Forward and Inverse Models in Motor Control and Cognitive Control

Richard P Cooper
Department of Psychological Science
Birkbeck UNIVERSITY OF LONDON

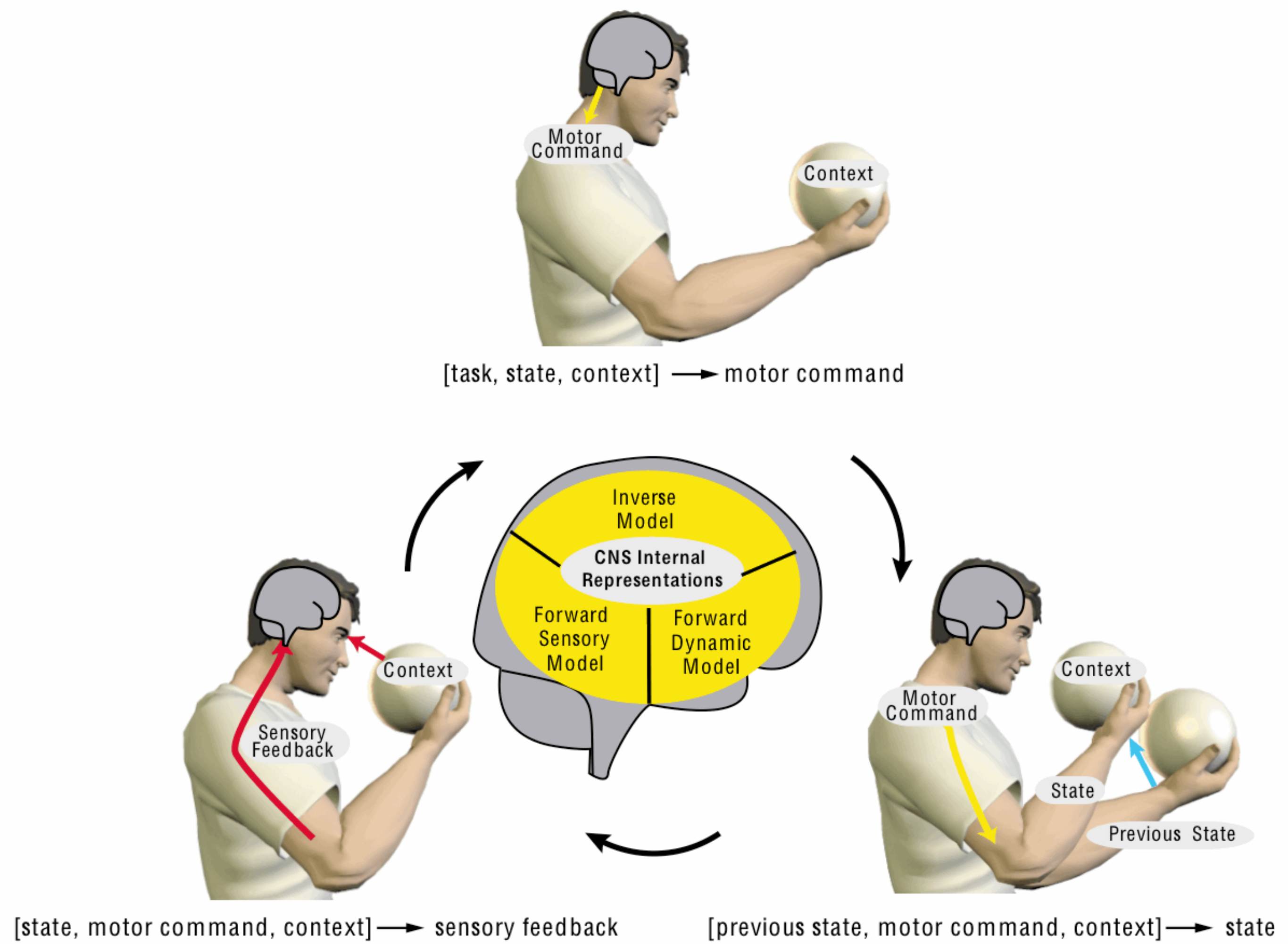
Overview

- The problem of Motor Control
  - Inverse and forward models
- The problem of Cognitive Control
- Two accounts of Cognitive Control
  - Botvinick et al (2001)
  - Alexander & Brown (2010)
- …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:

  [current state x desired outcome] $\rightarrow$required action

Biological Evidence for Inverse and Forward Motor Models

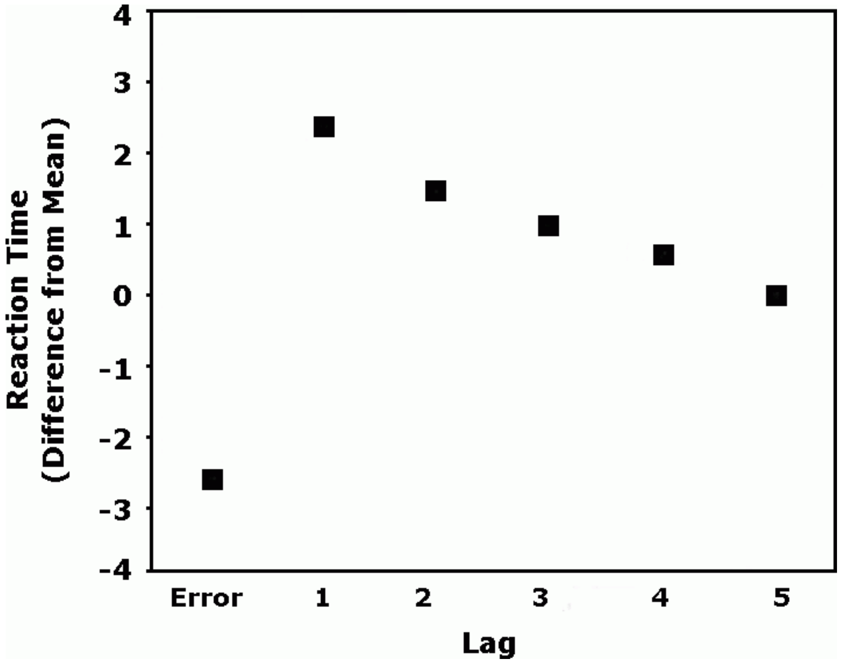
- Kawato (1999):
  - The cerebellum contains multiple forward and inverse models that compete when learning new motor skills
- Ideomotor apraxia may be understood in terms of deficient internal models:
  - Sirigu et al (1996): Parietal apraxic patients show motor imagery deficits
  - Buxbaum et al (2005): Motor imagery and performance on an imitation task correlate ($r > 0.75$)

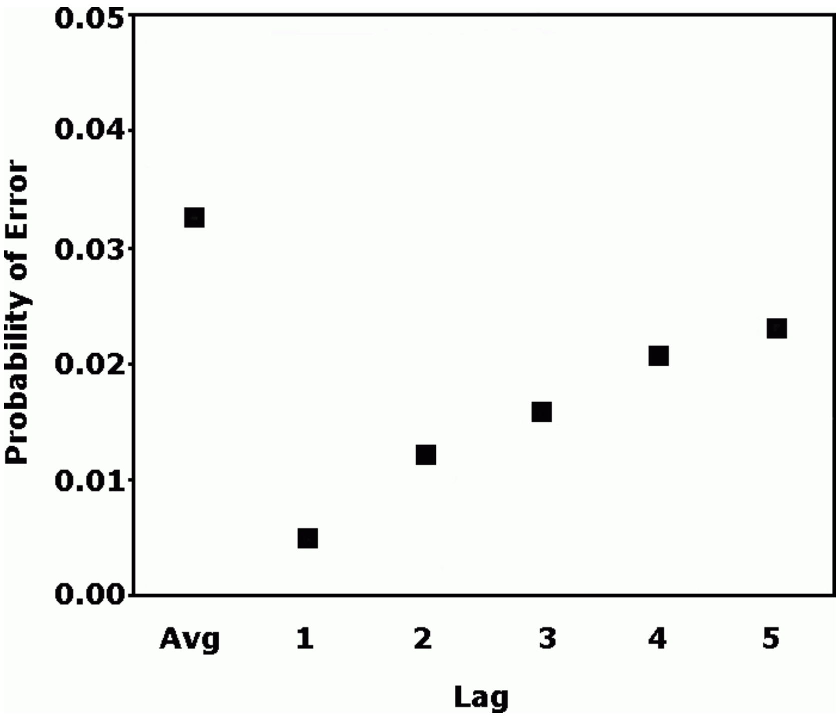
The AIIB Question

- 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?

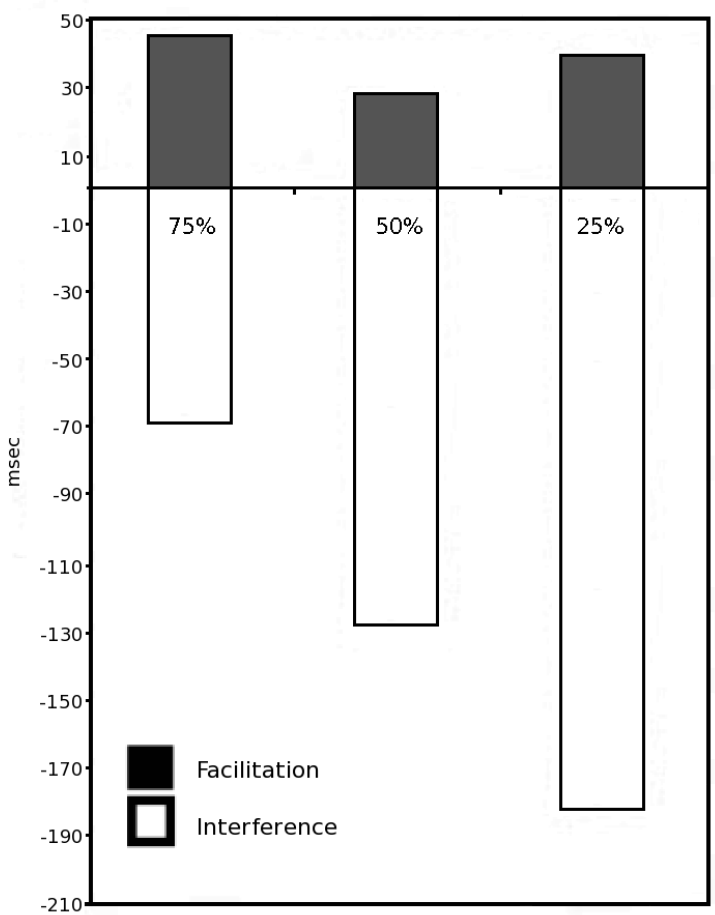
The Problem of Cognitive Control:
Online performance adjustments in CRT

- Lamming (1968):





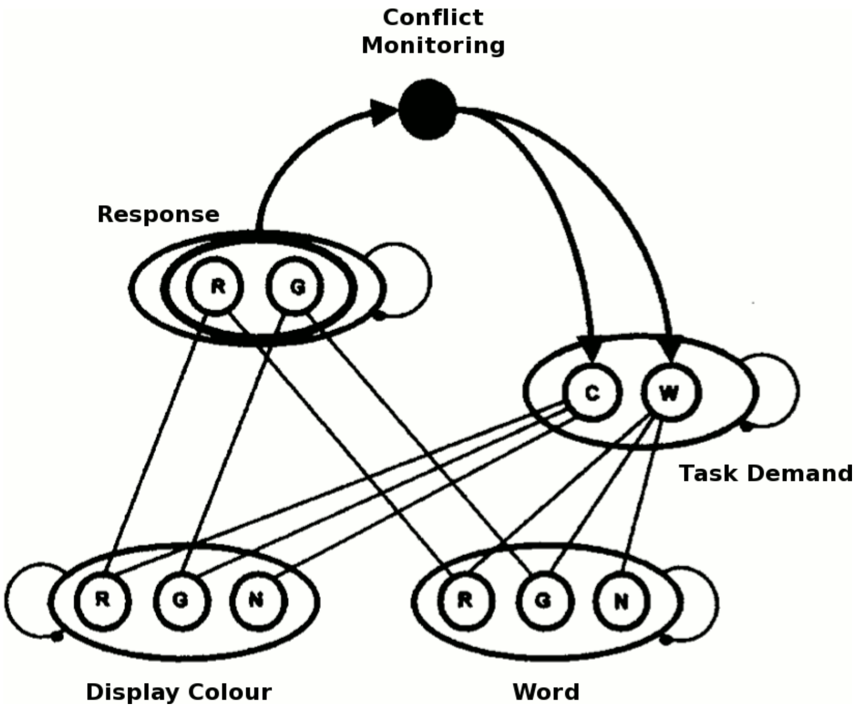
The Problem of Cognitive Control:
Online performance adjustments in Stroop



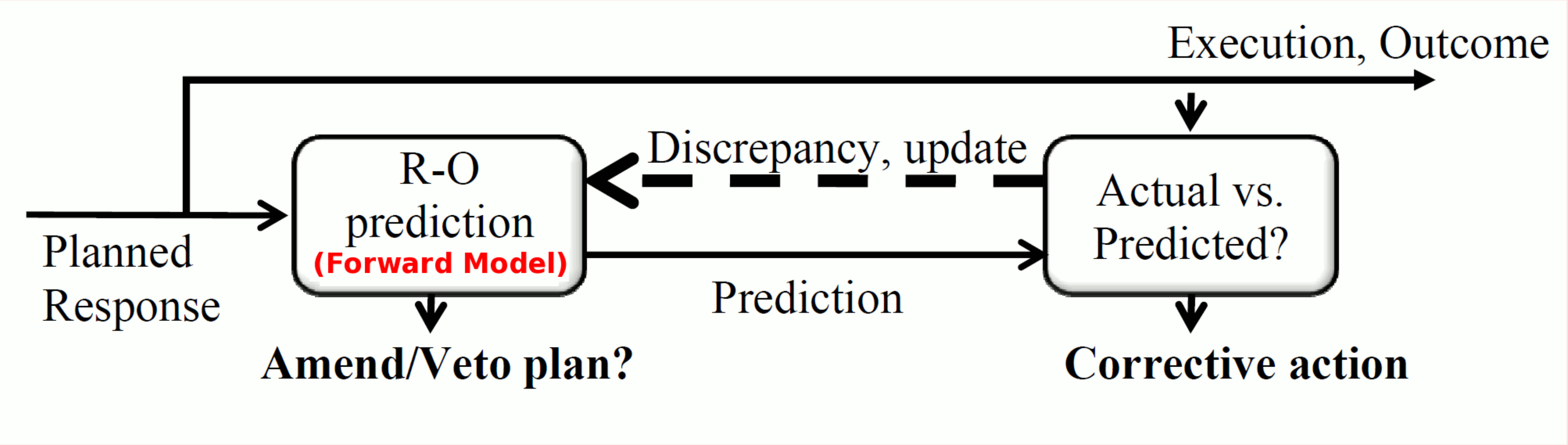
- Tzelgov et al (1992) on Stroop interference:
  RED
  XXX
  RED
- Stroop interference is:
  - Low, when incongruent Stroop trials are frequent
  - High, when incongruent Stroop trials are rare

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

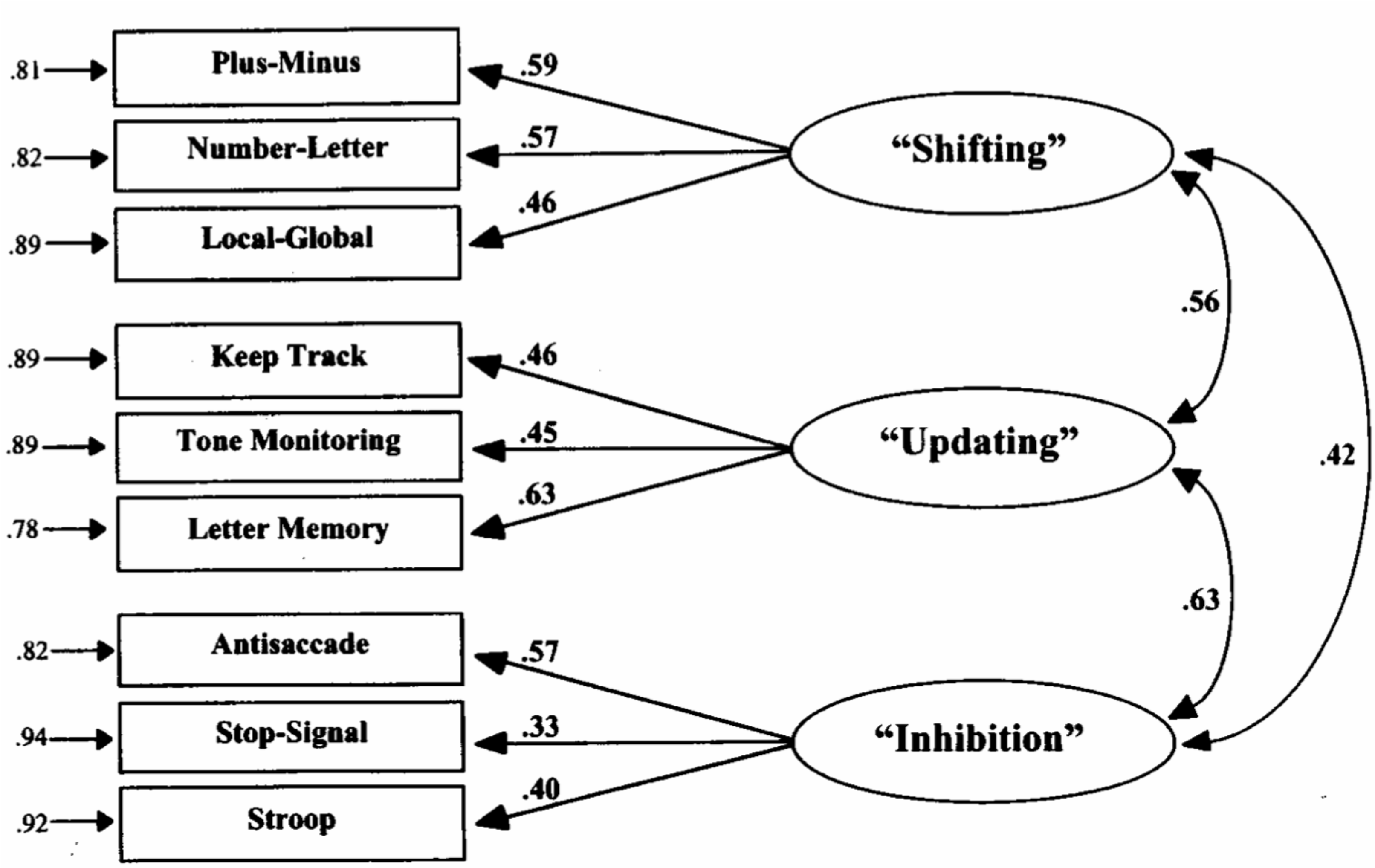


- Given a planned response, the model makes an outcome prediction (i.e. a forward model)
- Pro-active control may then:
  - Veto the plan (and presumably adjust control parameters)
- Discrepancies are used to learn R-O mapping

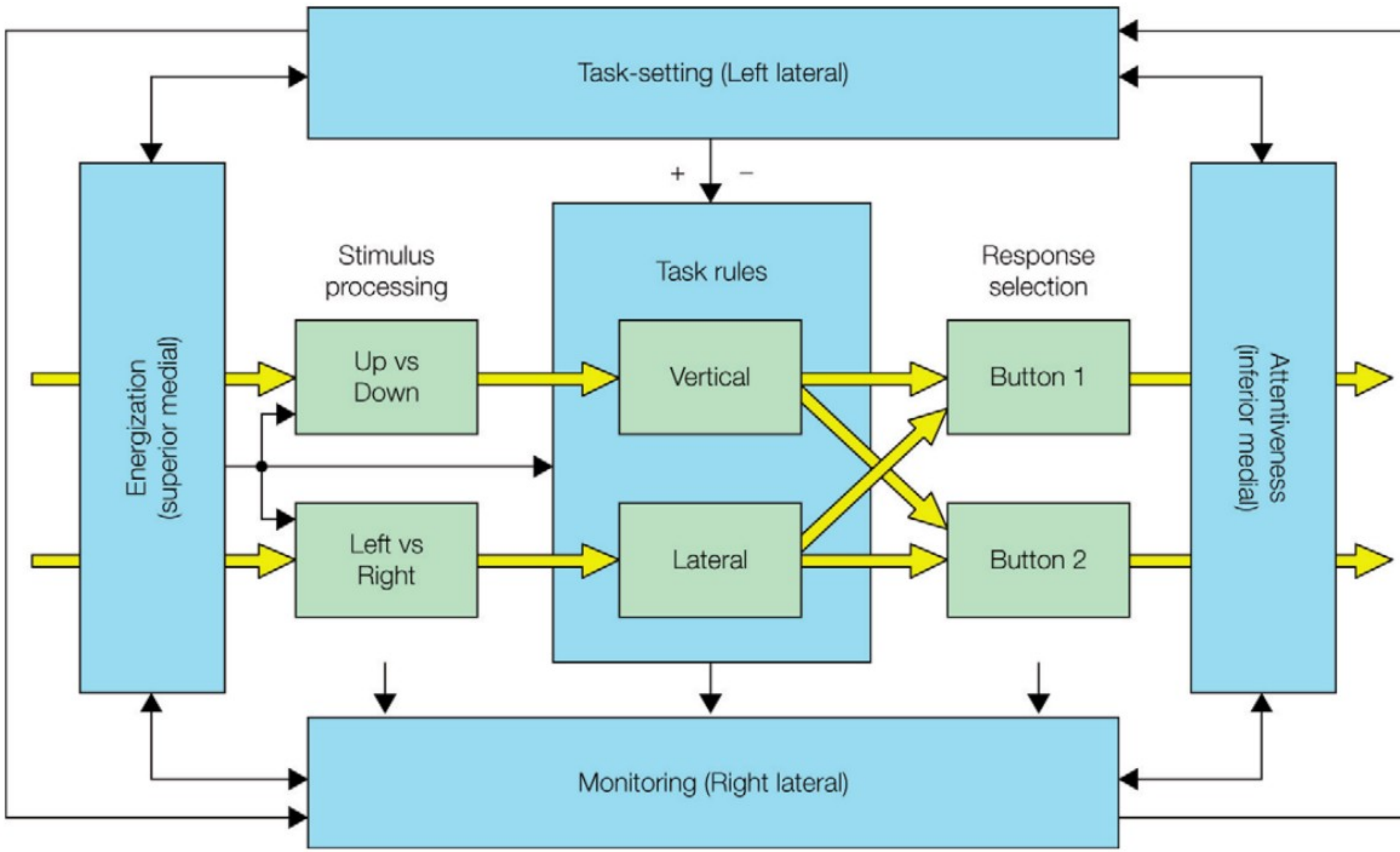
Issues Arising from Models of Control

- 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 $\rightarrow$attentional bias)

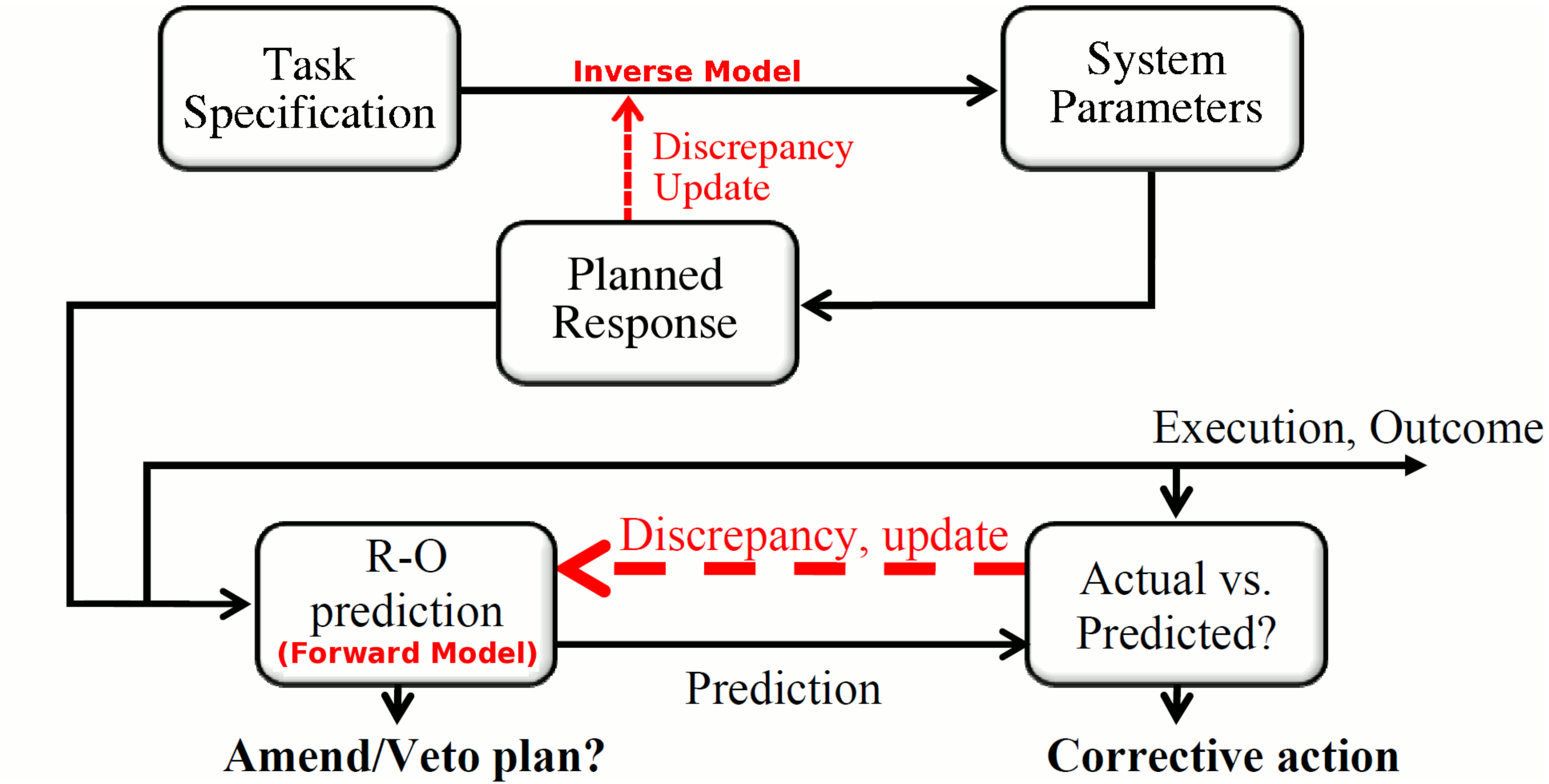
And Another Thing …

- 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



Further Speculations (Learning)

- 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

Further Speculations (Novel Tasks)

- 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