Available online at www.sciencedirect.com
ScienceDirect
Neural Networks 19 (2006) 1408–1421
Neural Networks
www.elsevier.com/locate/neunet

2006 Special Issue

Attention as a controller

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Received 23 June 2006; accepted 1 August 2006

Abstract

We investigate, by constructing suitable models, the manner in which attention and executive function are observed to interact, including some aspects of the influence of value/emotion on this interaction. Attention is modelled using the recent engineering control model (Corollary Discharge of Attention Movement, CODAM), which includes suitable working memory components. We extend this model to take account of various executive functions performed in working memory under attention control, such as rehearsal, substitution and transformation of buffered activity. How these are achieved is specified in suitable extension of CODAM. Further extensions are then made to include emotional values of stimuli. All of these extensions are supported by recent experimental brain imaging data on various working memory tasks, which are simulated with reasonable accuracy. We conclude our analysis by a discussion on the nature of cognition as seen in terms of the resulting extended attention model framework.

Keywords: Attention; CODAM; Working memory; Emotion; Motor attention; Ballistic model; Executive function

1. Attention as a controller

It has been suggested by many investigators since the time of Aristotle that attention is a crucial pre-requisite for awareness or consciousness. As such it appears necessary to investigate the powers that attention possesses most carefully in order to further probe inside its intimate recesses in order to tease out how consciousness can thereby be supported by attentive processing. The studies reported in this paper on attention can thus be seen as helping progress to uncover those parts of attention that are necessary, if not sufficient, for consciousness.

There are already various models of attention which have been studied in the recent past, ranging from those of a descriptive form, such as the influential 'biased competition' model of attention (DeSimone & Duncan, 1995) to the more detailed neural-network-based models involving large-scale simulations, such as those of Deco and Rolls (2005) or of Mozer and Sitton (1998). However these and other neural models of attention have not had a clear overarching functional model guiding their construction. If we consider the recent results on attention of brain imaging experiments (Corbetta & Shulman, 2002; Corbetta et al., 2005; Kanwisher & Wojciulik, 2000) then we find that the language of engineering control theory applies very effectively to help understand the complex-looking network of modules observed involved in attention effects. It is this engineering control approach we will employ in this paper to help develop a more detailed neural modelling framework to help understand the nature of networks involved in higher order cognitive processes.

The engineering control approach to attention was developed in the Corollary Discharge of Attention Movement (CODAM) model in Taylor (1999) (see also Taylor (2002), Taylor and Fragopanagos (2005)) and used in Taylor and Rogers (2002) to simulate the Posner benefit effect in vision. It was further developed in the CODAM model application to the attentional blink in Fragopanagos, Kockelkoren, and Taylor (2005), and more recently in numerous applications of CODAM to working memory tasks (Taylor, Fragopanagos, & Korsten, 2006) as well as to help understand results observed by brain imaging of paradigms involving emotion and cognition in interaction (Taylor & Fragopanagos, 2005). Here we wish to bring these various applications together to provide a unified description of the observed effects, as well as to lay a framework for further extensions to reasoning, thinking and planning and ultimately to language understanding.

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doi:10.1016/j.neunet.2006.08.008

The paper commences with a brief summary of the CODAM approach to attention. In Section 3 we develop a unified approach to working memory executive function for the tasks of rehearsal of items in short-term memory (STM), of replacement of one item by another in STM, and of the transformation of one item in STM by another using a forward model and inverse model controller for motor control.

2. A review of the CODAM model engineering control approach to attention

Attention has been shown experimentally to arise from a control system in higher order cortex (parietal and prefrontal) which initially generates a signal which amplifies a specific target representation in posterior cortex, at the same time inhibiting those of distracters. As noted in Section 1, we apply the language of engineering control theory to this process, so assume the existence in higher cortical sites of an inverse model for attention movement, as an IMC (more fully termed an 'inverse model controller' in engineering control terms), the signal being created by use of a bias signal from prefrontal goal sites. The resulting IMC signal amplifies (by contrast gain singling out the synapses from lower order attended stimulus representations) posterior activity in lower level 'semantic memory' sites (early occipital, temporal and parietal cortices). This leads to the following ballistic model of attention control:

Goal bias (PFC)
→ Inverse model controller IMC (Parietal lobe)
→ Amplified lower level representation of attended stimulus (in various modalities in posterior CX). (1)

We denote the state of the lower level representation as $\mathbf{x}(\ ,t)$, where the unwritten internal variable denotes a set of co-ordinate positions of the component neurons in a set of lower level modules in posterior cortex. Also we take the states of the goal and IMC modules to be $x(\ ,t;\text{goal})$, $x(\ ,t;\text{IMC})$.

The set of equations representing the processes in Eq. (1) are

$$\tau\, \mathrm{d}x(\text{goal})/\mathrm{d}t = -x(\text{goal}) + \text{bias} \quad (2a)$$

$$\tau\, \mathrm{d}x(\text{IMC})/\mathrm{d}t = -x(\text{IMC}) + x(\text{goal}) \quad (2b)$$

$$\tau\, \mathrm{d}x(\ ,t)/\mathrm{d}t = -x(\ ,t) + w^{*}x(\text{IMC}) + w'^{**}x(\text{IMC})I(t). \quad (2c)$$

In (2c) the single-starred quantity $w^{*}x$ denotes the standard convolution product $\int w(r,r')\text{IMC}(r')\,\mathrm{d}r'$ and $w^{**}x(\text{IMC})\,I(t)$ denotes the double convolution product $\int w(r,r',r'')x(r';\text{IMC})I(r'')$, where $I(r)$ is the external input at the position r on the input cortical sheet. These two terms involving the weights w and w' and the single and double convolution products correspond to the additive feedback and contrast gain suggested by various researchers.

Eq. (2a) indicates the presence of a bias signal (from lower level cortex) as in exogenous attention, an already present continued bias as in endogenous attention, or in both a form of value/emotional bias as is known to arise from orbitofrontal cortex and amygdala. The goal signal is then used in (2b) to guide the direction of the IMC signal (which may be a spatial direction or in object feature space). Finally this IMC signal is sent back to lower level cortices in either a contrast gain manner (modulating the weights arising from a particular stimulus, as determined by the goal bias, to amplify relevant inputs) or in an additive manner. Which of these two is relevant is presently controversial, so we delay that choice by taking both possibilities. That may indeed be the case.

The amplified target activity in the lower sites is then able to access a buffer working memory site in posterior cortices (temporal and parietal) which acts as an attended state estimator. The access to this buffer has been modelled in the more extended CODAM model (Fragopanagos et al., 2005; Taylor, 2003) as a threshold process, arising possibly from two-state neurons being sent from the down to the up-state (more specifically by two reciprocally coupled neurons almost in bifurcation, so possessing long lifetime against decay of activity). Such a process of threshold access to a buffer site corresponds to the equation

$$x(WM) = xY[x - \text{threshold}] \quad (3)$$

where Y is the step function or hard threshold function. Such a threshold process has been shown to occur by means of modelling of experiments on priming (Taylor, 1999) as well as in detailed analysis of the temporal flow of activity in the attentional blink (AB) (Sergent, Baillet, & Dehaene, 2005); the activity in the buffer only arises from input activity above the threshold. Several mechanisms for this threshold process have been suggested but will not occupy us further here, in spite of their importance.

The resulting threshold model of attended state access to the buffer working memory site is different from that usual in control theory. State estimation normally involves a form of corollary discharge of the control signal so as to allow for rapid updating of the control signal if any error occurs. But the state being estimated is usually that of the whole plant being controlled. In attention it is only the attended stimulus whose internal activity representation is being estimated by its being allowed to access the relevant working memory buffer. This is a big difference from standard control theory, embodying the filtration process being carried out by attention. Indeed in modern control theory partial measurement on a state leads to the requirement of state reconstruction for the remainder of the state. This is so-called reduced-order estimation (Phillips & Harbour, 2000). In attention control it is not the missing component that is important but that which is present as the attended component.

The access to the sensory buffer, as noted above, is aided by an efference copy of the attention movement control signal generated by the inverse attention model. The existence of an efference copy of attention was predicted as being observable by its effect on the sensory buffer signal (as represented by its P3 ERP signal) (Fragopanagos et al., 2005); this has just been observed in an experiment on the attentional blink, where the N2 of the second target is observed to inhibit the P3 of the first when T2 is detected (Fragopanagos et al., 2005; Sergent et al., 2005; Taylor, 1999).