Forward and Inverse Models in Motor Control and Cognitive Control
Overview

- The problem of Motor Control
  - Inverse and forward models

- The problem of Cognitive Control

- Two accounts of Cognitive Control
  - Botvinick et al (2001)

- ...and some limitations of those accounts

- Inverse models in cognitive control?
The Problem of Motor Control

- Many simple acts require us to bring together simultaneously multiple objects/limbs:
  - Consider serving a tennis ball

- Many sequential tasks require fast motor movements that, due to neural timing constraints, must be programmed in advance:
  - Consider a musician sight reading

- What properties are required of a (motor) control system with these capabilities?
Inverse and Forward Models in Motor Control (Wolpert & Ghahramani, 2000)
Inverse and Forward Models in Motor Control

- **Inverse model (motor planning):**
  - Allows us to derive the motor command required to bring about a desired state

- **Forward dynamic model (state prediction):**
  - Allows us to derive the anticipated state of the motor system when we perform a motor act

- **Forward sensory model (sensory prediction):**
  - Allows us to predict the anticipated sensory feedback from a motor act, as required by error correction
An Aside: Models and mental simulation

- The use of forward/inverse models does not necessarily imply mental simulation

- Models may be impoverished

- Simple learnt associations:
  
  \[
  \text{[current state } \times \text{ desired outcome]} \rightarrow \text{required action}
  \]
Biological Evidence for Inverse and Forward Motor Models

- Kawato (1999):
  - The cerebellum contains multiple forward and inverse models that compete when learning new motor skills

- Ideomotor apraxia may be understood in terms of deficient internal models:
  - Sirigu et al (1996): Parietal apraxic patients show motor imagery deficits
  - Buxbaum et al (2005): Motor imagery and performance on an imitation task correlate ($r > 0.75$)
The AIIB Question

- Control theory has helped understand the biological basis of motor control

- Do similar problems arise in cognitive control?

- Can control theory inform cognitive theories of control?
The Problem of Cognitive Control:
Online performance adjustments in CRT

Lamming (1968):
The Problem of Cognitive Control: Online performance adjustments in Stroop

- Tzelgov et al (1992) on Stroop interference:
  - Low, when incongruent Stroop trials are frequent
  - High, when incongruent Stroop trials are rare

- Stroop interference is:
  - Low, when incongruent Stroop trials are frequent
  - High, when incongruent Stroop trials are rare
The Botvinick et al (2001) Solution: Conflict Monitoring

- Claim: ACC monitors “information processing” conflict
- High conflict causes an adjustment in online control
- But what is “information processing conflict”, and how is control adjusted?
The Alexander & Brown Solution: Performance Monitoring and the PRO model

- Given a planned response, the model makes an outcome prediction (i.e. a forward model)
- Pro-active control may then:
  - Veto the plan (and presumably adjust control parameters)
- Discrepancies are used to learn R-O mapping
Issues Arising from Models of Control

- So the concept of (forward) model has some currency in the cognitive control literature

- But ... Alexander & Brown (2010):
  - The rationale for forward models is limited (basically so we can veto erroneous responses)

- And ... a problem for both Botvinick et al (2001) and Alexander & Brown (2010):
  - In both cases the control signal is a scalar, yet current theories of control suggest multiple control functions
Multiple Control Functions: Miyake et al (2000)
Multiple Control Functions: Shallice et al (2008)
Putative Control Parameters

- Attentional bias
- Response inhibition
- Response threshold
- Memory maintenance
- Task switch strength
- Energisation
- Attentiveness
Can the Models be Extended to Multiple Control Functions?

- Not easily:
  - There is a problem of credit assignment

- Typically the feedback is a scalar value

- How can the system know which of several control parameters to adjust to improve performance?

- One possibility: one scalar for each parameter (e.g., response conflict → attentional bias)
And Another Thing ...

A second problem for both models:

- How does the system know/set sensible control parameters (e.g. on the first trial of a task)?

If I explain to you the rules of CRT (or the Flanker Task or Stroop), then it is possible to answer correctly on the first trial

- And even more so if you have done the task before
A Speculative Solution

- Both problems can be answered if the cognitive control system makes use of inverse models:
  - What control parameter settings are required to generate the desired response?

- Moreover, an inverse model can associate a set of control parameters with a task
  - So it avoids the problem of being limited to a single scalar control parameter.
Extended PRO Model

Task Specification → Inverse Model → System Parameters

Planned Response → Discrepancy Update → Execution, Outcome

R-O prediction (Forward Model) → Discrepancy, update → Actual vs. Predicted?

Amend/Veto plan? → Prediction → Corrective action
Inverse models of control may be learnt through reinforcement learning much as in Alexander & Brown’s PRO model.

But there is no credit assignment problem at this stage:
- We are just associating a task with a set of control parameters.
How do we construct an inverse model for a novel tasks:
- Very speculatively (and extrapolating again from the motor control literature), they may be based on a mixture of experts idea

An initial inverse model for a novel task will require online adjustment:
- The problem of credit assignment is pushed onto learning appropriate online control parameter adjustments
Tentative Answer to the AIIB Question(s)

- Do similar problems arise in cognitive control?
  - Yes - similar problems do arise in cognitive control

- Can control theory inform cognitive theories of control?
  - Yes - Control theory quite possibly can inform cognitive theories of control