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Executive attention, task selection and attention-based learning in a neurally controlled simulated robot

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Abstract

We describe the design and implementation of an integrated neural architecture, modelled on human executive attention, which is used to control both automatic (reactive) and willed action selection in a simulated robot. The model, based upon Norman and Shallice's supervisory attention system, incorporates important features of human attentional control: selection of an intended task over a more salient automatic task; priming of future tasks that are anticipated; and appropriate levels of persistence of focus of attention. Recognising that attention-based learning, mediated by the limbic system, and the hippocampus in particular, plays an important role in adaptive learning, we extend the Norman and Shallice model, introducing an intrinsic, attention-based learning mechanism that enhances the automaticity of willed actions and reduces future need for attentional effort. These enhanced features support a new level of attentional autonomy in the operation of the simulated robot. Some properties of the model are explored using lesion studies, leading to the identification of a correspondence between the behavioural pathologies of the simulated robot and those seen in human patients suffering dysfunction of executive attention. We discuss briefly the question of how executive attention may have arisen due to selective pressure.

Keywords: Attention; Action selection; Autonomous robotics; Cognitive robotics; Adaptive learning

1. Introduction

When performing high-level behaviours that require the appropriate sequencing of lower-level tasks, performing the right action at the right time is important. In designing autonomous robots, the challenge in solving this problem is to sustain successful task performance in dynamic environments where relatively unfamiliar or even entirely novel circumstances arise unexpectedly. In such situations, many robots exhibit one or more pathologies of action selection; examples include excessively frequent changes of behaviour, appearing either as distractedness or as indecision so that tasks are not completed in sensible timescales, if at all; inappropriate persistence of a behaviour, behaviour, in which the robot appears to lack awareness of its failure to make progress towards completion of some goal [38]. Many of these errors leave an observer with a sense that the robot is simply inattentive to important cues in the world [27]. Our strategy for developing robot control systems is born of a recognition that analogous, if not identical, pathologies of task performance are observed in humans who are diagnosed as suffering *disorders of executive attention* [44,46,47]. Thus, we are led to adopt and explore a model of human attentional control as the basis for robot development.

In humans, successful action selection is believed to have two manifestations: automatic (also non-voluntary or routine) action selection and willed (also voluntary or deliberate) action selection [42,47]. Automatic action selection ranges from wholly reflex actions (e.g., recoiling from something uncomfortably hot) through to actions that have become very well-learned (e.g., driving in familiar and unproblematic conditions). Automatic actions are the

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actions we perform naturally, without any apparent awareness. In contrast, willed behaviour involves deliberate, conscious, control of action (e.g., playing an unfamiliar piece of music).

Baars describes how the consciousness associated with willed action involves a selective attention system under dual control of frontal executive cortex and automatic interrupt control involving the brain stem, pain systems, and emotional centres [5]. This distinction between the dual attention systems is of significance here; the interrupt system invites a deliberative response from the executive system. Executive attention is associated with a variety of categories of response [47]: temporary suppression of an otherwise reflex action (e.g. intentionally clasping something uncomfortably hot in the time it takes to quench it under a tap); dealing with minor distraction (e.g. listening intently to another person in a noisy environment); dealing with novel situations requiring unfamiliar courses of action (e.g. pulling off a busy road safely when a tyre bursts). Willed attention to action selection may be transient (Attentional effort is exerted momentarily), intermittent (attention is exerted periodically) or sustained (attention is constantly applied) and to accommodate this, Baars suggests that once expressed, a willed response is unconsciously monitored [3].

LaBerge identifies three characteristics traditionally associated with *executive attention* and considers that they should be evident in any model [37]. Grounding these three properties in the domain of action selection, we have:

1. *Selection* of a willed action over a more salient, automatically selected, action. Here, the notion of salience is intimately connected to environmentally derived stimuli in the degree to which they accord with the relevance of contending actions. However, it may also derive from internal/innate drives. For example, the salience of feeding behaviour is determined both by the availability of food in the environment and by a sense of hunger/satiation. Willed action selection involves the application of an internally derived attentional signal which results in the (more likely) performance of a less salient act in preference to a more salient act. The attentional effort needed to will one familiar action in place of another is usually intermittent, or even momentary. The willing of wholly unfamiliar actions may require more persistent attention.
2. *Priming* of an anticipated future action. Priming, too, is associated with an internally derived attentional signal. On this occasion, the potentiation does not result in the immediate expression of the behaviour, rather it enhances the salience of the behaviour so that, when the appropriate anticipated circumstances arise, there is a greater likelihood that the anticipated task will be selected. Priming is associated with enhanced speed of task switching.
3. Use of memory for *sustained task focus*. Memory is particularly important when resumption of a suspended task requires recall of some past state or stimulus that cannot itself be inferred from observing the current state of the environment.

This view of executive attention features a possibly false dichotomy between automatic and attended behaviour. In humans (and some animals), tasks which are initially novel and demanding of executive attention, if encountered and attended to frequently, or addressed with sufficient sustained attentive effort, become learnt to the point where they become automatic, needing an expression of will on rare occasions [3]. Thus, to the three characteristics of executive attention listed above we may add a fourth:

4. Attentional effort leads to increased automaticity in task performance. A task which initially needs sustained attention comes to need intermittent, and then momentary or transient effort, until it is 'automatic' (e.g., learning a piece of music, through practice, to performance standard).

In respect of the perceived features of attention, LaBerge seeks an account of why executive attention, as a phenomenon, seems to have emerged, suggesting that selective advantage might be assumed to underpin the emergence of executive attention. Aleksander and Dunmall suggest that attention is necessary when the building and maintaining of an internal representation of the perceivable world cannot be done in parallel, specifically, when there is a restriction on the degree of parallelism available at the input of a system [1]. A resolution of these issues is not the focus of this paper, nonetheless, we will return to the topic in discussion.

The remainder of this paper gives an account of the design and implementation of a neuro-computational architecture, possessing each of the above features, as part of a project to develop a control system for a simulated robot capable of autonomous cognitive development in respect of task performance. It is an appreciably extended version of an earlier paper presented at Brain Inspired Cognitive Systems (BICS) 2004 [29]. Papers at BICS addressed one of a number of themes, one of which was biologically inspired computation, another, consciousness. The focus of this paper is mechanisms for executive attention in autonomous robots; we touch upon consciousness only in so far as it helps to delineate executive attention and consciousness, two intimately related phenomena. The remainder of the paper is organised as follows. Section 2 gives an account of relevant neuropsychological models of attention at a functional level. Section 3 briefly motivates our view of attention-based learning. Section 4 discusses neural models of automatic and executive action selection. Section 5 describes our architecture for attention-driven learning, and elaborates an innate learning mechanism that leads to autonomous cognitive development expressed as behavioural adaptation to novel events and problems. Section 6 describes the