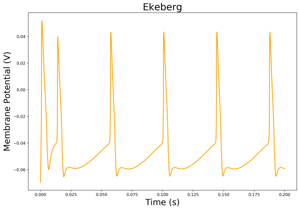
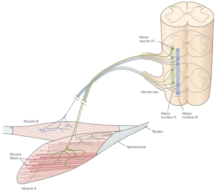
General Concepts and Terminology

OFC

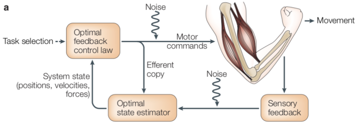
Motor Commands



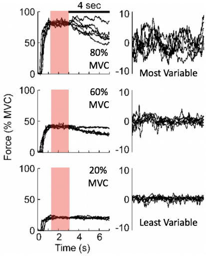




OFC
Motor Noise



Multiplicative and Additive



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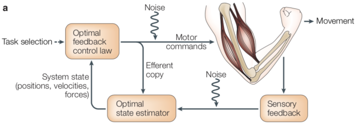
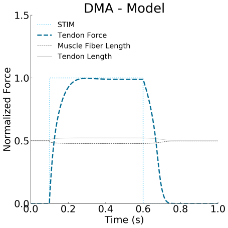
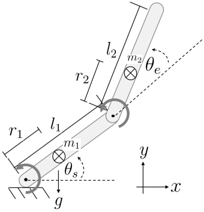
OFC
“Plant” (Biomechanics)

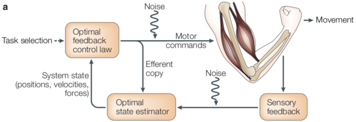




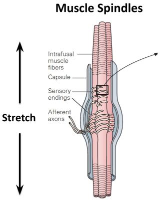


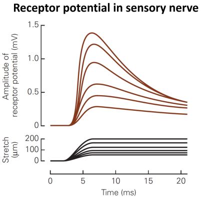
OFC

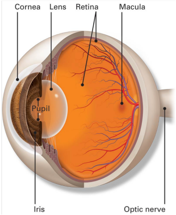
Sensory Feedback and Measured State



States: position, velocity, force

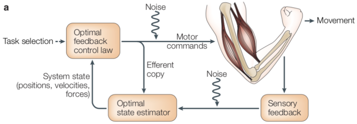




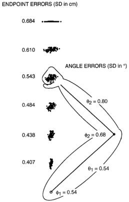


OFC

Sensory Noise



(Scott and Loeb, 1994)



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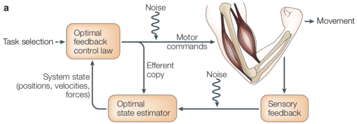
OFC
Efference Copy

Efference Copy

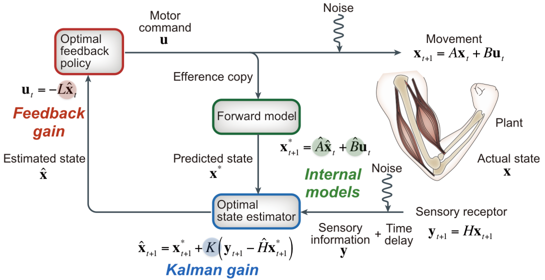
an internal copy of an outflowing (efferent), movement-producing signal (motor command) generated by the motor system.



OFC
Forward Model

Forward Internal Model

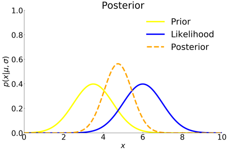
Efference copy of a particular set of motor commands are passed through a particular neural representation of plant dynamics to make a prediction of state.

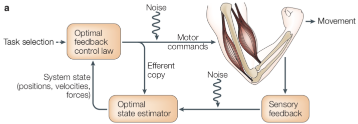


OFC
Optimal State Estimator and Posterior State Estimate

Optimal State Estimator

Combines noisy sensory feedback (time-delayed state measurement) with the forward model predicted state in a statistically optimal (Bayesian) fashion to produce a **posterior state estimate.**





OFC

Optimal Feedback Control Law

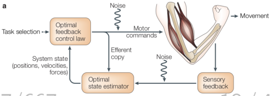
Feedback Gains

Transform posterior state estimates into motor commands

Optimal Feedback Control Law

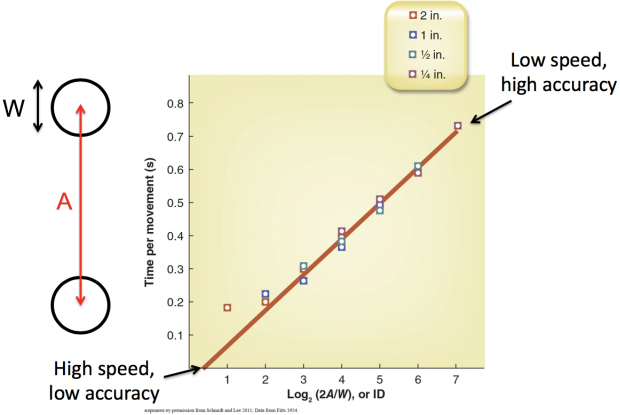
The optimal set of feedback gains that minimize some cost

1. cost function: typically includes desired state (target) and minimizing motor commands
2. movement trajectories emerge from the optimal control law

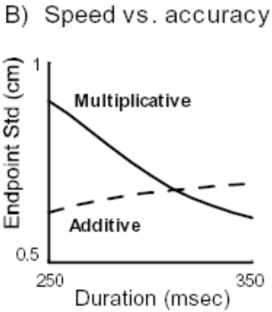


OFC — Stereotypical Human Behaviour

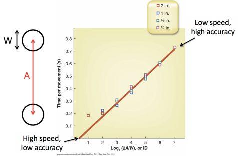
Fitt’s Law — Speed Accuracy Tradeoff



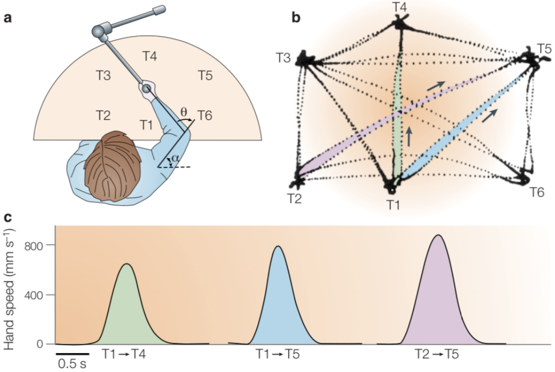
Fitt's Law — Speed Accuracy Tradeoff



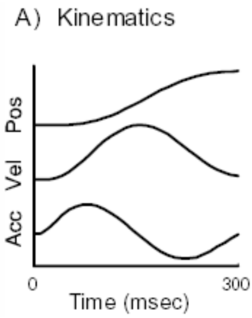
(Todorov, 2005)



Bell-shaped Velocity Profiles



Bell-shaped Velocity Profiles



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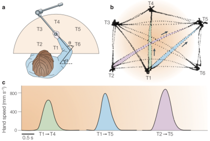
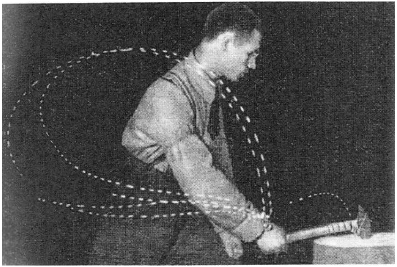


Behaviour of Redundant Systems

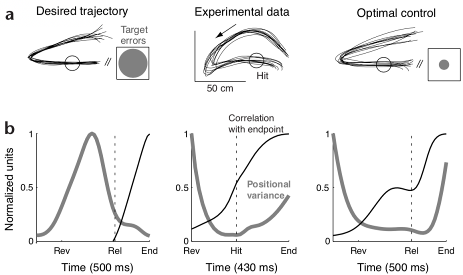
Minimal Intervention Principle (Todorov 2002)

Deviations from the average trajectory are only corrected when they interfere with the task goals.

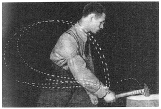


Behaviour of Redundant Systems

Virtual Ping-Pong Task

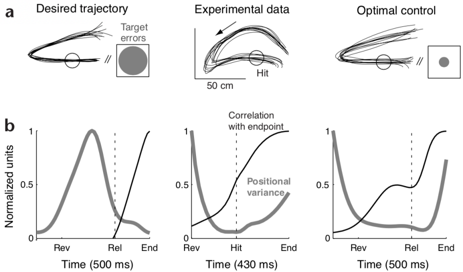


(a) trajectory control (b) experimental data (c) optimal feedback control



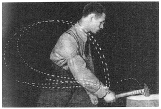
Behaviour of Redundant Systems

Virtual Ping-Pong Task



(a) trajectory control (b) experimental data (c) optimal feedback control

OFC mean trajectory and task-irrelevant variability are emergent features!



Behaviour of Redundant Systems

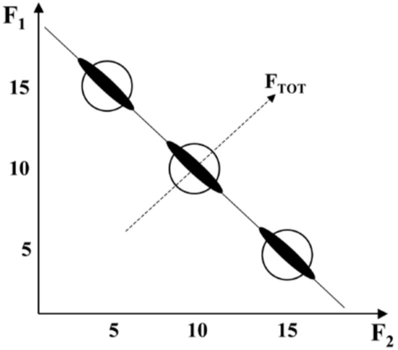
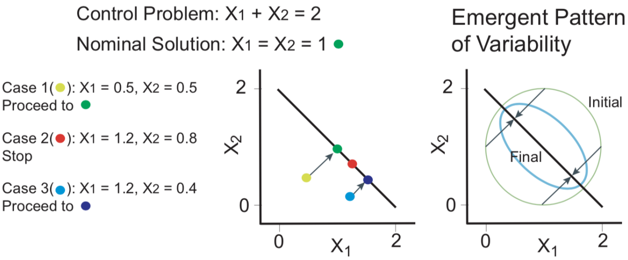


Figure 1—An illustration of the two basic features of synergies. A person tried to produce the same total force of 20 N with two fingers. Three sharing patterns are illustrated: 5:15 N, 10:10 N, and 15:5 N. This means that with changes of total force (F_{TOT}) both finger forces change in the same direction (i.e., positive co-variation along the dashed lines). Data distri-

Behaviour of Redundant Systems



The optimal feedback control goes directly to the goal

Greater variability (covariance matrix) along the task-irrelevent dimension

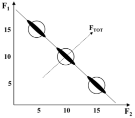


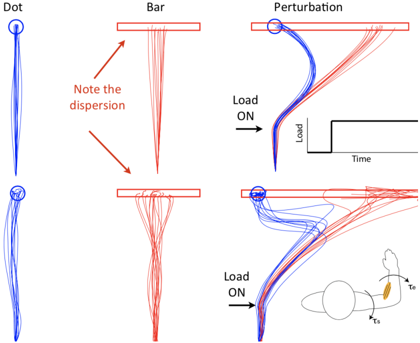
Figure 1—An illustration of the two basic features of synergies. A person tried to produce the same total force of 20 N with two fingers. Three sharing patterns are illustrated: 5:15 N, 10:10 N, and 15:5 N. This means that with changes of total force (F_{TOT}) both finger forces change in the same direction (i.e., positive co-variation along the dashed lines). Data distri-

Behaviour of Redundant Systems

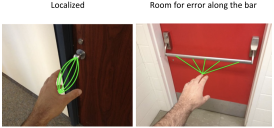
Localized

Room for error along the bar

Behaviour of Redundant Systems

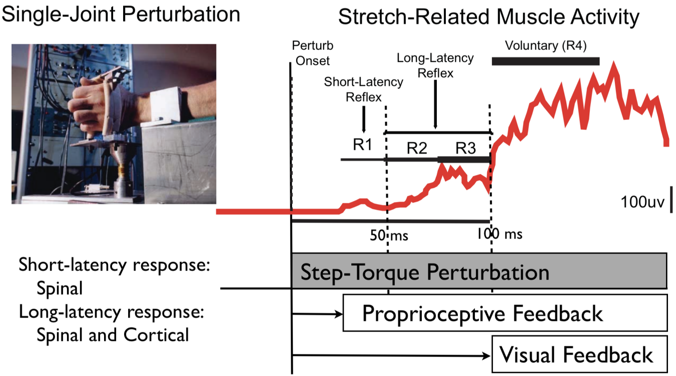


Top row: OFC model; Bottow row; Human data (Nashed et al., 2012)

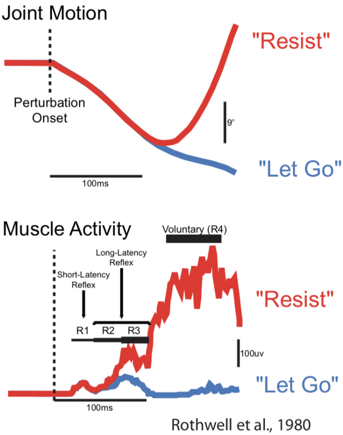


Probing Feedback Gains

Probing Feedback Gains
Experimental Design



Feedback Gains — Task Goal

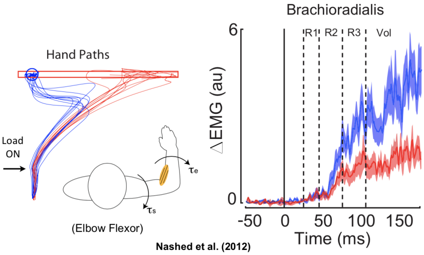


The Long-Latency reflex displays ‘intelligence’

by responding to the task goal

Feedback Gains

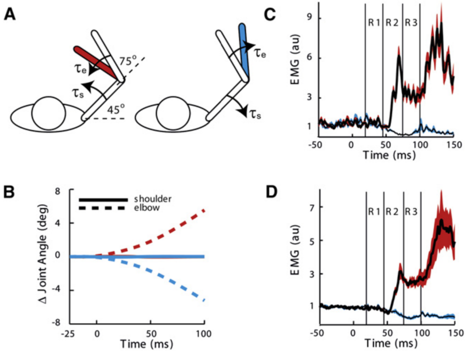
Minimum Intervention Principle



Long-Latency mirrors the minimum intervention principle (and OFC)

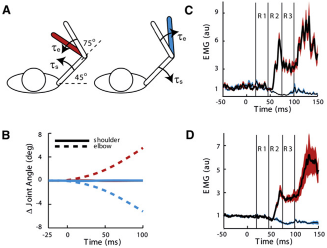
1. Greater gain with task-relevant perturbation
2. Less gain with task-irrelevant perturbation

Feedback Gains
Knowledge of Limb Dynamics



a) applied moment b) individual PD EMG c) group kinematics d) group PD EMG (Kurtzer et al., 2008)

Feedback Gains
Knowledge of Limb Dynamics



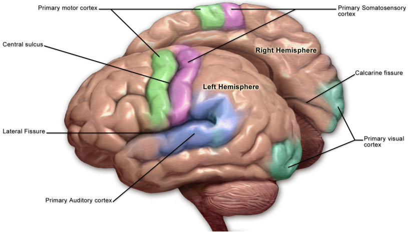
a) applied moment b) individual PD EMG c) group kinematics d) group PD EMG (Kurtzer et al., 2008)

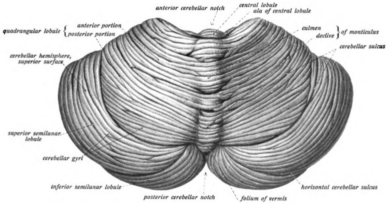
Long-latency reflects knowledge of interaction moments

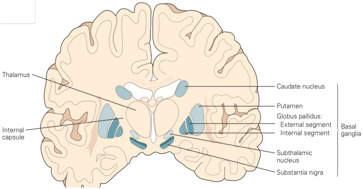
1. PD generates shoulder moment to counter interaction moment produced by TRI that corrects elbow angle.
2. PD inhibited to not assist interaction moment produced by BR and BB that corrects elbow angle.

Neural Basis of OFC

Neural Basis of OFC







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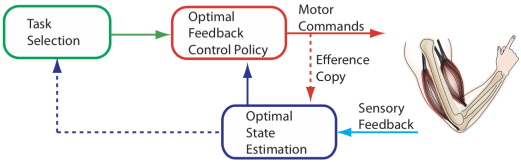
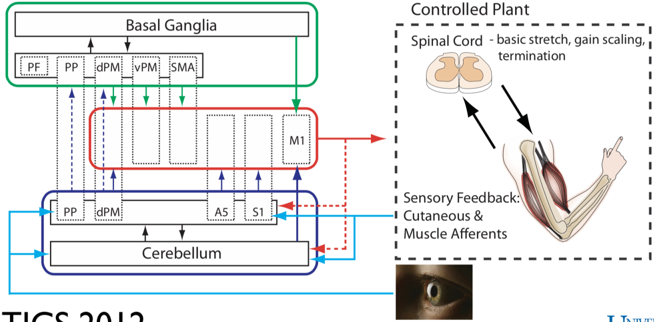
Neural Basis of OFC





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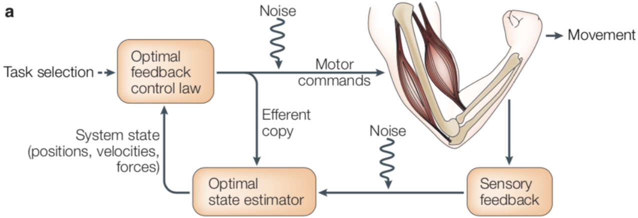
Take Homes

1. Brain and Biomechanics dictate Behaviour.
2. OFC (LQG) Captures MANY stereotypical features of human behaviour
   a. (Near) Optimal Control
   b. State Estimation

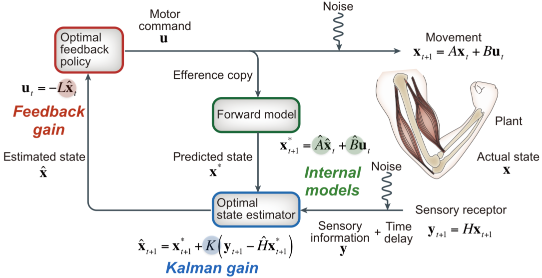


QUESTIONS???

Next Class

Optimal Feedback Control Model (LQG)

1. LQR
2. State Estimation



Acknowledgements

Stephen Scott (CoSMo Lecture)