Forward and Inverse Models in Motor Control and Cognitive Control

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Abstract. It is now commonly accepted that the motor system makes use of so-called forward and inverse models in order to control the musculoskeletal system during rapid, skilled, motor behaviour. Inverse models are held to allow the system to determine the motor commands necessary to achieve a desired state, while forward models are held to allow the system to predict the expected sensory feedback of a motor command, allowing rapid error detection when actual and predicted feedback do not match. It has recently been suggested that these ideas from control theory might also be applied to the control of cognitive processes, allowing (for example) the cognitive system to anticipate processing conflict and pre-emptively minimise it by adjusting processing strategies or the allocation of processing resources. This paper reviews theories of cognitive control that are broadly consistent with the use of complementary forward and inverse models. It is argued that there is indeed a role for such models in cognitive control – particularly in relation to a putative monitoring function – but that the models involved are likely to be somewhat impoverished.

1 INTRODUCTION: MULTIPLE MODELS IN MOTOR CONTROL

Consider a skilled musician, say a pianist, sight-reading a piece of music. The cognitive task of translating the sensory input, for example an F-sharp followed by a lower C, into a sequence of motor commands – press the F-sharp key and then the C key to the left of it – is clearly a complex one. But consider the motor task. The motor system can't just execute two simple finger presses over the appropriate keys. It must work out which digit to use given the current position of the hand and digits. It may need to raise a digit, shift the position of the hand, or move a digit horizontally as well as vertically. In skilled sight-reading, all this must be done at pace – yet there is an inherent time lag in the transmission of neural signals. The motor system must be able to take account of such lag, but it can also not afford to wait for proprioceptive feedback from one motor command (such that it can access a representation of the location of all relevant skeletal components and the state of all relevant muscular components) before formulating the next. This, and related problems in motor control [1], have led researchers in the area of motor control to propose, following simple control theory, that the motor system makes use of so-called forward and inverse models in planning and regulating motor behaviour.

In general, a forward model is a representation of the future state of a system. The motor system might profitably make use of such a model to predict its state following the performance of a motor command. That is, given the current state of the motor system and the intended action, a forward model allows the system to predict its future state. Wolpert and colleagues refer to the relevant type of model as a *forward dynamic model* [2].

For speeded motor activity, the prediction may be used in two ways. First, it allows the system to formulate the next motor command without waiting for proprioceptive feedback from the current command. How though does the motor system formulate this motor command? This is where an *inverse model* is held to play a role. Inverse models "invert the causal flow" [1]. Thus, given a future desired state, they generate the motor command that is required to bring about that state.

The second use of the predicted state is that it may be feed into a second forward model – a so-called *forward sensory model* [2] – that predicts the expected proprioceptive feedback based on the anticipated state. Any mis-match between this and the feedback subsequently received may be used by the motor system to fine-tune motor control in real time, as is required in skilled, speeded motor activity.

Wolpert and colleagues have amassed a substantial body of behavioural evidence that supports the claim that the motor system relies on internal forward and inverse models (see, e.g., [1,2,3]). These studies generally involve mapping moment-by-moment control of speeded movements in simple motor tasks, often in situations where proprioceptive feedback is manipulated so as to violate expectations. The studies are accompanied by neurological evidence which suggests that the cerebellum contains multiple forward and inverse models [4,5,6] and neuropsychological studies of patients with motor control deficits which suggest that the parietal lobes are involved in implementing forward models [7,8].

The concepts of forward models and inverse models have their roots in control theory where communication delays between a centralised control system, a motor system and sensory feedback render a sense-plan-act cyclic approach to action control inadequate. Application of the concepts to motor control is perhaps not surprising given that direct relationship between motor behaviour and action. However, the past 20 years has witnessed the increasing realisation that there is a second area of cognitive science where control is critical – namely in the generation and regulation of cognitive processes. Thus *cognitive control* is now recognised as a domain of research in its own right (see, e.g., [9]), paralleling the more classical domains of memory, perception, attention, reasoning, problem solving, etc. which populate the contents pages of standard cognitive textbooks. Two questions naturally arise. First, are there similarities between the problems of cognitive control and motor control? And second, if so, are the solutions apparently adopted in the case of motor control appropriate for the case of cognitive control? It is these questions which motivate the current work.

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2 THE PROBLEM OF COGNITIVE CONTROL

A well-established finding in the literature on speeded choice response tasks is that mean response time on error trials is generally shorter than on non-error trials and response time on trials immediately following an error is generally longer than on other non-error trials [10]. Following the initial report of this effect, subsequent studies have suggested that there is a gradient of response times, with RT decreasing within a run of correct trials until an error is made. RT then increases dramatically on the subsequent (post-error) trial, before gradually decreasing until another error is made [11]. Figure 1 illustrates the basic effect across five trials.

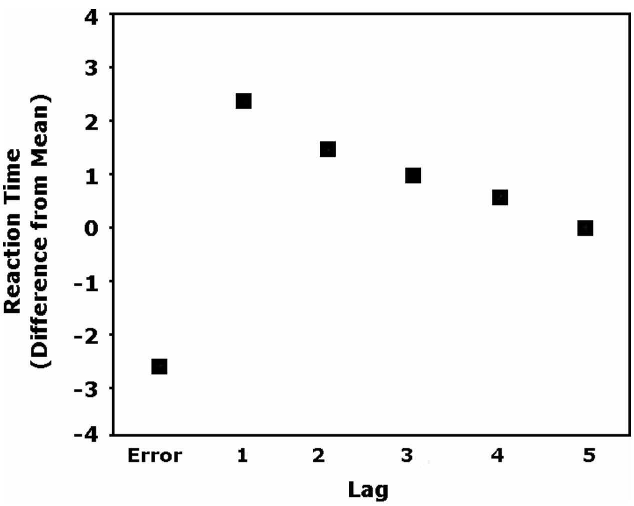

Figure 1: The effect of distance from error on RT over successive trials in a choice response task

What might lead to this effect? Botvinick and colleagues [12] suggest that it reflects the operation of a cognitive system that dynamically configures itself so as to optimise its performance. Essentially, in the absence of an error the cognitive system is held to adjust processing parameters so as to increase the speed with which a response is generated (e.g., by increasing the gain on one processing channel, or by decreasing the level of lateral inhibition operating across the system's output representations). If an error occurs, the system effectively recognises that it needs to take a more considered approach to its choice response and readjusts its processing parameters so as to slow processing. Botvinick et al consider three distinct reaction time tasks with similar characteristics where processing involves the resolution of conflict between competing responses (as in the standard choice reaction-time task), and argue for a general mechanism of *conflict monitoring* that applies across the tasks and has the control function described above.

Conflict monitoring and the subsequent adjustment of processing parameters in response to processing conflict reflects just one of a range of proposed cognitive control processes. Miyake and colleagues, for example, provide behavioural evidence based on a large individual-differences study for three specific cognitive control functions: task shifting, response inhibition and memory updating / maintenance [13]. These functions are not intended to be exhaustive. Thus other studies have suggested that dual-tasking might involve some additional, separable, control process [14; see also 13]. Alternative partitionings of control functions are also available. Thus Stuss, Shallice and colleagues argue on the basis of the behaviour of neurological patients with lesions to different regions of prefrontal cortex for four identifiable control functions, which they label as task-setting, monitoring, energisation and attentiveness [15].

3 EXISTING COMPUTATIONAL ACCOUNTS OF COGNITIVE CONTROL

A critical difficulty relating to the studies of Miyake and colleagues and Stuss, Shallice and colleagues is that they lack operational accounts of the various control functions identified [16]. A strength of the Bovtinick et al account [12], regardless of its veracity, is that it is instantiated in a set of computational simulations. These simulations stimulated a series of models of the potentially more general control function of *performance monitoring*, with the most recent being the ACC-RO model of Alexander and Brown [17]. We review each of these models as they represent two ends of a continuum where, at one end at least, concepts of prediction (and hence forward and inverse models) have been invoked.

The structure of one of the conflict monitoring models of Botvinick et al is shown in Figure 2. The model is of the well-known Stroop task, and is designed to capture the fact that the amount of Stroop interference (i.e. the difference in naming latency between incongruent and congruent Stroop trials) varies within subjects as a function of the proportion of trials within a block that are incongruent or congruent. When most trials are incongruent, subjects show less interference than when most trials are congruent [18]. This is captured within the model (which is based on an earlier, well-tested, model of Cohen and Huston [19]) through the conflict monitoring unit, which calculates a measure of conflict in the response layer and, dynamically adjusts gain on the task demand units. On incongruent trials, response layer conflict is high. This results in what the authors refer to as "a tightening of control", via an increase in input to the colour-naming task demand unit (effectively increasing the gain of the non-dominant channel). This in turn leads to faster responses on incongruent trials.

The Botvinick et al account of conflict monitoring therefore does not make explicit use of forward or inverse models in the sense of the motor control literature. However, the models may be criticised because the consequence of response conflict differ across the three tasks which they consider. Thus, while in all cases conflict monitoring operates on response units (suggesting that it might be related to Miyake et al's response inhibition function, which those authors hold is reflected in Stroop task interference), in two of the cases the functional consequence of high response conflict is to increase attentional bias (i.e., the gain on one channel of attention), but in the third it functions by modulating the baseline activation of response units. A further problem is that, at least in the case of the Stroop model, it is unclear whether conflict can be plausibly controlled by amplifying task demand units. Other models of Stroop have used the same mechanism to account for task switching effects within the paradigm [20], yet these effects on most accounts are concerned with a cognitive control function that is distinct from that related to the resolution of conflict.

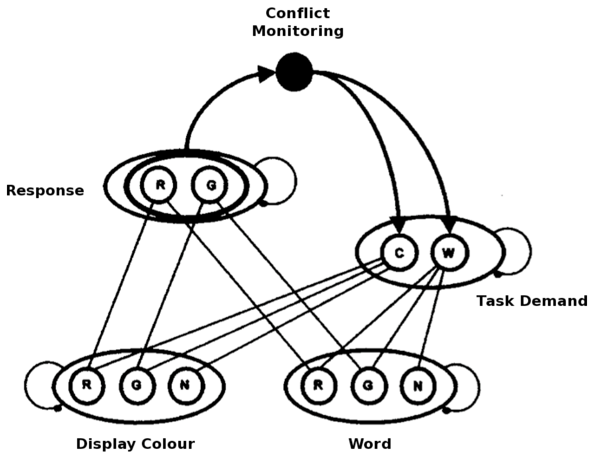

Figure 2: The Botvinick et al conflict monitoring model of the Stroop task.

A more recent model that builds on the ideas of Botvinick and colleagues and in some ways elucidates the above issues is the ACC-RO model of Alexander and Brown [17]. The model, which is illustrated in Figure 3, makes explicit use of a forward model to predict the outcome of a planned response. The response-outcome mapping (i.e., the forward model) is, it is argued, acquired through reinforcement learning. The prediction it provides is then compared with the action's actual outcome. Any discrepancy may be used as a control signal to adjust processing within the cognitive system.

Two features of the ACC-RO model warrant special attention. First, since the control signal is based not on conflict but on the mismatch between predicted and actual outcomes, the model provides a more general solution to the problem of cognitive control because it is not anchored to the type of interactive activation model considered by Botvinick et al. Second, it is conceivable that the control signal is used in different ways in different tasks. Within the model as it stands the control signal is a scalar value. This demands only a very impoverished forward model – possibly just a look-up table of actions and expected outcomes. The goal of cognitive control can then be phrased in terms of minimising this scalar value. Conceivably this may be achieved in different ways – increasing gain on one processing channel, reducing lateral inhibition between competing output nodes, allocating greater resources to a task, and so. In principle the preferred use of the control signal may be learned on a task-by-task basis. The downside of a scalar error signal however, is that it is necessarily non-specific – it can indicate sub-optimal configuration of the cognitive system, but it cannot differentiate between different causes for this sub-optimality.

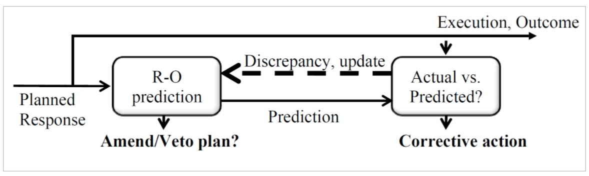

Figure 3: The performance monitoring ACC-RO model of Alexander and Brown.

CONCLUSION

We have seen that some aspects of control theory, at least relating to forward models and the use of prediction, also have a potential place in cognitive control. Existing models that make use of this, however, adopt an extremely impoverished concept of a forward model. Whether this impoverished view is sufficient is the focus of current research.

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