Executive Attention, Task Selection and Attention-based Learning in a Neurally Controlled Simulated Robot

Jason Garforth[a], Sue L. McHale[b], Anthony Meehan[a,*]

[a]Department of Computing
The Open University
Walton Hall
Milton Keynes MK7 6AA
UK

[b]Department of Psychology
Sheffield Hallam University
Pond Street
Sheffield S1 1WB
UK

*Corresponding author:
Tel: +44 (0)1908 659049
Email: a.s.meehan@open.ac.uk
URL: http://mcs.open.ac.uk/am4469/

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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* [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 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 (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 [36]. 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 implementation of this architecture. Section 7 illustrates its use in a simulation used to validate and investigate the model and Section 8 contains a discussion and an account of related work.

2 Neuropsychological Models of Executive Attention

In considering willed behaviour, we confine ourselves to top-down, as opposed to bottom-up or inline, mechanisms. The former is associated with conscious, deliberate attention, and, in humans, is associated with the pre-frontal cortex (PFC) in an area which is functionally labelled the 'executive' [6] [4]. The latter are associated with regions of the cortex, especially sensory cortex, which are responsible for information processing, e.g. feature extraction. We also focus upon motor task selection.

Several accounts of the executive and attention exist, most notably those of Baddeley [10], Baars [3], and Norman and Shallice [42]. Both the Baddeley and the Norman & Shallice models contain a functional system assigned a 'supervisory' role, initiating, monitoring and modulating higher-level behaviours. Baars' model of control is more distributed in character. Baddeley's executive was postulated in the context of his theory of working memory [6], an important function of which is to maintain a representation of goals and intentions; it may also hold representations of currently active behaviours. Whilst most attentional models of the time dealt with perceptual selection or filtering of sensory stimulus [11], Baddeley assumed the central executive to be an attentional *controller* concerned with integration of information and action selection.

In articulating a theory of conscious perception, Baars' Global Workspace Theory (GWT) assigns a central role to executive attention. Following the 19th Century psychologist William James, Baars sees attention as "taking possession of the mind" through "focalisation" and "concentration", selecting one experience over another [4]. A definitive feature of GWT is the proposition that multiple specialist processors, operating in parallel, compete for access to a limited-capacity global workspace which selects a

winning coalition of such processors and then broadcasts associated information back to the set of all processors. This cyclical flow of information produces an experiential sequence in which there is a conscious decision to attend followed by unconscious attentional activity, which produces targeted conscious contents [3].

The Norman and Shallice model features a Supervisory Attention System (SAS) which detects the expression of unwanted action (an interrupt mechanism) and attempts to assert willed action. Elaborated as a functional architecture, the Norman and Shallice model integrates both automatic and executive action selection and comprises several functional subcomponents (Figure 1).

FIGURE 1

In the model, a perceptual subsystem receives input from the world and its state is mapped, via an associative memory (trigger database), to a range of behaviour schemas, which may be triggered for possible expression. For each behaviour scheme, the strength of the triggering depends upon the applicability of that behaviour to the perceived state of the environment. The associative mapping takes account of the internal state of the agent and any goals that it has. When two or more selected behaviours are incompatible, a contention scheduling mechanism is invoked. This compares contending behaviours and selects between them, depending upon the situation. A ‘willed’ action component is applied by a Supervisory Attention System (SAS) which modulates behaviour selection to correct errors and invoke actions to deal with novelty in the environment.

In order to correct errors and determine non-routine courses of action the SAS is assigned a number of distinct sub-functions: Shallice distinguishes some of them as follows:

Monitor: the SAS must be able to compare the currently expressed action with an intended action (as formulated by the SAS or other ‘planning’ units). The monitor may be thought of as an arousal mechanism that induces the activation of the other, deliberative, attentional subunits.

Modulate: when so triggered, the SAS must provide a modulatory signal that attenuates the salience of inappropriate tasks and potentiates the salience of appropriate tasks. (It is important to recognise that the modulation is a biasing mechanism, not a deterministic mechanism.) Shallice suggests three possible modulatory responses:

- attenuate the currently expressed behaviour for a given time and potentiate an intended behaviour;
- attenuate the active behaviour for a given time and potentiate a 'default' or 'if all else fails' response;
- attenuate all intended behaviours for a given time, allowing the contention scheduler to express a behaviour governed by perception of the environment alone.

Generate: the SAS must create new strategies for solving novel problems.

The issue of learning is left open in this model though there is an acknowledgement that there must be a means by which behaviour that is initially novel becomes more automatic. Similarly, the role of affect in attention is not addressed in the original model.

A somewhat different view of the attentional mechanism is taken by O'Regan and Noë [41] [43]. In their account, the effects of attention are brought about not by top-down modulation of a *mental representation* of the world, but by control, both willed and automatic, of *exploratory activity* in relation to the world itself. The activity involves application of the perceiver's (acquired) knowledge of the sensory changes that are produced by motor actions, so-called *sensorimotor contingencies*. For example, the sensorimotor contingencies governing vision involve movements of the eye, altering the point of view; those of audition involve movement of the head, etc. Subsets of sensorimotor contingencies are associated with specific sensory effects, revealing specific sensory information about the object or scene being produced, e.g. shape, colour, orientation, location in relation to other objects, etc. O'Regan and Noë share the view of

attention as bringing to awareness, in their case, by an integration of a mastery of sensorimotor contingencies for the purposes of thought or planning action. Shifting attention involves switching between one subset of sensorimotor contingencies and another. Mastery of sensorimotor contingencies implies a high level of automaticity in their expression (i.e., we are largely unaware of them), but we may anticipate too, novel contexts in which there must be a sustained, willed effort to secure the desired sensory information. A distinctive feature of this model is that there is no explicit mental representation of the world that is subject to processing, manipulation, or reasoning; it captures the notion that the world is its own representation.

In looking to select one model of executive attention as the basis for subsequent implementation and experimentation, we note that Gathercole has suggested that Norman and Shallice's SAS meets the needs of Baddeley's executive, at least at a functional level [30] (cited in [16]) and that Baddeley, when relating models of attentional control to his model of working memory, concluded that only the Norman & Shallice model matched the properties of information integration and control of action [7]. Further, in comparison to the GWT model, the Norman and Shallice model features a clearer *architectural* separation between the mechanisms for automatic and willed action selection that corresponds well with the evolutionary morphology of the vertebrate brain [45]. In respect of O'Regan and Noë we consider that their model of willed and automatic action serves to highlight the sensorimotor contingencies as a subset of the motor actions over which there is executive attentional control. These considerations led us to take the Norman and Shallice model as our preferred functional architecture.

3 Attention-based learning

Executive attention as described above is concerned with problem solving. It is invoked when there is a need to respond to a novel or relatively unfamiliar situation. The degree of novelty may be large or small. An adaptive agent can combine a repertoire of behaviours in novel ways when attempting to solve new or unfamiliar problems. But, in the absence of learning, and with limited attentional capacity (humans have difficulty

maintaining attentive focus on more than just a few tasks or issues at any one time - typically, seven plus or minus two), the agent is destined to repeatedly devote attentional resources and effort each time the same problem arises.

The architecture for attention-driven cognitive development outlined in this paper extends Shallice's original model, bringing into scope an intrinsic mechanism by which willed actions become progressively more automatic (see Section 5.4). The significance of the use of an intrinsic signal is that it bestows autonomy of learning on the robot; no teacher is needed.

Shastri reviews the evidence suggesting that episodic learning may be mediated by the hippocampus [49]. Whilst there is widespread agreement about the role of the hippocampus in episodic learning, there is currently no consensus as to the neural mechanisms at work. Normal functioning of the hippocampus depends upon attention and interactions with other elements of the limbic system, a group of brain structures (hippocampus, amygdala, fornicate gyrus, archicortex, hypothalamus) associated with emotions and the endocrine system.

4 Neural Models of Automatic and Attentional Action Selection

For researchers exploring task selection within the connectionist/PDP paradigm, the overwhelming majority of the work undertaken has focussed upon automatic or reactive behaviour; by comparison, less work has been undertaken on willed behaviour. (Given the focus of this paper, when reviewing work in automatic action selection we confine ourselves to considering that which has informed our implementation of the automatic action selection pathway in the Norman and Shallice model.)

4.1 Automatic Action Selection

The recent emphasis on reactive behaviour in robots appears to have been initiated by the coincidence of the renewed focus on reactive robotics occurring in the mid 1980s [12], [13] and the renewed interest in neural computation that emerged at about the same time; the latter stimulated by the development of efficient training algorithms for multilayered

networks that extended the computational capabilities of single layer networks. Reactive robotics, characterised as it was by a desire to achieve a tight coupling of perception and action, did not seek to address higher level cognitive functions associated with 'reasoning' and willed behaviour; indeed, almost by definition, it sought to avoid such mechanisms.

One aspect of the literature on unattended action selection that illustrates the above point, and is of relevance to the work described in this paper, concerns selection between contending actions (contention scheduling). The need to select between contending tasks arises because in any complex environment more than one action will have a high level of salience, and in a dynamic environment the salience of contending actions may vary rapidly such that no expressed action persists long enough to be completed. This problem can be overcome by using an internal positive reinforcement to bias positively the apparent salience of the currently expressed behaviour so that it persists longer than would be the case if environmental stimuli alone determined expression [50]. Further, many actions are not mutually exclusive. Some tasks require access to wholly different effectors than others (walking and talking), some tasks require complementary use of different effectors (playing the piano); yet other tasks demand the same effectors (walking and sitting). Some tasks are partially complementary (if two objects are more or less adjacent, one can progress towards picking either up by extending the arm, without having committed to either task).

Traditionally, the problem of contention scheduling was addressed by incorporating high level reasoning mechanisms which resolved the conflict and imposed an outcome. However, more recently, unattended reactive mechanisms have been developed. Shallice [47] observed that in humans and many other animals the basal ganglia appeared to be associated with contention scheduling. Guided and constrained by knowledge of basal ganglia neuroanatomical architecture, neural models for contention scheduling have been developed successfully [32], [45].

The primary function of the contention scheduling mechanism of the basal ganglia is to select which behaviours are given access to effectors, and hence expression in observable

behaviour. The basal ganglia contention scheduling is realised by a layered network in which the layering reflects ‘adjacency’ of effector systems. (Such somatotrophism is seen in other areas of the brain, including parts of the sensory, motor, and pre-motor cortex). Localised lateral inhibition serves to prevent contradictory behavioural requests being made on a single effector system. This architecture allows the basal ganglia to resolve conflicting behavioural requests in ways that support the expression of wholly and partially complementary behaviours but prevents expression of contradictory behaviours, all without recourse to deliberation or executive attention.

4.2 Attentional (Willed) Action Selection

Within the connectionist/PDP paradigm, it is possible to discern a sequence of studies of attention driven task switching that can be traced back to an early experiment by Cohen, Dunbar and McClelland [15]. More recently, there has been renewed interest in attentional action selection, due, in part to the shortcomings of robots with close-coupled reactive control systems. Such machines often exhibited 'distractibility' in the face of powerful environmental stimuli (c.f. utilisation behaviour and capture errors in humans) and reveal the existence of attractors that 'lock' the system into fixed behaviours (c.f. human stereotypy/perseverance) [38].

In their early paper on attentional control of task selection, Cohen et al. [15] developed an architecture which allowed them to examine the so-called Stroop effect. When humans switch between cognitively distinct tasks there is a perceptible delay in task execution. The classic Stroop experiment presents a subject with words representing colours (red, blue, green, etc.) written in different coloured inks; the word and the ink in which it is written may or may not be the same (e.g. the word red, may be appear in red, green or blue inks). The subject is instructed to utter either the word or the ink colour when presented with a subsequent stimulus. Whilst the task remains unchanged over a sequence of stimuli, responses to each new stimulus are relatively fast; however, whenever the subject is required to switch between tasks, there is a very marked delay in responding until they settle to the new task.

The network developed by Cohen et al [15] to perform this task dealt with two word-colour alternatives (red, green), featured a winner-takes-all response layer, and the attentional or willed input was provided by a "context layer" providing a sustained exogenous control signal. The context layer encoded which of the two tasks was to be performed at any time. Switching the pattern of activation in the context layer caused the network to change task. This system was later modified to incorporate continuous as opposed to discrete processing and was adapted to perform other task switching exercises [16].

Gilbert and Shallice developed a related model of attentional control [31]. This model dealt with three word-colour alternatives, and modified the architecture so that there were two separate networks, each trained to perform one of the two tasks, integrated with a task demand layer, serving a similar function to the context layer of Cohen et al. The task demand layer was controlled by a top-down exogenous control input.

We can consider these related models in relation to the three features of attentional systems sought by LaBerge (described earlier). The issue of whether the networks considered so far exhibit willed selection of a less salient task over a more salient task is not entirely straightforward. In this experimental paradigm, task salience cannot be derived from the stimulus itself - when presented with the word red written in green ink, there is nothing that indicates whether the response should be utterance of the word ‘red’ or the word ‘green’. Task salience is governed entirely by an (exogenously derived) attentional signal encoded in a task specification layer. If one takes the view that salience derives from the stimuli embedded in the environment, then these models do not exhibit this feature. However, if one accepts that salience is simply the current level of task activity, however derived, then the fact that in these networks task salience is determined wholly by the bias provided by the task specification layer is of no account and the desired feature is present.

In all cases, the maintenance of the current task is governed by a persistent attentional signal. Gilbert and Shallice [31], acknowledge that this represents a departure from

standard attentional theory, which holds that attentional effort in task switching is selective and intermittent. The property of preparation (or priming) requires that expression of one task readies the subject to express a different but related task. None of the networks considered featured such a property. None of the models use memory to sustain task focus, unless one includes the persistent expression of current intention by the task specification as memory.

In respect of the functionality required of a SAS, these networks demonstrably apply modulation of information flow to focus and sustain attention to task. However, by virtue of the experimental paradigm, there was no need for an autonomous monitoring function (it is only needed when attention is not persistent), nor for a capacity to generate and learn responses to novel problems, and so these features are understandably absent.

Cooper [17] has augmented an earlier system for managing routine action selection [18], [19] to include rudimentary supervisory processes, including some monitoring and error recovery. The system is capable of generating sequences of basic actions associated with the high-level task (packing a lunch box). In the model, each task is realised as a hierarchy of subtasks. Each task in the hierarchy is assigned pre- and post-conditions whose truth values will depend on the current state of the environment. Having introduced pre- and post-conditions for tasks and subtasks, Cooper is able to implement a monitoring and error correction system. Once each selected subtask of a higher task has been attempted, its post-condition is evaluated. If false, the task is deemed incomplete and failed subtasks continue to receive selective excitation from their parent task schema.

As before we can consider this model in terms of the features sought by LaBerge [36]. The model does select between subtasks of differing salience, where the use of task preconditions allows salience to be driven by the state of the environment. There does not appear to be an explicit preparation of priming mechanism in which a currently active subtask raises the excitation of the next task in sequence. However, the fact that the existence of noise in the signals passing between task nodes appears to lead to task skipping, in which an ensuing task is invoked prematurely, suggests that priming may be

implicit in the implementation. Attentional persistence is realised through the error detection system which maintains the activity of a task whose post-condition has not been satisfied. Cooper describes two conceptual approaches to ordering of subtask expression (p52). The first approach (which appears to have been implemented) involves a task selectively exciting some of its own subtasks. The second approach (which may have been adopted, though this is not clear from the paper) would involve external inhibition of tasks whose pre-conditions are false or whose post-condition is true. As Cooper observes, the former approach constitutes automatic control; the latter approach would constitute attentional task selection.

Taylor has articulated the CODAM model of attentional control, based upon engineering control theory [51]. The illustrative domain involves control of motor function in response to a visual stimulus. The model features an inverse model control (IMC), which modulates activity in analogues of early sensory and motor cortices. The IMC receives inputs from a goal module, which encodes the action to be performed and provides a biasing attentional signal as well as processing; and from a monitor which calculates any error between the goal and either the actual or the predicted sensory input (considered as distinct working memory buffers). The monitor gives rise to an attention-based signal that is used by the IMC to learn less error-prone motor responses. Taylor [51] presents the results of three simulation experiments which lend weight to aspects of the CODAM model. First, he demonstrates at least qualitative agreement of temporal information flow (understood as relative timing of attention-related potentials) between actual EEG signals and information flow in the simulation. Secondly, he reproduces a well known lesion study (*simultaneous extinction*) to illustrate that attentional control of the sensory and motor cortices is distributed (right and left hemispheres respectively). Finally, he demonstrates that the model reproduces the *attentional blink* in which the ability to respond to distinct visual targets which require an attentional shift of focus is diminished as the delay between occurrence of the related stimuli approaches the time needed to process the first image and prepare for the onset of the second.

Fragopangos and Taylor [21] describe an application of a closely related control model, investigating the behaviour of the model in relation to two further standard explorations of human attention. The control model is similar to the CODAM model described above, except that the monitor compares the motor output with the visual input and does not draw upon a predicted sensory input state. In the first simulation, the controller, responding to an error signal from the monitor, learns which of two motor responses (analogous to finger movements) to make in response to visual stimuli. In the second simulation, the IMC controllers of visual and motor cortices respectively are lesioned. The results of both simulations accord well with results from human subjects; the second simulation serving again to suggest distribution of the controllers for vision and motor function.

Kasderidis and Taylor [37] use an extended attentional architecture to control a simulated robot. In this instance, the monitor compares the expected sensory state of the robot with the actual sensory state, producing an attentional arousal signal (called the *attentional index*) which is proportional to the error detected. The arousal signal is used both as a learning signal to the controller so that it learns motor responses and as input to a process that evaluates competing actions. The elaboration of the earlier control model relates to the representation of goals as goal trees, with high level goals being decomposed to lower level goals. At any level, the goals compete for expression through mutual inhibition. The simulated robot has three sensors (power, proximity of other objects, and position/speed) and one effector capable of moving the robot one step at a time in a discrete Cartesian grid. The robot has a high level goal: ‘transport an object from A to B whilst avoiding collision’. This goal decomposes to a ‘transport’ sub-goal and an ‘avoid collision’ sub-goal. In turn, ‘transport’ decomposes to four sub-goals: ‘goto A’, ‘pick item up’, ‘goto B’, ‘drop item’. At the next level of decomposition, ‘Goto *x*’ reduces to the goals ‘plan route’ and ‘move’, respectively. The ‘plan route’ action determines the next move based upon predictive assessment of the movements of other objects in the environment. If these predictions are in error, an attentional signal (*collision avoidance index*) is generated, the signal being inversely proportional to the proximity of the potential obstacle. An *action index,* which incorporates the attentional and collision avoidance

indices, is calculated and if a decision threshold is exceeded the collision avoidance behaviour is selected preferentially over the transport behaviour. The collision avoidance index is used as a (back-propagation) learning signal for a neural network that predicts the movement of the threatening obstacle. The model is used in a simulation that compares the relative performance of the robot as described, compared to two lesioned robots: the first lesioned to remove learning; and the second lesioned to remove both learning and prediction.

Taylor and Fragopanagos [52] [53] have extended the CODAM control model to incorporate the effect of emotion on attention. In humans, the attentional blink (described above) is attenuated by the emotional content of the second stimulus (e.g. the effect is diminished if one's own name or a familiar face is the stimulus to be recognized). In patients with a lesion to the amygdala, there is no attenuation. By incorporating an emotional signal comparable to that generated by the amygdala (part of the limbic system) into a simulation, and using lesion studies, they are able to reproduce this phenomenon.

Taken collectively, the applications of Taylor's CODAM model described above exhibit the properties associated with executive attention, along with the requirement for learning of automatic responses. The goal module serves as a memory to maintain task focus. It receives directly a representation of the input from which CODAM determines which of a number of attentional goals apply at any instant. Thus task salience is derived entirely from the environment. In this sense the term 'goal' is synonymous with 'currently specified task'. The concept of goal is more clearly present in [37] where willed control is exercised over more than one possible task (e.g., suppression of the transport task in order to avoid collisions). There is task-related priming of anticipated actions in [37] and there is error-driven learning to reduce the occurrence of errors. It is not clear whether the input from the goal module to the IMC is intermittent or sustained, it appears to be the latter.

A distinctive treatment of attention occurs in Franklin's IDA model [22]. IDA can be viewed as an implementation of Baddeley's working memory using Baars' concept of Global Workspace Theory (GWT) [5]. IDA is a multi-agent system [23], an early implementation of which was able to billet US Navy personnel, responding to (electronic) notices of vacancies and requests for postings by assigning staff appropriately. IDA can communicate in natural language via email, and the application solves a nontrivial instance of constraint satisfaction. Although Franklin's implementation of GWT in IDA contains no neural networks, it does incorporate some connectionist elements, (e.g. software agents exhibit 'levels of activity' which are used in computation by other agents and thus determining the flow of information within the agent network [24]) justifying its inclusion here. In the most recent elaboration of the IDA model, which extends the working implementation described above to include some features which are not yet implemented, Franklin, Baars, Ramamuthy and Ventura [22] present a nine-step cycle of computation that makes concrete the cycle of computation implicit in GWT. Sensory stimuli are 'chunked' to form current percepts. These are combined with representations of recent percepts from transient episodic memory and from long term memory. Event specific *attention codelets* seek to build a coalition of associated information codelets on the basis of the amount of relevant information content found in the current internal representation of the environment. A winning coalition is selected and its contents broadcast. Behaviour codelets respond depending upon their relevance to the information broadcast. Some behaviour codelets initiate a behaviour stream, if one is not in place. Competition between behaviours is resolved by selection of a single behaviour for execution. Execution of the behaviour codelet results in the creation of an expectation codelet (a type of attention codelet), which competes for attention in the ensuing cycle(s) if the anticipated results of the behaviour are not manifest in the perceived environment.

Clearly, IDA selects less salient over more salient tasks through a number of biasing mechanisms, e.g., agents representing affective states, timekeeping agents, etc. In IDA, the affective content of external and internal representations is recognised during perception (early stages of the cycle) and thus informs the unfolding of the information

flow in later stages and cycles [24]. Priming is also implemented, as described above. The operation of attention, in respect of any one task, is intermittent. And the frequency with which a task is revisited is governed by the dynamics of the competition between attention codelets (with their coalition of information agents) and the rates at which the activity levels of the codelets decays in episodic memory. From the perspective of SAS functionality, IDA has a monitoring mechanism (e.g., expectation codelets). The model stipulates a role for a planning mechanism to tackle non-routine problems but the mechanism for this is unpublished [22]. One form of learning in IDA uses internal reinforcement mechanisms, the details of which depend upon the target memory subsystem. The reinforcement signal is derived from selection of an attention or behaviour codelet so that frequently attended perceptual or behavioural associations are sustained whilst others are allowed to decay. The model specifies a mechanism to enhance the automaticity of unfamiliar skills. (Publication of an account of the processes by which this may be achieved is anticipated [22])

Shanahan [48] has developed a neural implementation of Baars' GW model in which attention (as 'bringing to consciousness') is implicit in information flow through the architecture. In the context of robot action selection, Shanahan's action selection architecture features a first order, purely reactive, system, modulated by a higher order system. The first order system evaluates (assigns salience to) sensory input to determine, in parallel, alternative courses of action. In response to the same sensory input and the currently selected action, the higher order system predicts, off-line and in parallel, a number of trajectories through the robots sensory motor space. The outcomes of these parallel rehearsals inform an affective assessment of the currently selected action based upon the extent to which it leads to a rewarding or punishing outcome. This affective assessment provides a signal which modulates the salience of the selected action, either reinforcing its expression or causing it to be suppressed in favour of a more rewarding alternative.

Shanahan's model and its implementation exhibit a mechanism by which action salience is modulated in accordance with the outcome of higher-order processing, and the architecture closely reflects Norman and Shallice's separation of the pathways for

automatic and higher-order action. There is no explicit representation of will or intention to form the basis of willed action selection. Rather, in so far as there is a will, it is implicit in the architecture and is introduced through the affective biasing of action selection: ‘prefer actions which are relatively the most rewarding’. A distinctive element of the model is its ability to use imagined future outcomes to evaluate courses of action. Shanahan uses forward association from the current input, as opposed to backward association, which would demand the representation of some goal state [26].

5 Functional Neural Architecture

Having described the functional architecture of Norman and Shallice's original production system (Figure 1), and having examined models of attention-based task selection developed within the neural/PDP paradigm, this section gives a corresponding functional account of our neural architecture for unattended and attended action selection. This architecture extends the models described above, and our own previous models [28] [29], both in terms of scale of integration and by introducing a degree of autonomous operation and an attention-based learning mechanism that leads to increased task automaticity and reduced attentional burden.

The architecture, which provides for executive attention and action selection, has three integrated subsystems (Figure 2):

- **Reactive System**, containing episodic and procedural memory that together with the contention scheduler, provide for automatic (instinctive or already learnt) behavioural output.
- **Supervisory Attentional System**, including working memory, providing executive functions for autonomously detecting circumstances in which attentional effort is appropriate and adapting and modulating attended to behaviours to express willed behaviour.
- **Affective System**, which provides elements of an affective (emotion-based) mechanism which mediates acquisition of initially willed behaviours by the reactive systems.

FIGURE 2

At a functional level (as opposed to implementation level), the reactive and supervisory attentional systems described in this paper are largely faithful to Norman & Shallice's architecture for executive control of behaviour. We have reinterpreted their production system architecture as a large scale, modular, neural network in which we have sought to maintain neuropsychological and neuroanatomical plausibility at the functional-structural level. In doing so, we have elaborated and incorporated additional subsystems, especially, episodic memory, procedural memory and working memory. We introduce a simple model of working memory based on [6] and then extend the model to include elements of the limbic system associated with some forms of emotion-based learning. We consider the major components of the model in turn.

5.1 The Reactive System

The world is directly perceived through the Perception Layer, which encodes sensory information and maps this into episodic memory [8]. Episodic memory encodes previously encountered situations, narrative structures and routinised plans or behaviour schemas. At an unattended level, episodic memory expresses the salience of episodic associations and maps this into procedural memory and working memory.

Procedural memory, which includes central and motor pattern generators, is heavily interconnected with episodic memory and encodes procedural motor skills. This coupling between the episodic and procedural memory provides the tight coupling of perception and action characteristic of automatic task selection and reactive robot control.

In respect of automatic action selection, the Contention Scheduler allows all salient behaviours to be expressed as long as there is no contradictory demand placed upon any effector. It also provides modulatory feedback to episodic and procedural memory [35] to reinforce the ‘persistence’ [40], or ‘perseverance’ [50], of the current behaviour(s) so that minor fluctuations in perception do not result in rapid behaviour switching.

Behaviours selected for expression by the effector contention scheduler are routed through Output Gates (in the thalamus) to effector systems. By default, the gating system

inhibits the expression of salient behaviours (directly from procedural memory). The contention scheduler actively *disinhibits* those behaviours selected for expression. (It is interesting to note that this mechanism enables an organism to always do something; evolution seems to have selected for organisms for which doing anything is better than doing nothing). (Although present, local reflex ganglia, through which the sensory and motor signals are routed - a 'spinal cord' - are not shown in the figure 2.)

5.2 Working Memory

Working Memory provides the Supervisory Attentional System with representations of current goals and intentions, salient biographical episodes from episodic memory, and salient actions from procedural memory. The connections from both episodic and procedural memory converging in pre-frontal cortex [25] are governed by contention scheduling. (Achieved by circuits of the basal ganglia, not explicitly represented in Figure 2, that are distinct from those controlling action expression, above). Thus, *all* salient non-contradictory episodes and possible actions are 'observable', in parallel, by the SAS at once. Having episodic and procedural memory connected through working memory may provide the attentional system with a means to combine episodes and representations of motor functions that can be 'ranged through' or even 'played forward', in the absence of behavioural expression, thus providing a means to predict, or look ahead (c.f. Shanahan, above).

5.3 The Supervisory Attentional System

The SAS has three subsystems, corresponding to the three functions as specified by Shallice [47] and described above. The SAS Monitor can be thought of as a system for detecting novel circumstances defined as departure from expectation. By monitoring working memory, the SAS Monitor is able to observe the unfolding pattern that derives from observation of the perceived world (from episodic memory), currently intended actions, expressed actions (from procedural memory and effector contention scheduler), and the outcome of expressed action perceived through the changed state of the world (made apparent, once again, in a subsequent state of episodic memory). If the SAS monitor detects departure from expectation, it generates an arousal signal to the SAS

Modulator. This is the point at which deliberative (conscious) attentional effort is invoked.

The SAS Modulator expresses willed intention by attenuating the salience of inappropriate (unplanned) actions and potentiating the salience of intended tasks. Note that this limited mechanism (modulation) deals only with minor levels of variation of action selection; it only allows expression of actions that are related to current intentions and are relatively salient.) If the intervention of the SAS modulator proves inadequate to the novelty of a situation, the SAS Generator must be able to produce novel approaches to problem solving. Strategies might include creating entire novel sequences of intended actions (new plans).

5.4 Learning

Episodic memory and procedural memory appear to have different learning mechanisms. The limbic system and especially the hippocampus are known to be involved in episodic learning [14] [49]. The mechanism for procedural learning is less certain, but may integrate attentional effort and self-priming positive feedback derived from selection for expression by the contention scheduler.

5.4.1 Episodic Learning and the Limbic (Emotion) System

The limbic system is intimately associated with the sensation of emotion, indirectly inducing release of hormones which trigger physiological changes (e.g., in heart rate, respiratory rate, distribution of blood flow, etc.) associated with emotional sensations. However, it is important to be clear that our model does not seek to encode representations of emotions themselves as system states. Rather, it is concerned with the role that neuromodulatory chemicals released by the limbic system, and especially the hippocampus, are known to play in promoting episodic learning. The hippocampus (part of the limbic system) is extensively connected to the prefrontal cortex, providing a material basis for the hypothesis that it promotes learning related to attentional activity. Activity in the limbic system is expressed in a number of ways, including the release of neurotransmitters and neuromodulatory chemicals such as noradrenalin, 5-

hydroxytryptamine, dopamine, acetylcholine, etc. In contrast to neurotransmitters, neuromodulators are slow acting, diffuse, and non-specific in information content [16]. Within the limbic system, the hippocampus is known to take input from episodic memory, procedural memory and the SAS, and provides connections back into episodic memory. In our model, this system allows for episodic learning by using the level of attentional activity in the SAS as the basis for a hippocampal signal that reinforces the association between the currently willed action and the currently active episode. Over time, the attention-based reinforcement of this association means that a diminishing level of attentional effort is needed to enhance its likelihood of expression.

5.4.2 Procedural Learning

In contrast to episodic learning, the learning of new procedural skills does not seem to depend directly upon the hippocampus. Thus we need a second mechanism to support this form of learning. We have already seen that the SAS modulates the expression of behaviour by potentiating and/or attenuating the salience of behaviours contending for expression by the contention scheduler. This, in itself does not appear to constitute a learning signal. However, once the contention scheduler expresses a procedural behaviour, reinforcing (thalamo-cortical) feedback to procedural memory seeks to promote the persistence of the expression of this behaviour. This self-priming mechanism serves to avoid constant switching of behaviour arising from very minor change in the perceived environment [50]. This feedback mechanism is a plausible basis for a reinforcement signal to procedural memory that results in the learning of the attended response.

6 Implementation

In this section, we give an account of the implementation of the architecture described above as a large-scale, modular neural network linked via a defined interface to a simulated robot which allows us to illustrate the operation of the architecture and explore its properties through simulation and lesion studies.

The Java Programming Language is used to implement all the simulation code, including the neural controller, which has approximately 10^3 neurons in the design represented

here. (Scalability tests done with a 1Ghz Pentium III PC indicate the current software, without modification, can support about 10^4 neurons operating in real-time (together with the simulated environment, machine and trace monitors) within one composite network.) The 'network of networks' is specified in a model description file (XML) which 'builds' the network, relating individual neurons to clusters (or nodes), clusters to functional modules and functional modules to the composite network that controls the simulated robot. A functional module, cluster or individual neuron can be declared as sensitive to the concentration of one or more chemical modulators associated with learning. All neurons and connections between neurons are typed (input, output, excitatory, inhibitory).

A graphical interface to the network description file is incorporated into the simulation tool to facilitate network modifications, e.g., altering connection weights, suppressing input or output, adding neurons/connections or altering their transfer functions, etc.

6.1 The Simulated Robot

The robot has two, forward facing sonar sensors and eight olfactory sensors that allow it to sense the presence of obstacles or objects of interest such as food, nesting materials and other robots. Its effectors are two independent drive wheels and a gripper for picking up and transporting objects of interest. Other sensors, such as a simple vision system, infrared sensors and micro-switch based whiskers are available but they are not connected in the implementation of the robot used here. The coding of the simulated robot uses the techniques and algorithms prescribed in [20]. The neural controller implementing the extended Norman and Shallice architecture interfaces with the simulated robot using a defined interface.

6.2 The Controller

The fifty-one neural clusters that make up the current controller are organised into functional modules (episodic memory, contention scheduler, hippocampus, etc.) corresponding to the architecture of figure 2. A neural cluster comprises a collection of highly interconnected neurons; most are four or eight input, recurrent (Elman or Jordan) networks with up to three hidden layers. Each cluster is individually trained to a

specification defined by the functional model. Every cluster is independently tested and, if necessary, hand tuned using the simulation environment. The full model is system tested in a variety of environments featuring mazes, obstacles and other robots.

Initially, the control network is in an undefined state, but it can be driven to a known state to facilitate controlled experiments. Similarly, the systems that interface to, but are not part of the controller per se (executive planning module, individual sensors and effectors, etc.) have to be enabled for the model to operate.

The Perception Layer

The perception layer processes and fuses sensor signals and presents a representation of the environment to episodic memory.

Episodic Memory and Procedural Memory

Episodic and procedural memory are organised to achieve the reactive coupling between perception and action (Figure 3). Accordingly, the salience of any single behaviour has a distributed representation across episodic and procedural memory.

FIGURE 3

Episodic memory (EM) is composed of clusters of neurons organised in layers. Nodes at the bottom of the tree interface to the perception layer and represent 'atomic' episodes (e.g. food is present); nodes further up the tree represent increasingly compound episodes (e.g. food is present + there are no obstacles between me and the food = Orient to Food).

Procedural memory (PM) clusters are layered in a similar fashion; nodes at the bottom of the tree represent primitive motor actions (e.g., close gripper), with nodes further up the tree representing compound motor actions. Activation is propagated from higher to lower levels.

Nodes in EM and PM are connected to adjacent nodes in the same layer by both inhibitory and excitatory connections. Higher-level nodes represent compound episodes (in EM) or a compound behaviours (in PM). As such, they can be thought of a plan expression nodes as they encode collections of behaviours. Such nodes excite (prime) their sub-nodes, causing them to respond more readily when the conditions for their activation arise. In this way, EM exhibits priming in respect of anticipated perceptual input and PM exhibits priming of the relevant sub-behaviour. In order to facilitate the sequencing of sub-behaviours, plan expression nodes behave as neural finite state machines; changes in inputs trigger a state dependent transition to a next state and it associated output. The sequencing of behaviours is not deterministic as the exact state of the network is a function of the current state of the environment, the history of the machine and any executive attentional activity.

In our implementation, the combination of episodic and procedural memory realises a small number of reactive basis behaviours (c.f. Mataric [39]). Basis behaviours are low-level behaviours that may be combined to provide higher-level compound behaviours. The basis behaviours, and higher-level behaviours arising from them, serve the same role as “schemata” in the Norman & Shallice model. (An analogous decomopositional treatment, but using different representations, is given by [17] and [37].)

Every memory cluster (episodic and procedural) has inputs from other memory clusters and feedback from the contention scheduler (see below) where it competes for access to resources (working memory or effectors). The output of each memory cluster to the contention scheduler represents strength of a request for expression of the memory (its net salience).

All inter-nodal connections in EM and PM are subject to a constant base rate of Hebbian learning. This learning is potentiated by emotion- mediated attentional activity.

Contention Scheduler

Within the model, the contention scheduler is based on the computational properties of the basal ganglia [6], [34] and is an independent implementation of the contention scheduler described by Prescott et al. [45]. The properties of the contention scheduler were described above.

Working Memory

Working memory encodes salience of high-level nodes in episodic and procedural memory, providing the executive with a representation of how perception is currently related to action at a reactive level (Figure 4). It also encodes the currently intended task so that the SAS monitor (below) can detect any disjuncture between intention and reactive action.

FIGURE 4

The Supervisory Attentional System

As already outlined, the SAS has several functions; currently two functions are implemented: Monitor and Modulate, described above (see Figure 5). The full SAS has a Generate function to create novel plans but this function has not yet been implemented; instead we simulate the output of the SAS Generator as an encoding of sequences of intended tasks (i.e. plans) competing for access to working memory. Thus, human intervention in the normal operation of the controller is confined to specifying at the outset the intended goal of the robot, expressed as a sequence of behaviours.

FIGURE 5

The SAS Monitor nodes receive input from three sources: the salience levels of the perceptually driven associations from EM, which express the reactive intention of the system; the salience of behaviours which are allowed expression by the contention scheduler, i.e. the reactive response of the system; and the salience of intended behaviours from working memory. The SAS monitor raises an arousal stimulus to the SAS modulator if a behaviour is expressed which has not been planned. Once triggered, the arousal signal continues to be generated until the conflict is resolved by changes in

the relative salience levels of the input behaviours, which can, of course, arise in a number of ways.

SAS Modulation clusters generate output patterns that modulate the signals from memory clusters into the working memory contention scheduler so that intended behaviour is potentiated and other behaviours (competing for access to working memory) are attenuated. It is important to recognise that this does not *guarantee* the selection of the intended behaviour, as this risks overriding behaviours strongly and appropriately triggered by the environment, e.g., those designed to prevent harm to the machine or its surroundings.

Emotion (Limbic) System - Hippocampus

The overall level of activity of the SAS modulator provides the basis for a signal to the Emotion Centre. Low levels of activity in the SAS Modulator are associated with routine (minimally-attended) responses to familiar circumstances; high levels of activity reflect attentional effort in the face of unfamiliar circumstances. As described above, each episodic memory cluster has inhibitory and excitatory connections from neighbouring clusters. The clusters are sensitive to neuromodulatory chemicals (released by the limbic system), which have different effects based on the neurons' activities and connection types. When the emotion system becomes active due to raised attentional activity, a modulatory chemical signal is propagated through the entire neural network, reinforcing inhibitory links from active nodes in episodic memory that are not suppressed by the SAS to active nodes which are suppressed by the SAS (Figure 6). Over time, this results in a reinforcement of the association between the attended to episode and expressed action so that, in future, reduced, or zero attentional effort will be required for the appropriate action to occur automatically.

FIGURE 6

7 Normal Operation and Lesion Studies

An important tool for studying attention in humans is the use of lesion studies. The nature of human lesions may be inferred using one of a number of scanning technologies or by post mortem examination. Lesion studies are also used to interpret the nature of lesions in artificial neural systems [33] and to validate networks by looking for concordance with human lesions [51] [21] [52] [53]. Using the interface to the software simulation of our controller we are able to introduce lesions at will and observe the effects on the behaviour of the simulated robot allowing us to validate the architecture of the model against behavioural pathologies associated with dysfunction of executive attention in humans. Before describing the lesion studies, we first demonstrate normal functioning of the model in a given task.

7.1 Normal Behaviour in an Inexperienced Machine

We use the simulation to a monitor a robot that has the goal of foraging for food. To achieve this task, the robot must undertake a series of subtasks: make its way to the food, collect it and take it to a specified location (home). These subtasks are broken down further until a subtask is realised by a specific effector response, such as 'rotate left wheel forward', or 'open gripper'. The simulation environment allows us to observe the activity on connections between components of the model, be they single neurons, clusters of neurons, or major architectural elements of the model.

The normal functioning of the relatively inexperienced robot as it learns to deal with unfamiliar distraction is illustrated in Figures 7-10. In figure 7, the foraging robot (Penny) has started without food at point A, collected food at point B and is taking it home. When the robot is at point C, additional food (distraction) is introduced, inducing a momentary orientation (barely visible in the figure) towards the food, before continuing with the task.

FIGURE 7

In Figure 8, we observe some of the relevant activity in the control network as this experiment unfolds. Recording of each of the seven traces in Figure 8 commences shortly

after the robot has picked up the food at B but before the distracting food is introduced at C.

FIGURE 8

Trace 1 shows the salience of the Orient to Food behaviour in PM; as the robot has already collected some food, salience of this behaviour is initially low.
When a distracting food source is introduced and is detected, salience of the Orient to Food behaviour increases, initially in EM (rising edge trace 2), and consequently in PM (rising edge trace 1). Thus, the action seeks expression via the contention scheduler. As the robot is currently attempting to Orient to Home, Orient to Food is not the intended action (trace 3 is low). However, for this relatively inexperienced robot, the strength of the Orient to Food response leads the contention scheduler to select the Orient to Food behaviour, albeit inappropriately (the rising spike of trace 5). The SAS monitor detects this unexpected action (rising edge trace 4) and induces the SAS modulator to attenuate this behaviour at the input to the contention scheduler (trace 6). This attenuation is successful (falling edges of trace 1 and consequently of trace 5) and so it is no longer expressed. Meanwhile, the limbic system has been excited by the modulatory SAS activity (trace 6), inducing release of a diffuse neuromodulatory signal (trace 7). Accordingly, the weight of the inhibitory connection from the intended Orient to Home behaviour cluster *to* the active but unintended Orient to Food behaviour cluster in EM is increased (over two to three seconds), the effects of which can be seen in the gradually falling activities of traces 2, 4. Once the inhibitory response from Orient to Home to Orient to Food becomes strong enough, the SAS no longer needs to continue the suppression (falling edge of trace 6). Cessation of SAS activity ends the hippocampal activity (falling edge of trace 7). At this stage, the robot has learnt to avoid the nature and the level of distraction encountered and no longer needs attentional resources to act appropriately in the presence of a similar level of distraction.

At this point, we extend the experiment described so far to expose the robot to a more potent distraction by bringing the food source progressively nearer (Figure 9). (Note: in figures 9-16, the labelling of the individual traces is consistent with that given in the

legend of Figure 8.) Trace 2 shows that as potency of the distraction increases, the EM salience of the Orient to Food behaviour increases.

FIGURE 9

However, the previous learning means the salience of the behaviour in EM, and consequently PM (trace 1) remains low (imperceptible in the robot's movements). As the potency of the distraction increases (food brought nearer) the salience of the (inappropriate) behaviour reaches a level at which the SAS momentarily applies an inhibitory signal (rising spike of trace 6). This induces another short burst of limbic activity (trace 7) and associated learning, which is results in further inhibition of Orient to Food by Orient to Home and the robot resumes its intended behaviour without further attentional effort. Eventually, the robot is able to avoid this particular distraction in a wholly unattended way (Figure 10).

FIGURE 10

7.2 Lesion Studies

We now conduct a sequence of five simulated lesion studies to explore the induced behavioural pathology of the control network. The locations of the experimental lesions to the attentional architecture (A-E) are shown in Figure 11. In this section, we describe the lesions introduced along with the resulting behavioural pathology. The relation of these pathologies to human pathologies of executive attention is considered and discussed later.

The five lesion experiments (A-E respectively) are:

- Lesion A involves removing the arousal link between the SAS modulator and the emotion center, effectively preventing attention based learning.
- Lesion B removes the modulatory link between the SAS modulator and the contention scheduler.

- Lesion C prevents the SAS monitors being aware of the salience of episodic memories trying to gain access to working memory.
- Lesion D prevents the SAS monitors being aware of planned or 'supported' behaviours.
- Lesion E removes the contention scheduler input to the SAS monitors, removing any awareness of active behaviours.

FIGURE 11

7.2 Lesion Study A

In this first experiment on a relatively inexperienced robot, the executive attentional control network was lesioned by blocking the excitatory signal from the SAS to the limbic system (Figure 11, marked A). Comparing the activity traces (Figure 12) with those of the normal, similarly inexperienced, robot (Figure 8) we see that, outwardly, the robot behaves normally (compare trace 1) because the SAS applies the appropriate suppression of the unwanted behaviour. However, hippocampal learning (trace 7) is never induced and so this machine will never acquire the ability to exhibit the desired behaviour without attentional effort.

FIGURE 12

7.3 Lesion Study B

Removing the modulatory pathway from the SAS to the Contention Scheduler (figure 11, marked B) results in the traces shown in figure 13.

FIGURE 13

The traces start as in lesion study A, however, when the distraction is introduced, although the SAS generates the modulatory signal in an attempt to suppress Orient to Food (trace 6), in keeping with the lesion, it is no longer able to modulate input to the contention scheduler. As Orient to Food becomes active the machine moves directly

towards the source of the distraction. As the SAS has generated a modulatory signal, it has also generated an arousal signal to the learning subsystem. However, in the absence of the modulatory signal from the SAS, the contention scheduler has inappropriately selected Orient to Food; Orient to Home is no longer active so the inhibitory link between Orient to Home and Orient to Food is inappropriately adjusted and, as can be seen from the traces, the machine never learns to escapes from the distraction, indeed its error behaviour is reinforced by the learning. It is possible that in an expanded model other active clusters with inhibitory links to Orient to Food would eventually suppress it.

7.4 Lesion Study C

In this third experiment, the executive attentional control network of an experienced robot is lesioned by preventing the SAS from monitoring the salience of a behaviour prior to its expression by the contention scheduler (Figure 11, marked C). Thus, in this case, the SAS only detects expression of an inappropriate behaviour after it is expressed at the contention scheduler. The traces of Figure 14 illustrate this failure.

FIGURE 14

As in the previous experiments, new food is introduced to the inexperienced robot as a distraction whilst it is taking home food it already holds. The distraction results in the salience of Orient to Food increasing (trace 2). Again, this isn’t the currently intended behaviour in the foraging plan (trace 3). As in normal operation (Figure 6) the salience of the unfamiliar distraction causes the contention scheduler to expresses the behaviour (first rising spike of trace 5) and the SAS monitor detects that a modulatory signal is required to attenuate this (first rising slope in trace 6). This suppresses the inappropriate behaviour, which is then no longer selected by the contention scheduler (the first falling slope in trace 4). However, the lesion introduced to the network prevents the SAS from recognising that the inappropriate cluster is still strongly salient; accordingly, when Orient to Food is no longer enabled by the contention scheduler. The SAS ceases its modulation of the signal, resulting in Orient to Food again achieving expression via the contention scheduler and the oscillatory cycle of expression and modulation is

established (traces 5 and 6). The resulting observed behaviour of the robot is that it repeatedly switches between moving towards home and moving towards the distraction (Orient to Food and Orient to Home) moving very slowly in fits and starts in what is characterised as dithering.

Whilst the machine oscillates between Orient to Food and Orient to Home, the SAS is generating an oscillating arousal signal to the learning subsystem. This eventually manages to increase the inhibitory connection between Orient to Home and Orient to Food so that the appropriate behaviour is eventually learnt (falling edge of trace 2), though the time taken to do this is over eight seconds compared with the two to three seconds of the unlesioned model.

7.5 Lesion Study D

Lesioning the working memory of an inexperienced robot such that the SAS cannot see the currently intended behaviour renders any and all behaviour which is expressed by the contention scheduler inappropriate, as any and all actions appear to the SAS monitor as unplanned. The resulting traces can be seen in figure 15.

FIGURE 15

For the inexperienced robot, the introduction of the distraction induces the inappropriate response of Orient to Food. The SAS correctly attenuates its expression (trace 6). However, whilst suppressing Orient to Food, the SAS is generating an arousal signal to the learning subsystem (trace 7), the effect of which is to reinforce inhibition of all other behaviours when Orient to Food is inactive.

7.6 Lesion Study E

In this final experiment the SAS is lesioned so that it does not see which behaviours are selected for expression by the contention scheduler (figure 11, labelled E). The traces from this experiment can be seen in figure 16.

FIGURE 16

Traces 1 to 4 accord with the normal case in which the distraction is introduced. However, on this occasion, no rising edge is seen on trace 5 (as the contention scheduler output to the SAS is lesioned). Accordingly, the SAS view of the currently intended action and the (lesioned) output of the contention scheduler input (trace 5) are the same. Accordingly, no suppression of the inappropriate Orient to Food behaviour is generated. The small spike in the suppression output seen a second into the trace is from the priming induced by the behaviour input (trace 4), which causes SAS suppression to persist for clusters which seek to remain active even when they are suppressed. The resulting behaviour of the machine is simply to move towards the distraction, though unlike lesions B to D, since the SAS monitor does not detect anything is wrong, the arousal signal for the learning subsystem is not invoked.

8 Discussion and Conclusions

The goal of this work was to develop an integrated neural architecture modelled on human executive attention which was capable of supporting autonomous control and developmental learning in a simulated robot. In particular, we sought to make progress in respect of a model displaying features commonly associated with executive attention as set out at the beginning of the paper [36]: selection of a less salient intended task over a more salient automatically selected task; priming of tasks that are anticipated; use of memory to maintain task focus along with appropriate persistence of willed attention to action, requiring that attentional effort should be invoked only when needed. We also recognised that attention-based learning played an important role in allowing willed selection of appropriate tasks to become increasingly automatic, reducing the need for attentional effort. Our approach to the problem was to adopt a functional model of executive attention [42] [47], extending it to incorporate an innate learning mechanism based upon emotion-mediated attentional burden. An integrated modular neural control system for a simulated autonomous robot was developed which exhibits the behavioural and mental attributes sought.

Although the task used for the illustration is comparatively simple, it serves as an example of a task requiring a sequence of subtasks to be carried out - in that sense, the length of the sequence is relatively immaterial. The choice of distraction (a powerful, prepotent stimulus for another highly relevant task that was within the scope of the intended goal) ensured it was maximally distracting. In operation, the simulated robot, as documented in figures 8-10, exhibits the desired attentional attributes.

- There is attentionally-driven selection of a less salient but intended task over an alternative response associated with a highly salient, pre-potent, source of distraction. The intention is not derived, either directly or indirectly from the environment, rather it is derived from an intended plan. Further, the plan is a set of tasks and exactly which task is to be performed at any given time is determined autonomously as opposed to be specified or explicitly cued in the environment.
- The model provides priming of future actions. In EM, high-level nodes (encoding remembered episodes) primes lower-level nodes so that they are more likely to be activated when the anticipated environmental stimuli relevant to a new task in the intended plan become evident. At the same time, in PM, high-level nodes encoding behaviours prime the associated lower-level behaviours so that they are more likely to be expressed as the associated EM nodes become activated.
- Memory is used to maintain task focus, but, importantly, this does not involve persistent attentional effort – the goal is remembered without awareness, serving to provoke an attentional arousal signal when expressed action departs from intended action.
- Attentional effort is used to induce learning of the intended goal-related responses so that performance of intended tasks becomes increasingly automatic, freeing attentional resources to deal with new levels or types of distraction.

In observing robot behaviour and the internal activity of the network, it is possible to identify phenomena that may be considered analogous to effects seen in humans.

In normal operation, the robot progressively learnt to suppress unintended reactive motor activity. As the learning progressed, the expression of unwanted motor action became imperceptible to the observer of the machine itself without the use of the network activity monitor (Figure 7 and trace 1 of Figures 8 and 9). This effect may be associated with the Chevreul Pendulum phenomenon (described in [3]) in which a subject is given two contradictory intentions to sustain. Initially, that are asked to hold still a pendulum suspended from their supported hand. This can be done successfully. When asked to will it to oscillate on one or another specified axis, whilst *simultaneously* maintaining it in a steady state, the pendulum is (usually) induced to oscillate against the will. The small motor actions seen in trace1 of Figures 8 and 9 may be consistent with a comparable phenomenon in the robot as the imperceptible motor actions might be expected to drive the pendulum.

The results of the lesion studies may also be related to recognised behavioural pathologies in human patients suffering lesions to areas of the brain associated with executive function and attention. Examples of such pathologies include the following [47]:

- utilisation behaviour is an inability to suppress a (strongly) triggered, but inappropriate behaviour, as demonstrated by a patient who reaches for a cup when presented with it even though it has been explicitly agreed by the patient that they will not do so;
- capture errors in which the task focus is not maintained (the classic example being that of the psychologist William James realising he was dressing for bed instead of dressing for dinner);
- akinesia is the inability to act, attributable to impairment of the ability to resolve selection between competing behaviours;
- stereotypy or perseveration is inappropriate persistence of a behaviour a failure to notice significant cues (e.g., those associated with successful completion of a task or subtask) that should result in the expression of a different behaviour.

All of these behaviours are explained as a failure in error correction, i.e. failure to interrupt one behaviour and subsequently will the initiation of another. The first two are sometimes considered as different forms or degrees of distractedness; in the first case, the subject wills the avoidance of the response, but the stimulus is so strong it is not suppressed, in the second case, the subject is initially unaware of the lapse, either because they are paying attention to something else or because they are not paying attention to anything in particular.

In lesion A, the observed behaviour of the robot, in the short term, is apparently normal (compare trace 1 of figures 8 and 12). However, consideration of the network activity demonstrates that the robot fails to adapt to the presence of the distraction. A normal robot learns to ignore the distraction - eventually proceeding without conscious awareness associated with SAS activity. The lesioned robot, by contrast, is continuously aware of the distraction (enduring attentional activity of traces 4 and 6 in figure 12). The normal robot is in a position to devote attentional effort to subsequent distractions, but the lesioned robot will not respond to any distraction less salient than the current one. Lesion B would seem to correspond to one form of utilisation behaviour. The robot maintains and responds to an intention to resist the distraction (traces 4 and 6 of figure 13), but cannot do so successfully (trace 1). Lesion C corresponds to a patient who experiences a different form of utilisation behaviour; here there is no awareness of committing an act until the act is executed and then noticed. In some cases the faltering movements made during a significantly prolonged learning period may be interpretable as another form of akinesia. Lesion D corresponds to akinesia with awareness. The SAS activity (traces 4 and 6 of figure 15) indicates that robot would experience a sense that it should make a response, but, unaware of its intention, it would have no sense of what it might do. Lesion E corresponds to the human experience of a capture error in which there is no (initial) awareness of the error being made.

The ability to reproduce these seemingly analogous pathologies supports the validity of the elaborations we have made to the basic functional model as we developed it towards its current implementation. An obvious extension to the programme of lesion studies is to

interpret the effects of combinations of the lesions A-E and to interpret the outcomes in terms of the known behavioural pathologies mentioned above. The studies do so that in diagnosing problems of behaviour in robots controlled by complex neural architectures it is not sufficient to rely upon phenomenological behaviour alone, as with human patients, it is necessary to apply sensing technology and interpret the results in the light of known or inferred (modular) function.

We turn briefly to the question posed by LaBerge [36]; why might executive attention, as a phenomenon, have emerged. As stated earlier, Aleksander and Dunmall [1] suggest that attention is necessary when the building and maintaining of an internal representation of the perceivable world cannot be done in parallel. It is possible to accept this proposition, whilst, at the same time, seeking to relate it to the operation of selective advantage, i.e. what might be the nature of the selective advantage of non-parallelism. Our partial answer to this relates to the model of executive attention we have developed and implemented. We have illustrated how the integrated architecture for automatic and willed attention induces learning in episodic memory and procedural memory so that initially novel perceptual patterns become more familiar, and the associated actions become capable of automatic expression. The learning arises from an innate mechanism (there is no 'teacher') and the mechanism assumes only a set of initial (basic) capabilities ‘at birth’. We suggest that in a dynamic and highly unfamiliar world, there is a fairly obvious selective advantage for any agent capable of distinguishing between the familiar and the unfamiliar; relegating behaviour which deal with the familiar to the level of the automatic and freeing executive attention to address issues of novelty.

Finally, we outline future developments of the work. An extension to the emotion (limbic) system in the model to include explicit elements of the endocrine system (intimately associated with limbic structures) would seem to offer a link between learning for enhanced automaticity with a potentially pleasurable, even addictive, underpinning to learning and problem solving. An organism possessing such a mechanism would be driven by the search for novelty and new problems to solve. Thus may evolution have selected in favour of organisms with limited attentional resources in the first place.

At this stage in the elaboration of our model and implementation, as presented, human intervention is required only to specify the robots overall goal in the form of plan representing its intended actions; this is stored in working memory. The machine itself has no significant planning function. In seeking to address unfamiliar problems, it can engage simple heuristics relating to its current plan, e.g. progressing or reverting to previous actions or engaging a default action. Integration of a basic planning mechanism such as that offered by Shanahan [48] and/or Garagnani, Shastri and Wendelken [26] offers further functional development in this respect. We have also indicated that extending the model to incorporate elements of the endocrine system might serve to allow exploration of how feedback from stressful and pleasant sensations might enhance performance and learning, adding a new dimension to awareness. This would provide a treatment of these effects that did not require a mental process of evaluation (c.f. [48]).

Another significant developmental test for the system requires the scaling up of the complexity of the task (number of valid paths, rather than length of sequence) and increasing the diversity of associated sources of distraction. The scalability of this architecture, yet to be tested in practice, is related to the degree of correspondence between the detailed neural architecture of many of the functional subsystems and elements of the architecture of human brain. In particular, the somatotrophism of the human sensory, motor, and pre-motor cortex is reflected in the structure of the sub-units for perceptual mapping to episodic memory and of procedural memory. Thus, increasing the number of sensors or effectors can be compared to increasing the number of sensory or effector organs of a human - this would be reflected in changes to the somatotrophic map associated with sensory motor cortex. Scaling of the contention scheduler is essentially the same; it maps behaviours onto effectors, and episodic memory into working memory. Thus it is the number of distinct effector systems and the structure of working memory that governs the rate at which the architecture scales up.

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FIGURE 1

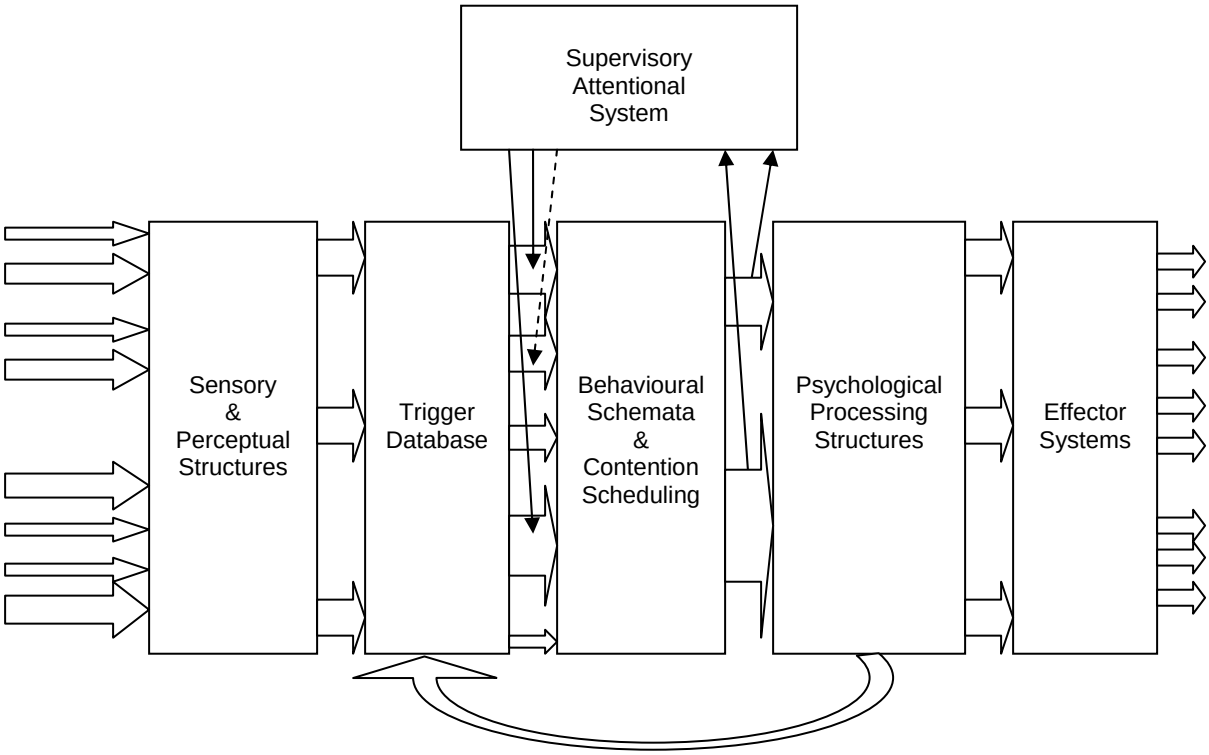

Figure 1. Norman & Shallice architecture for executive control of routine and non-routine behaviour (after Shallice [47]). Information from sensory pathways is mapped by a trigger database into a repertoire of behaviours (schemata); competing (contradictory) behaviours are subject to selection by contention scheduling; the output of psychological processing systems is mapped onto effector systems. Persistence is reinforced by effector feedback to the trigger database. The Supervisory Attentional System (SAS) modulates the triggering signals (solid arrow indicates potentiation, broken arrow indicated attenuation). The SAS monitors the selected behaviours, producing an ‘interrupt’ signal if there is a separation between intended and expressed action and subsequently applying a modulatory signal to contending behaviours.

FIGURE 2

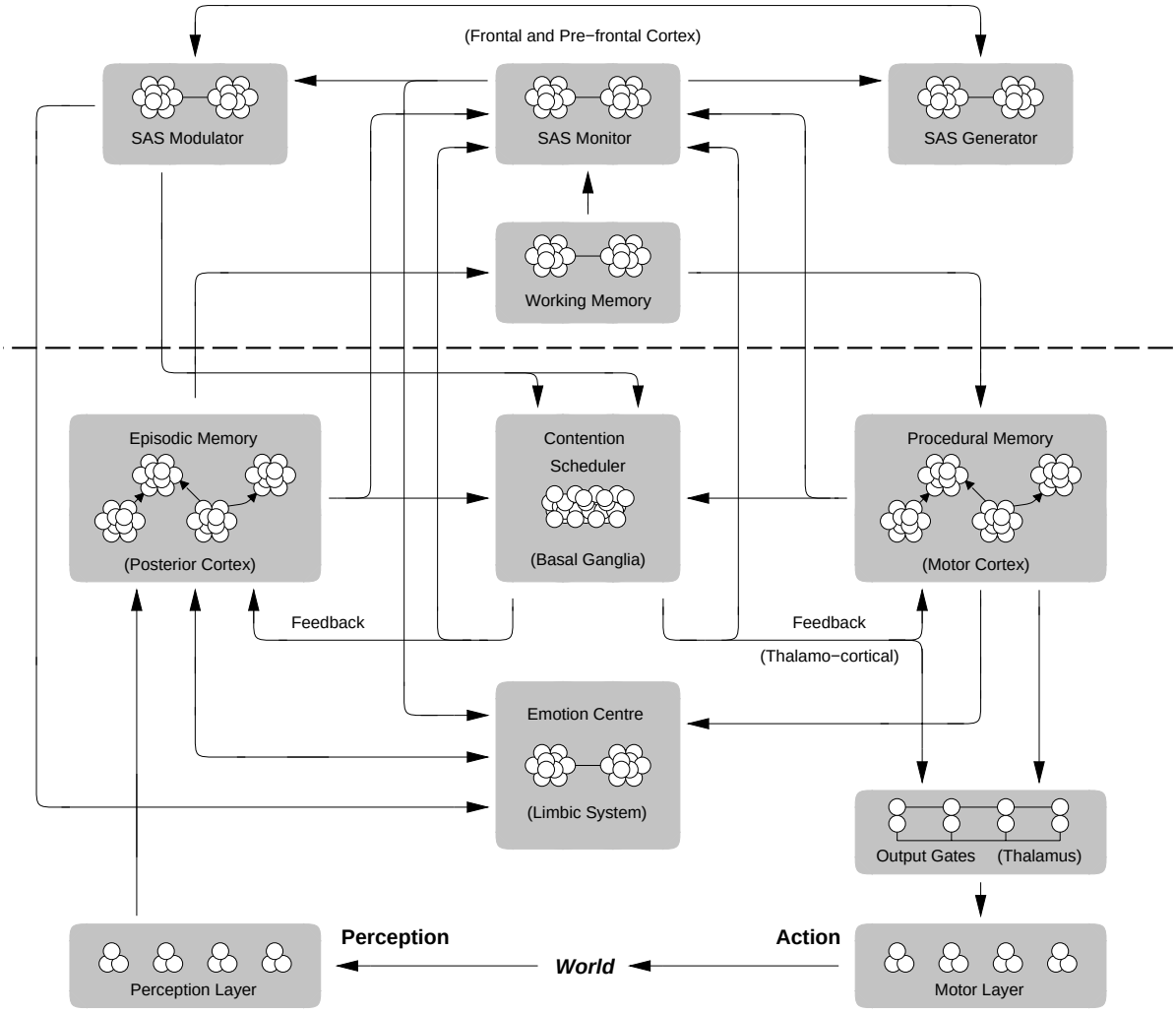

Figure 2. Architecture for neural control of action selection (the arrows represent information pathways and are not the output axons of single neurons).Unattended action selection is achieved by the elements below the dashed line. The dense connections between EM and PM, other than those via WM, are not explicitly represented. Attentional action selection is achieved through modulation of unattended behaviour by the executive above the dashed line. The diffuse neuromodulatory signal output by the Emotion Centre is not illustrated as it pervades the whole network.

FIGURE 3.

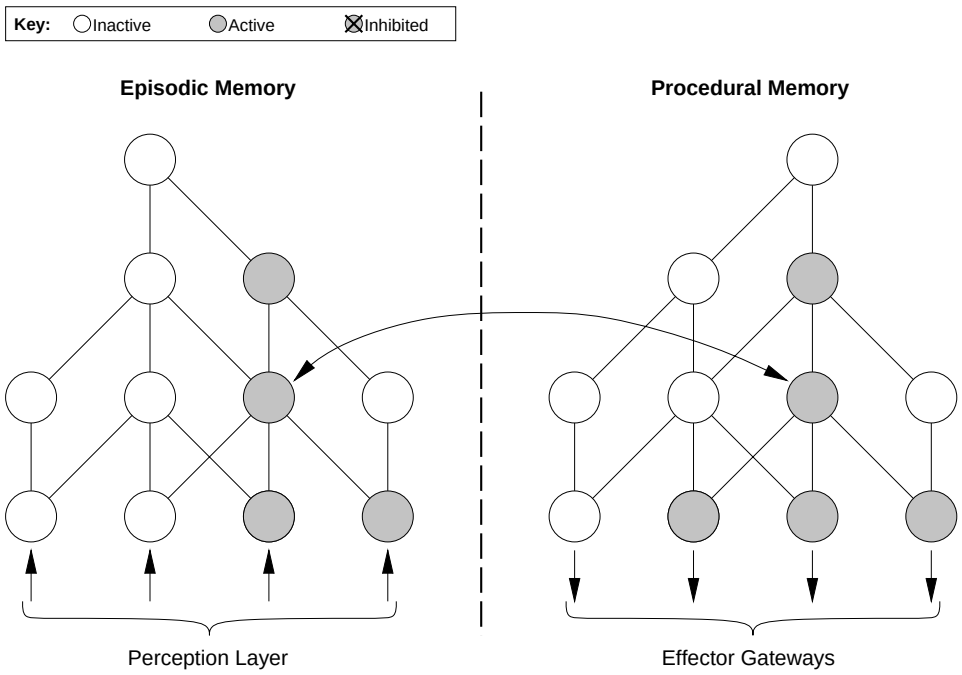

Figure 3. Structure of episodic and procedural memory and their interconnection. Activity in the perception layer induces a pattern of excitation in episodic memory. In turn, these nodes excite nodes at corresponding levels in procedural memory, which then propagate activation to nodes representing 'atomic' actions which then compete for expression at the effectors through the contention scheduler. (Note: mutually inhibitory links between layered nodes in EM and PM respectively are not shown).

FIGURE 4

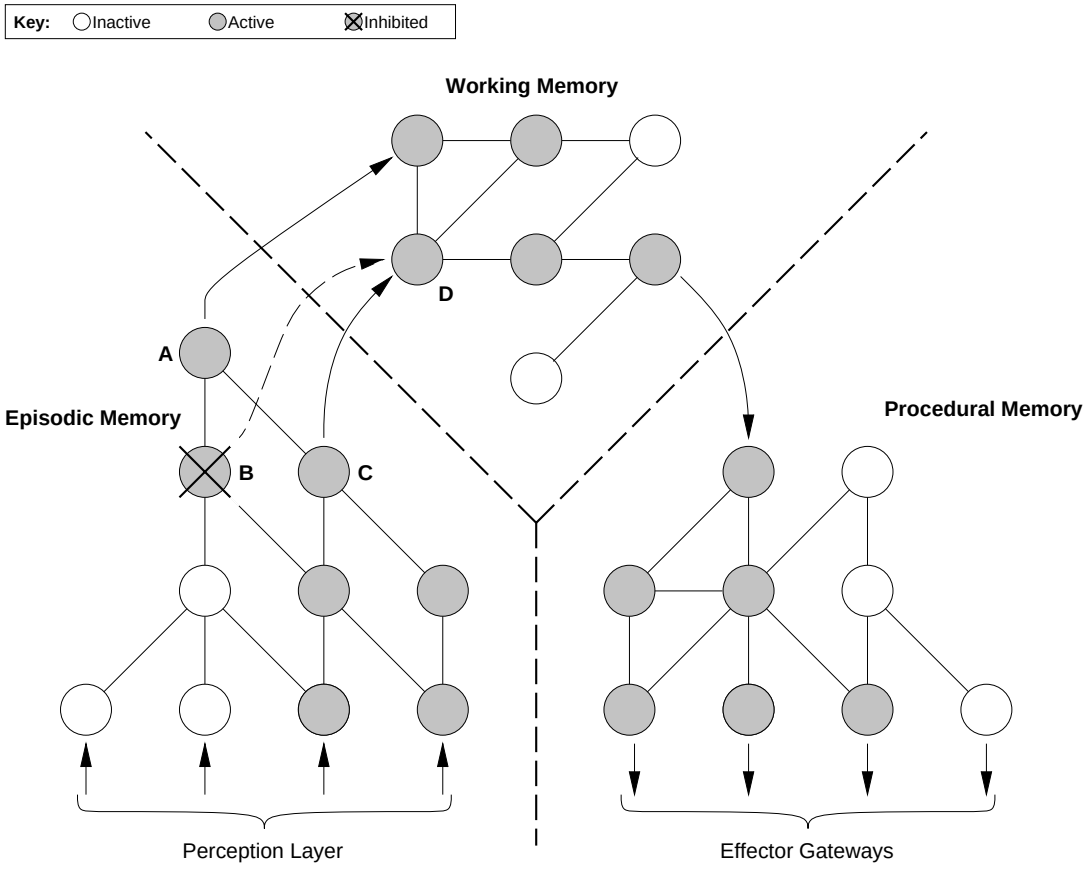

Figure 4. Illustration of how episodic, working and procedural memories interact. (Interaction between EM and PM through WM is *complementary* to the automatic activation illustrated in figure 3.) Node A is priming node C (as part of a plan expression sequence). However nodes B and C are competing via the working memory contention scheduler (dashed line) for access to working memory node D, resulting in node B being inhibited. Working memory has access to high level procedural memory nodes.

FIGURE 5

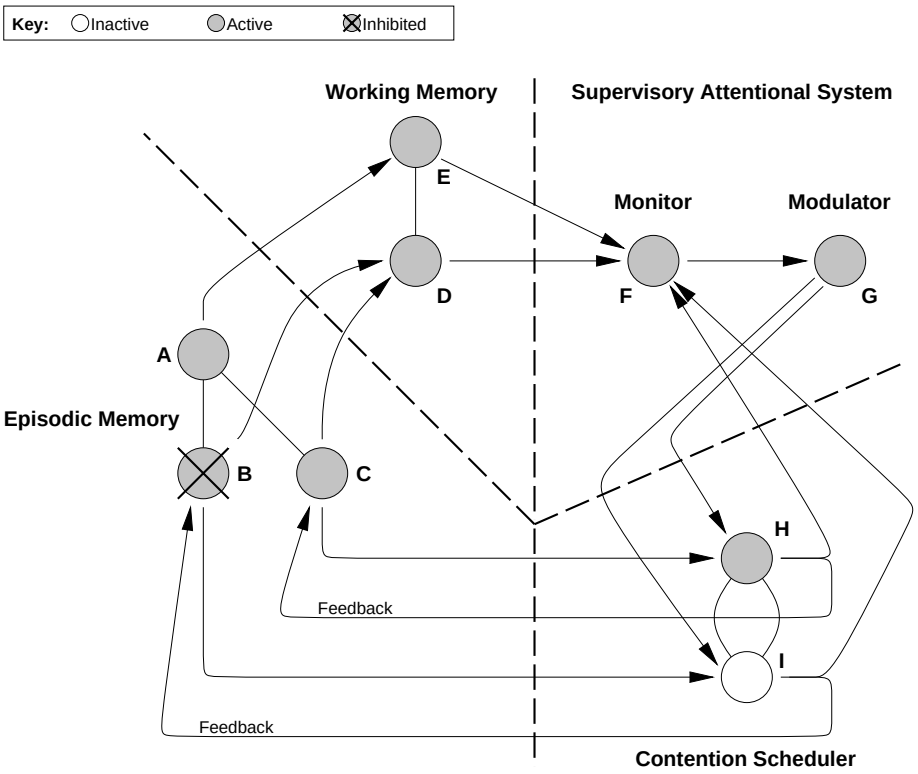

Figure 5. Interactions between episodic, working memory and the Supervisory Attentional System. Node A (representing the sequence of planned behaviours) has activated node C (as in figure 4). Both node A and node C have gained access to working memory (nodes E and D, respectively) and are thus subject to monitoring by the SAS monitor. However if activity of node B is significantly increased (e.g., through a strongly triggered habitual response) and gains expression at the contention scheduler and in working memory, the SAS monitor (node F) senses the difference between intended and activated behaviour. An arousal signal is generated which induces the SAS modulator (node G) to suppress the error behaviour. It does so potentiating both node C's excitatory inputs and node B's inhibitory inputs and via the contention scheduler (nodes H and I, respectively), increasing the likelihood that node B is inhibited relative to node C. Nodes H and I being adjacent in the contention scheduler architecture have mutually inhibitory links so that excitation in one node suppresses the other.

FIGURE 6.

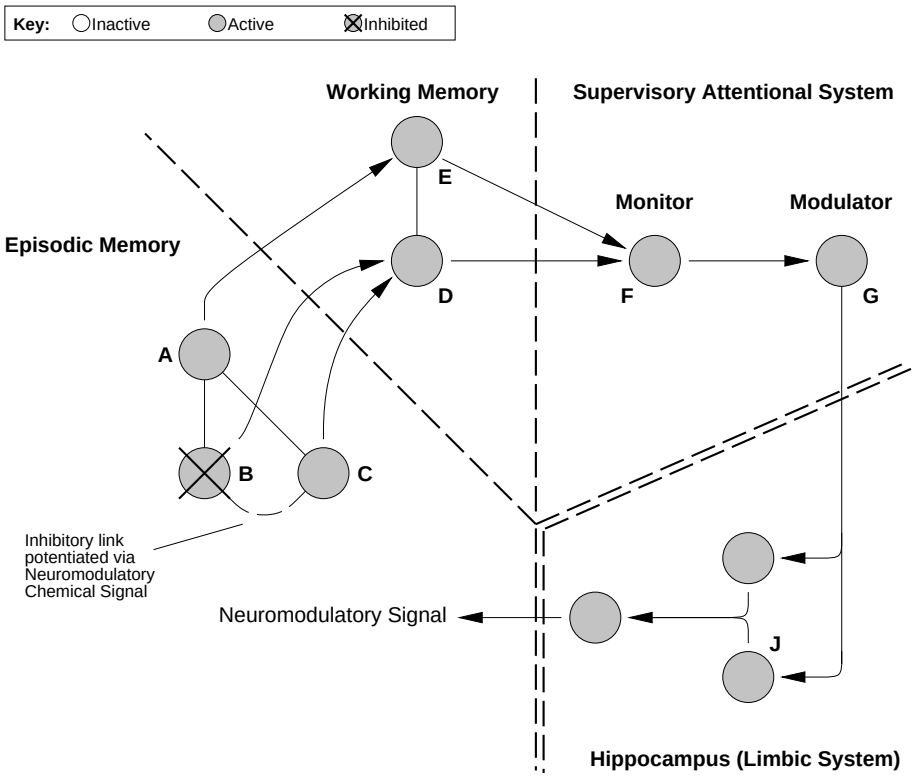

Figure 6. Learning to suppress an incorrect behaviour. This figure extends the scenario in figure 5. As the SAS attenuates activity of B and potentiates C, it also induces release of a diffuse neuromodulatory chemical signal from the limbic system. The presence of this substance reinforces the inhibitory connection between node C and node B in EM.

FIGURE 7

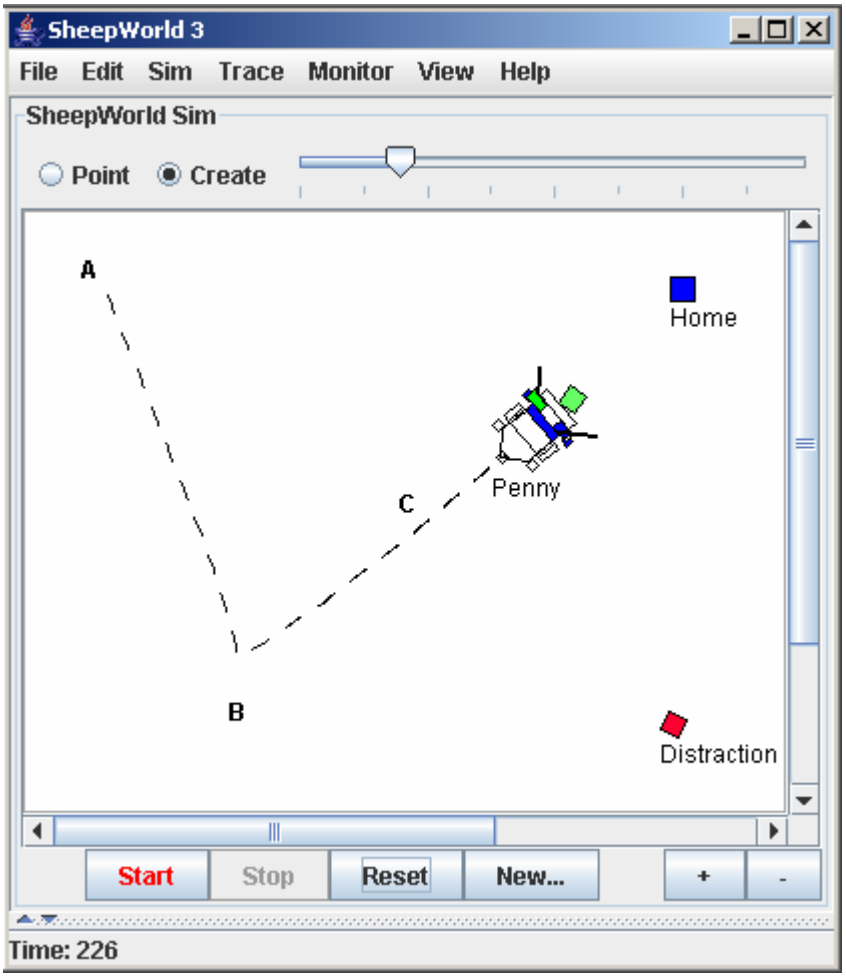

Figure 7. Simulation environment (normal operation of the SAS).

FIGURE 8

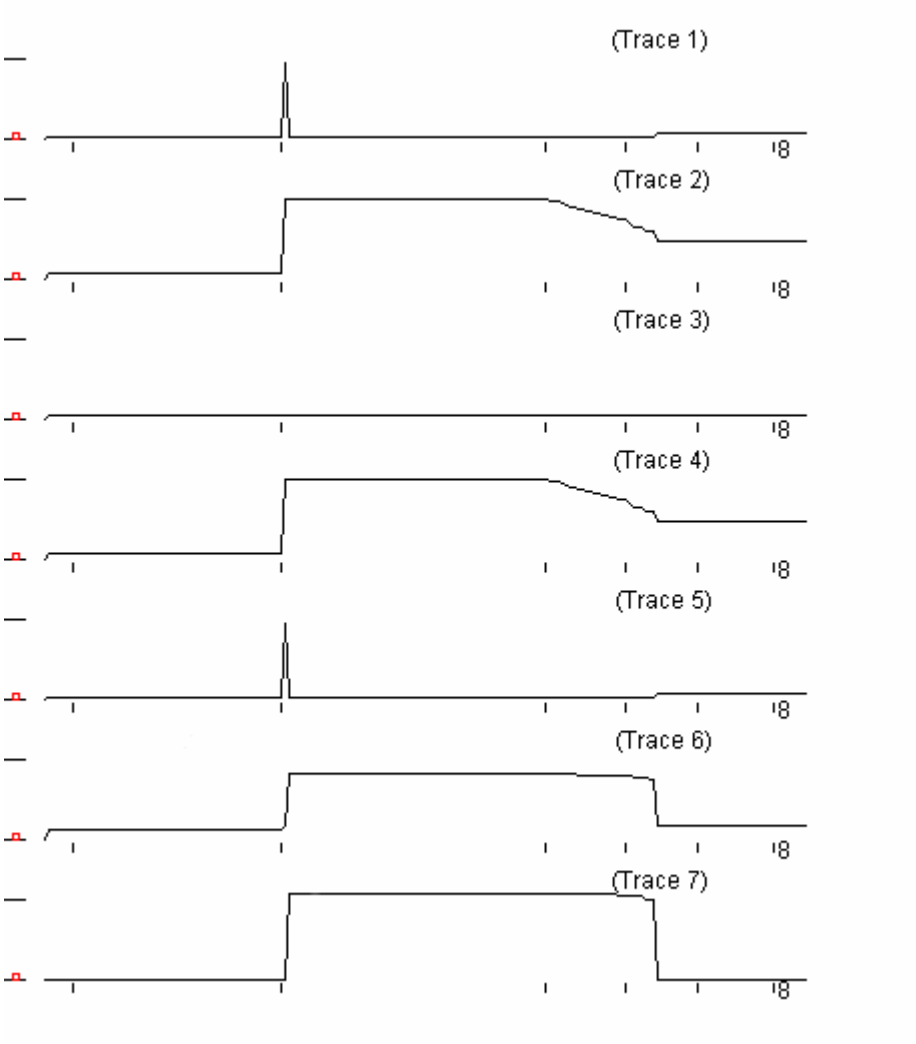

Figure 8. Normal Trace of an inexperienced machine. Trace 1 is salience in PM of the behaviour ‘Orient to Food’. Trace 2 is the salience in EM ‘Orient to Food’. Trace 3 shows the input into the SAS monitor from the working memory representation of the current plan. Trace 4 is the input to the SAS monitor from the EM representation of ‘Orient to Food’. Trace 5 shows the input to the SAS monitor from the PM representation ‘Orient to Food’. Trace 6 is the modulatory signal produced by the SAS which suppresses the PM representation of the unwanted behaviour, ‘Orient to Food’. Trace 7 shows the activity of the limbic system associated with release of the neuromodulators that induce episodic learning. The narrative associated with the figure is given in the body of the paper. (Note: the sample rate of the traces has been increased at the beginning of the

recording to better capture the input spikes, hence the second interval ‘ticks’, ending 8 seconds into the trace, are not uniformly placed.)

FIGURE 9

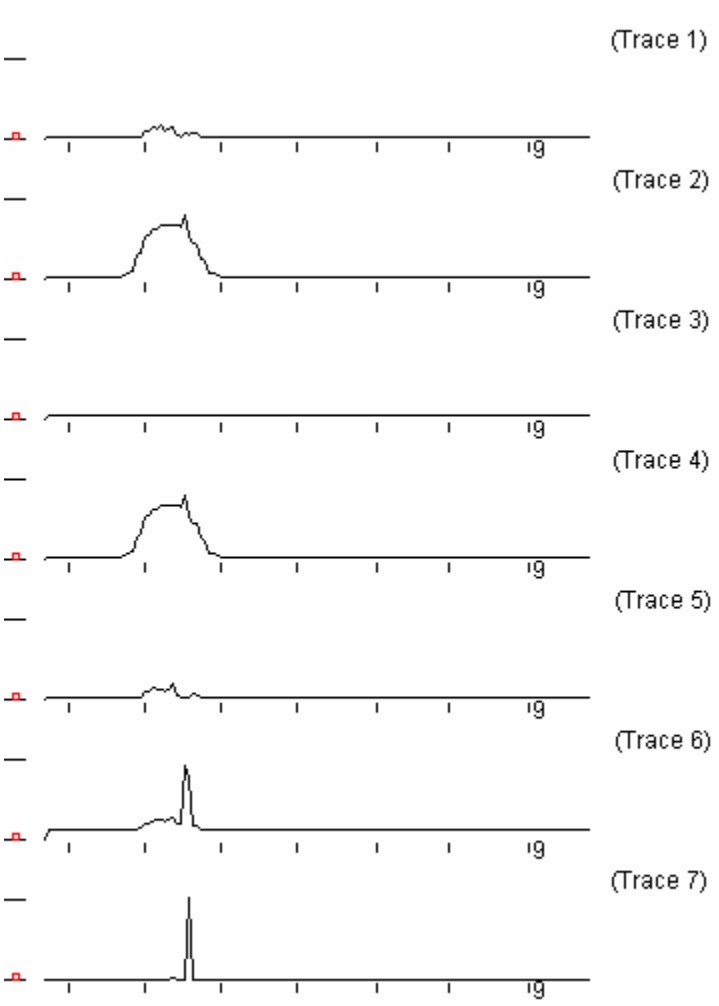

Figure 9. Traces from a second run of the experiment with an experienced machine (the network definition file was saved and the experiment was restarted). Extra food was introduced whilst the machine was returning home (shown by the activation of trace 2) and after a few moments it manages to cause the machine a momentary distraction (shown by the small disturbance in trace 5), which is rapidly suppressed by the SAS (trace 6), though a learning signal is generated (trace 7).

FIGURE 10

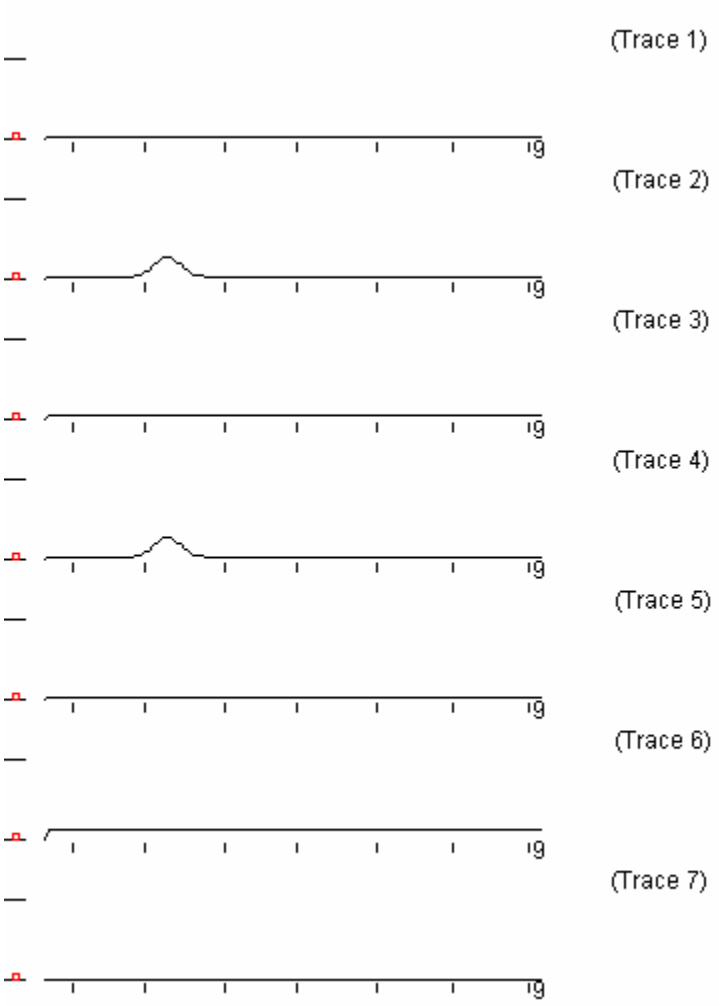

Figure 10. Traces from the fourth run of the experiment with an experienced machine (the network definition file was saved after each run and the experiment was restarted). No discernable SAS activity (trace 6) is observed when the distraction is introduced a few seconds into the trace.

FIGURE 11

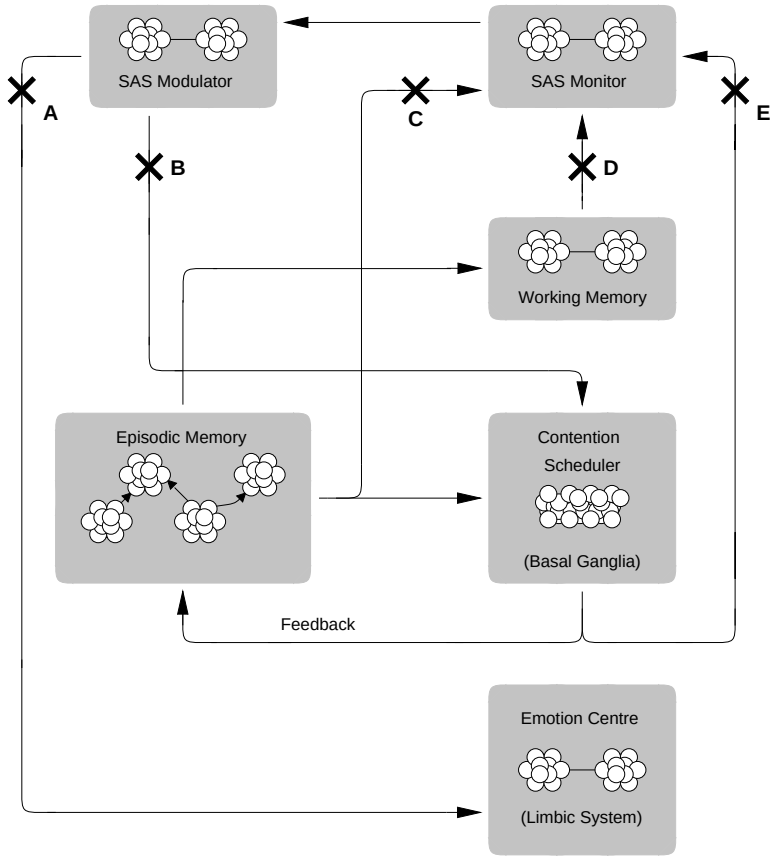

Figure 11. Lesions to the SAS (A-E).

FIGURE 12

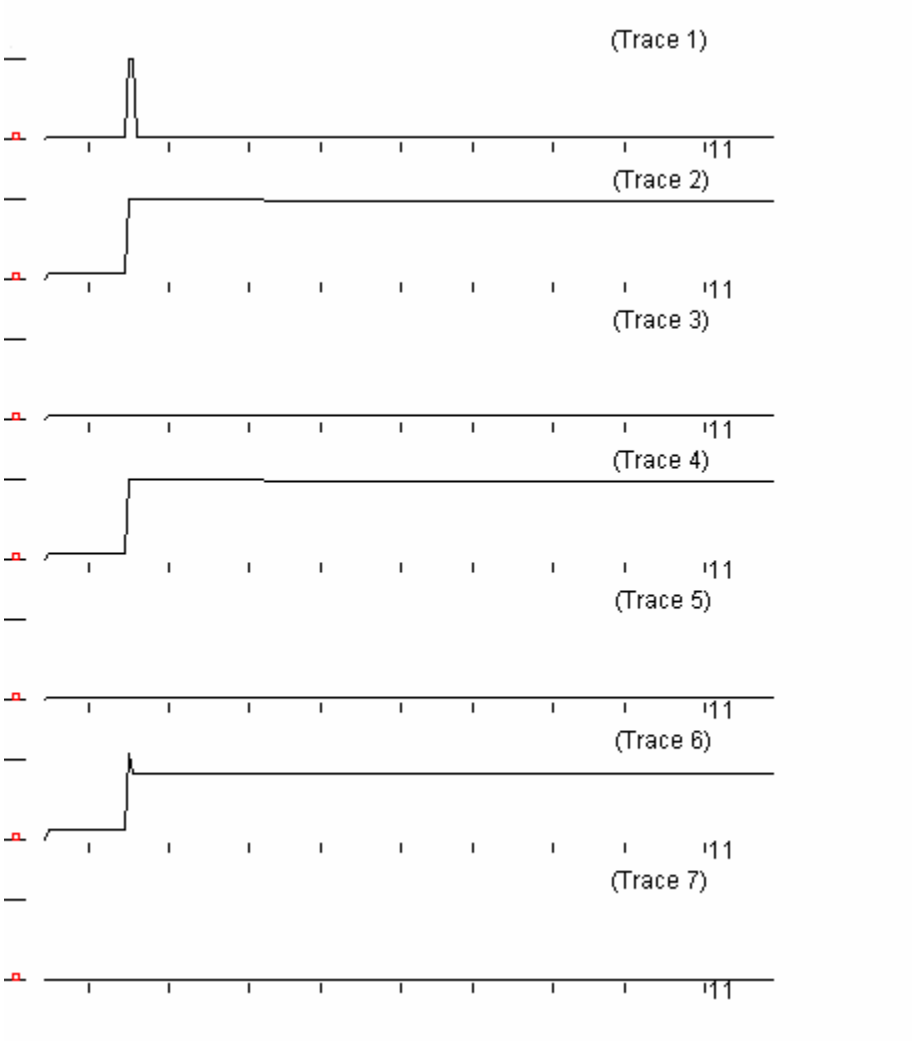

Figure 12. Lesion A

FIGURE 13

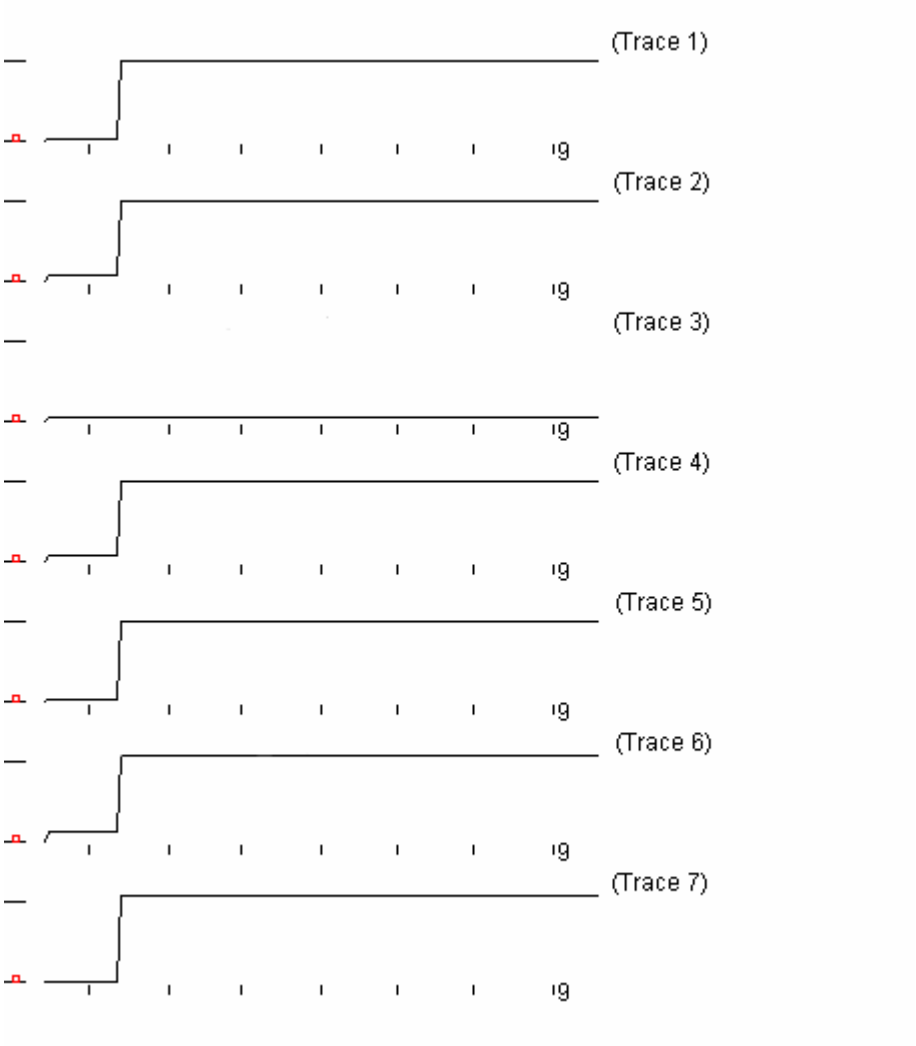

Figure 13. Lesion B

FIGURE 14

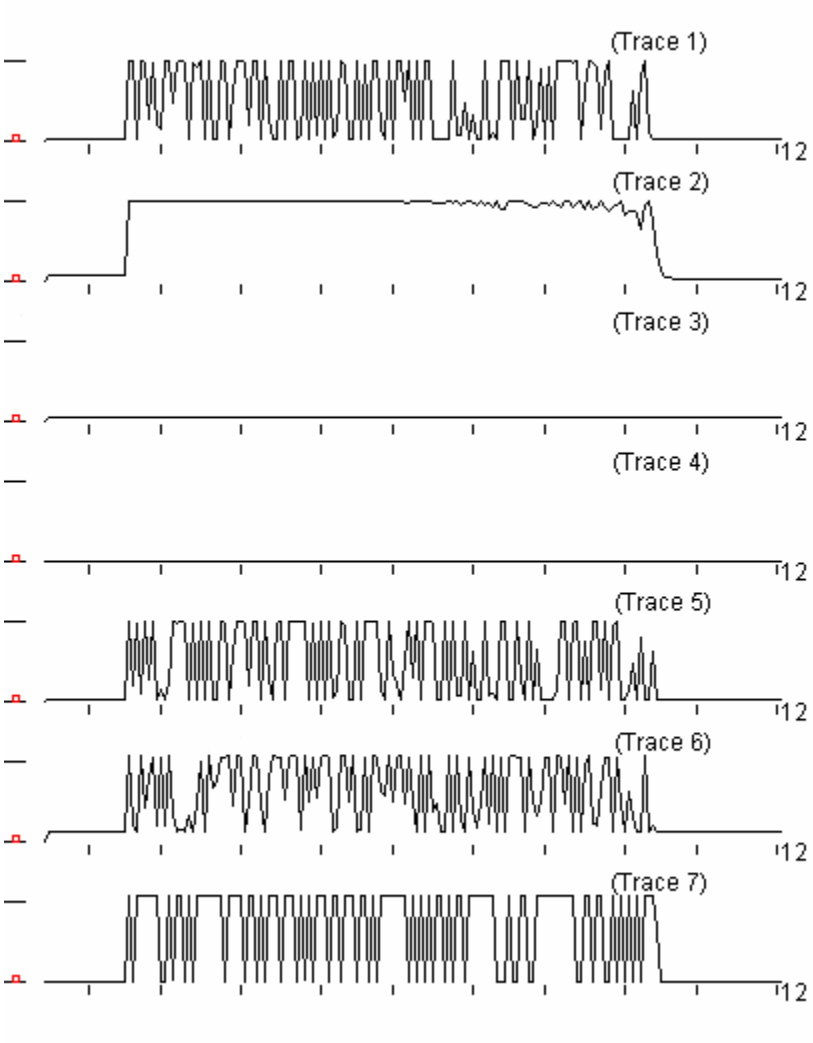

Figure 14. Lesion C

FIGURE 15

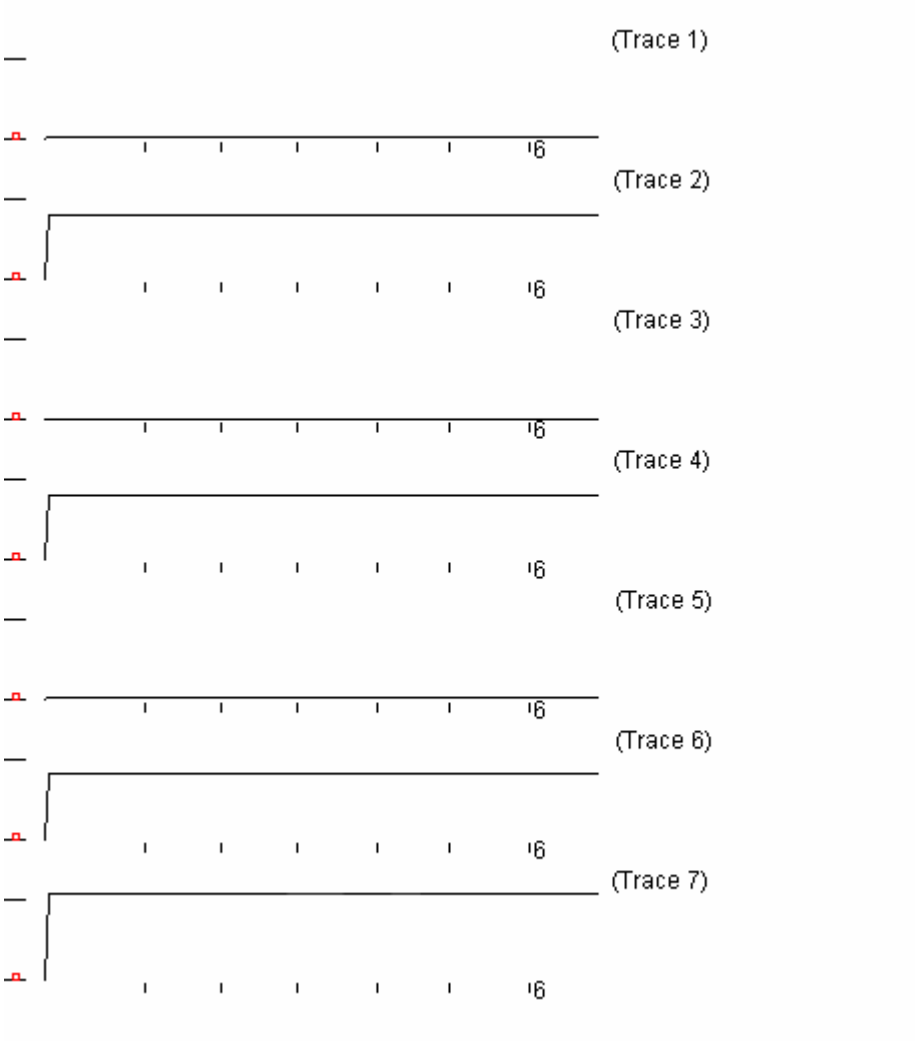

Figure 15. Lesion D

FIGURE 16

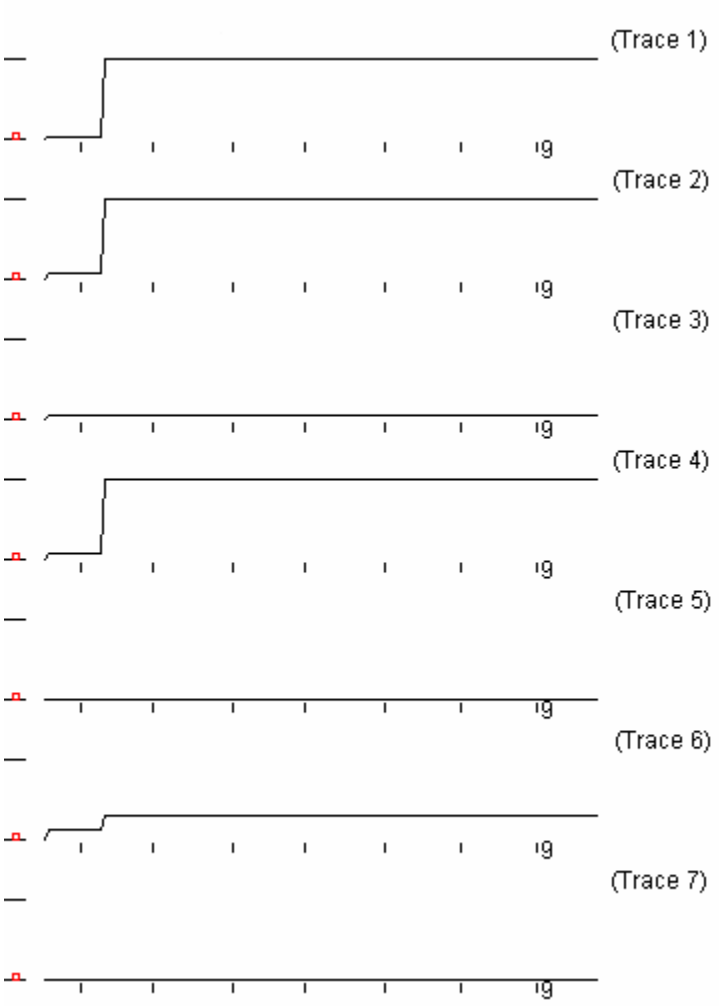

Figure 16. Lesion E