Toward a Robot Model of Attention-Deficit Hyperactivity Disorder (ADHD)*

Christian Balkenius Petra Björne

Lund University Cognitive Science
Kungshuset, Lundagård
S-222 22 Lund, Sweden

1 Introduction

The core deficit in attention deficit/hyperactivity disorder (ADHD) continues to present an enigma to scientists, professionals and parents alike. Medication with methylphenidate has to some extent proven successful, but it is still not known exactly what parts of the deficits in ADHD medication influences. It is thus important to further delineate the nature of ADHD and thoroughly investigate the possible subtypes.

In this paper we describe some experiments investigating the nature of inhibition, resource allocation, sustained and selective attention, distractibility and task switching among children with ADHD. The conclusions could be used to advocate for different models of ADHD, e.g., a model of deficient response inhibition or a model of non-optimal resource allocation.

Below we present our first steps toward a robot model of ADHD. The computational model can reproduce some of the behaviors shown in children with ADHD in experimental situations. The model suggests that a deficiency in a hypothesised context system can explain some of the superficially disconnected problems in ADHD. The computer implementation is a first step toward a robot system that will model a wider range of behaviors in ADHD and potentially other related disorders.

2 Diagnosis

ADHD is a cognitive and behavioral disorder within three areas: inattention, hyperactivity, and impulsivity. To be diagnosed as having ADHD according to DSM-IV (American Psychiatric Association, 1994) the following criteria must be met:

*Originally published as Balkenius, C. & Björne, P. (2001). Toward a Robot Model of Attention-Deficit Hyperactivity Disorder. In Balkenius, C., Zlatev, J., Kozima, H., Dautenhahn, K., and Breazeal, C. (Eds.) *Proceedings of the first international workshop on epigenetic robotics: modeling cognitive development in robotic systems.* Lund University Cognitive Studies, 85.

A. Either (1) or (2):
1. Inattention: at least 6 of the following symptoms of inattention have persisted for at least 6 months to a degree that is maladaptive and inconsistent with developmental level:

(a) often fails to give close attention to details or makes careless mistakes in schoolwork, work, or other activities;

(b) often has difficulty sustaining attention in tasks or play activities;

(c) often does not seem to listen to what is being said to him/her;

(d) often does not follow through on instruction and fails to finish schoolwork, chores, or duties in the workplace (not due to oppositional behaviour or failure to understand instructions);

(e) often has difficulties organising tasks and activities;

(f) often avoids or strongly dislikes tasks (such as schoolwork or homework) that require sustained mental effort;

(g) often looses things necessary for tasks or activities (e.g., school assignments, pencils, books, tools, or toys);

(h) is often easily distracted by extraneous stimuli;

(i) often forgetful in daily activities.

2. Hyperactivity-Impulsivity: at least 4 of the following symptoms of hyperactivity-impulsivity have persisted for at least 6 months to a degree that is maladaptive and inconsistent with developmental level:

Hyperactivity:

(a) often fidgets with hands or feet or squirms in seat;

(b) leaves seat in classroom or in other situations in which remaining seated is expected;

(c) often runs about or climbs excessively in situations where it is inappropriate (in adolescents or adults, may be limited to subjective feelings of restlessness);

(d) often has difficulty playing or engaging in leisure activities quietly.

Impulsivity:

(e) often blurts out answers to questions before the questions have been completed;

(f) often has difficulty waiting in lines or awaiting turn in games or group situations.

B. Some hyperactive-impulsive or inattentive symptoms that caused impairment were present before age 7 years.

C. Symptoms must be present in 2 or more situations (e.g., at school, work, and at home).

D. The disturbance causes clinically significant distress or impairment in social, academic, or occupational functioning.

E. Does not occur exclusively during the course of PDD, Schizophrenia or other Psychotic Disorder, and is not better accounted for by Mood, Anxiety, Dissociative, or Personality Disorder.

3 Experiments

The impairments in ADHD can be assessed in experimental studies. Here, we describe a number of experiments that will form the basis for the computational model presented below. The general strategy is to identify a set of experiments that can be implemented on a robot where there is clear difference in behavior between subject with ADHD and a control group.

3.1 Task-switching

Cepeda et al. (2000) have studied the executive control processes, i.e., selection from long-term memory of configuration in working-memory of appropriate processing algorithms, inhibition of previously used processing algorithms, etc, involved in task set inhibition and preparation to perform a new task. In order to do this, children with ADHD on and off medication and a control group were given tasks requiring a switch in attention. According to the authors, the two main models of ADHD, (i) deficient inhibitory processing and (ii) deficient resource allocation would yield disparate predictions. Thus, the results of the experiments would shed some light as to which model is most likely to be true.

The aim of the first experiment was to test aspects associated with executive control processes such as inhibition of inappropriate task sets and responses, and preparatory processes associated with switching between tasks. On a computer screen the digits 1 or 3 were presented, either alone or in threes. In the first and the second blocks, which both were non-switch blocks, the subjects had to tell either how many digits were presented on the screen, or the value of the digits. In the third task set the task switched every third trial. The current task was indicated above the digits by questions asking for number or value. The reaction time (RT) was measured in both non-switch and switch trials, and switch cost RT would be the switch trial RT minus non-switch trial RT. Furthermore, the performance on compatible and incompatible answers were compared as well.

The results showed that non-switch trials in trial blocks in which switches could occur produced faster reaction times than trials where the children had to switch tasks. RTs were also faster when the answers were compatible than when they were incompatible. Switch costs were higher for the children with ADHD when unmedicated compared to the same children when medicated. This appears to be mainly due to the results on the trials requiring incompatible answers. It seems as if it is more difficult for unmedicated children with ADHD to disengage from one task and switch to another, compared to the same children when medicated and control children. Comparing control children and children with ADHD on medication, results showed that the subjects did not differ in switch costs.

The aim of the second experiment was to investigate if the results from experiment 1 were possible to generalise to the real world, i.e., generalising from a predictable and rather frequent task-switch to a situation in which a task is repeated for some time and then abruptly and unpredictably being switched. The prediction was that the children with ADHD when off medication would be much slower to respond following a task switch than in task continuation, particularly when answers to the two tasks were incompatible, than the same children on medication. The procedure was the same as in experiment 1, except that the task changed unpredictably after 3 to 7 trials and that there were no single-task only trials. The results showed that there were large switch costs on the first trial following a task switch. Performance was faster and more accurate on subsequent trials and the compatibility effect interacts with the magnitude of switch costs, i.e., trials requiring incompatible answers caused larger switch costs. In summary, Cepeda et al. conclude that models arguing for deficits in inhibitory processing to account for the behavioural deficits in ADHD are in accordance with their experimental results, which those models depending on deficient resource allocation or reduced arousal are not. A related test that is used to diagnose prefrontal injury is the Wisconsin Card Sorting Test (WCST). In the test, participants have to find out a rule for sorting cards into piles. The cards are printed with geometrical figures in different colors. When the subjects have sorted ten consecutive cards according to the rule, based on shape, colour or number, defined by the experimenter, the rule is changed. Decreased performance has been found in children with ADHD (Cepeda et al., 2000, Pineda et al., 1999). They show a significant difficulty in inhibiting old responses when the rule has changed. This is often interpreted as an inability to change cognitive set, that is, a predisposition to respond (or not respond) in a certain way to a set of stimuli. It is clear that task-switching is very similar to switching cognitive set.

3.2 Effort allocation during sustained attention

Börger et al. (1999) and Börger and van der Meere (2000) present a model for studying resource allocation or effort allocation during a Go/No-Go test. Children with ADHD without any medication were compared with a normal control group with respect to their motor preparation during a continuous performance test. Subjects were presented with a Go-stimulus, the letter Q, or a No-Go stimulus, the letter O, and were asked to press a button in the case of the Go-stimulus being presented. Stimuli were presented at a slow rate, at an inter-stimulus interval of 6 seconds, and at a fast rate, at an interval of 2 seconds. Although there was no significant difference in the response inhibition between the 2 second and 6 second condition, an earlier study had shown that response inhibition was reduced for a longer inter-stimulus interval of 8 seconds, thus producing more errors.

Heart rate was also measured during the test. Prior to motor activation, subjects generally decelerate their heart rate in anticipation of the Go-stimulus. The greater the deceleration, the faster the responding to the Go-stimulus. This has been seen as a measure of motor preparation and inhibition of irrelevant actions facilitating the intended motor response. After the presentation of the

Go-stimulus, the deceleration of heart rate is followed by acceleration. If, instead, a No-Go stimulus is presented the shift in heart rate is delayed and deceleration continues.

Results of the studies showed that children with ADHD responded more slowly than the control group, particularly during the slow condition. The analysis of heat rate showed no difference between the groups during the fast condition. During the slow condition, however, children with ADHD showed a delayed shift of the inter-beat interval (IBI), from a longer IBI to a shorter IBI. This delayed heart rate acceleration after the presentation of the Go-stimulus indicates a delayed response initiation during the slow stimulus presentation condition. The authors conclude that children with ADHD have a poor readiness to respond, and they particularly have difficulties in keeping prepared at an optimal level over a number of seconds, thus not being able to allocate an optimal degree of effort during a task. According to Börger et al., the core difficulty of ADHD would then be not response inhibition, but poor motor activation and state regulation or effort allocation.

3.3 Inhibitory control deficit

Schachar et al. (2000) have designed an experiment to measure the stop-signal reaction time (SSRT) compared to the reaction time following a Go-stimuli. The SSRT, calculated by subtracting the Stop-stimulus delay from mean reaction time on Go-stimulus, is a measure of a latency of an inhibitory control process independent of reaction time following the Go-stimulus. A deficit in this process is, according to Schachar et al., characteristic of children with ADHD.

In the experiment, children were presented with 2 visual Go-stimuli, either X or O, and an auditory Stopstimulus. The task was to press the correct button corresponding to the letter in the screen as quickly as possible, or not to press any of them in case they heard the Stop-signal. As anticipated, children with ADHD were slower compared to the normal children to stop an ongoing action. Furthermore, the researchers found that children with ADHD had a slower reaction time to the Go-stimuli.

3.4 Selective attention and distractibility

One of the aims of the study done by Brodeur and Pond (2000) was to find out if distraction during tasks was influenced by the nature of the distracting stimuli. Children with ADHD on and off medication and a control group were presented with pictures of different pieces of clothing. If presented with more than one piece of clothing, the target would be the picture in the middle. At the same time as the pictures were shown on a computer screen, the children heard the names of different pieces of clothing through headphones. In some trials the distracting pictures were meaningful, such as presenting the pictures of two shirts together with the target picture of a tie. In other trials the distracters were irrelevant, such as pictures of purses together with the target, a tie. The names being said in the headphones could in the same way be either meaningful or irrelevant. In any case, what was being said in the headphones could always be ignored, since the completion of the task only depended on what was shown on the screen.

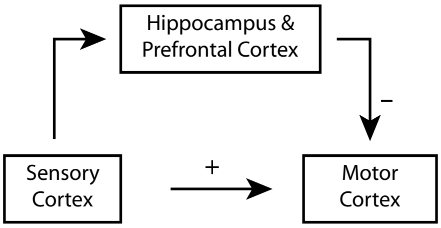

FIGURE 1: *Overview of the brain regions involved in cognitive set and inhibitory control*

The results showed, as in other studies, that the overall reaction time was slower for the children with ADHD. They were also distracted to a greater extent than the control group. As sustained attention develops with age, the children were divided into to groups, aged 6-8 and 9- 11. For both the ADHD and the control group, the younger children were affected more by the visual and visualauditory distracters than by the auditory distracters alone. All children were slower when confronted with distracters, but whereas children in the control group were significantly faster when the distracters were irrelevant than when they were meaningful, the children with ADHD were affected equally by the two kinds of distracters. Children with ADHD on medication were not as easily disrupted by distracters as the same children off medication, but medication did not influence the response pattern as to the meaning of the distracters. The authors conclude that medication seems to improve their staying on the task, but not their processing of visual information or stimulus relations.

3.5 Latent inhibition

Another task where children with ADHD have difficulties is in latent inhibition (Lubow & Josman, 1993). In a latent inhibition experiment, a stimulus is first presented on its own until the subject has habituated to it. The stimulus then starts to predict another event. Learning that the stimulus now predicts another event is quicker in children with ADHD than for a control group. This can be interpreted as an inability to habituate to a neutral stimulus that is repeatedly presented.

4 Neurophysiological correlates

Many of the disabilities in ADHD have been associated with the prefrontal cortex. This includes response inhibition, task-switching, cognitive set, working memory and sustained attention (Fuster, 1997). This suggests that ADHD involves a prefrontal dysfunction. This idea is supported by fMRI studies of persons with ADHD that show a less pronounced activation of the prefrontal cortex in many tasks. This hypofrontality may arise as a result of insufficient activation of the prefrontal structures.

Following Fuster (1997) we assume that the amygdala–medial prefrontal system is responsible for the intensive aspect of sustained attention, i. e., it is responsible for the sustained activation of a goal or a task representation. On the other hand, the lateral prefrontal system is involved in the selective aspect of sustained attention that inibitits reactions to stimuli that are not in the current set. It is primarily this second aspect of prefrontal control of behavior that we will investigate here.

We have argued elsewhere that the hippocampus together with the parts of the prefrontal cortex form a system for contextual modulation of attention and behavior (Balkenius, 2000). This idea is supported by a number of animal studies that show pronounced deficiencies in behavioral inhibition and contextual learning when either the prefrontal cortex or the hippocampus is lesioned (see Balkenius, 2000). Especially interesting is the fact that contextual modulation appears to be mainly inihibitory and that inhibitory learning is connected to the context and not to an individual stimulus (Bouton, 1992).

We would like to propose that in ADHD the contextual modulation of attention and behavior that is believed to be controlled by the prefrontal cortex is reduced. More specifically, we suggest that contextual or working memory representations are harder to activate. Consequently, the effect of cognitive set, such as inhibition of motor responses, will be slower and less pronounced than in normal subjects. Furthermore, we assume that contextual representations are more volatile. As a result, the goal or task representation will fall out of memory rapidly if it is not maintained by an external stimulus. This, we suggest, is the reason for the distractability that is charactersitic of ADHD. Below, we will show that the characteristic of impaired working memory, or set, as well as the slow reaction times in ADHD can be decribed by a single parameter reflecting the passive decay of a memory trace.

5 A computational model

In this section we describe a computational model of the brain regions thought to be responsible for the problems in ADHD. Here we only describe the dynamics during performance of a learned task. We do not consider the actual learning processes. For a description of some of the learning mechanisms involved see Balkenius (2000), Balkenius and Morén (2000) and Morén and Balkenius (2000). The model is formulated in neural network style but we do not claim to model the actual neurons in the areas involved. Instead, the mode should be conceptualized at a functional level.

We assume that stimulus response learning has already occurred in such a way that for each stimulus S_i the appropriate response is R_i. This implies that when stimulus S_i is presented, response R_i will automatically be produced unless it is inhibited in some way. The activation of the response is given by the following equation:

$$\Delta R_i(t) = \alpha(1 - R_i(t))S_i(t) - \beta R_i(t), \quad (1)$$

where S_i is the input signal shunted by the current activity of the node and α describes the activation of α trace and β describes the passive decay of the memory trace. A response is produced when the level or R_i reaches a specified threshold θ.

The activity of the nodes in the contextual system in prefrontal cortex and hippocampus $p_i(t)$ are described by a similar equation,

$$\Delta c_i(t) = \alpha(1 - c_i(t))S_i(t) - \beta c_i(t) - \gamma c_i(t) \sum_{j \neq i} S_j(t). \quad (2)$$

The last term describes a feed-forward inhibition that is responsible for a competition between different context representations. In the simplified model described here, a context is identical to a stimulus. A more advanced version of this model is described in Balkenius and Morén (2000) where a context depends on all the stimuli available in a situation. The context system inhibits associations from stimulus to response through a matrix M. Incorporating this into equation (1) we get:

$$\Delta R_i(t) = \alpha(1 - R_i(t))S_i(t) - \beta Ri(t) - \delta R_i(t)c_i M_{ji}. \tag{3}$$

M can be interpreted as the cognitive set corresponding to a certain contextual representation. Using this model we can code all the experiments described in the previous section by using different matrices M. To simplify the equations, we have assumed that several responses R_i can produce the same behavior.

6 Computer simulations

6.1 Slow reaction time

The slow reaction time of people with ADHD can be simulated by changing the value of either α or β in the equations above. A lower value on α or a higher β will result in longer reaction times (figure 2).

6.2 The stop-signal task

The delayed effect of a stop signal in the model is a result of the same parameter that makes reaction time slower in the ADHD case. Since the contextual representation is activated more slowly, inhibition will arrive at the motor system later. The stop-signal task was simulated with different parameters for the hippocampal–prefrontal α. With an α at 0.2 the maximal delay before the stop signal from the initial stimulus was 7 simulation steps, while for the ADHD condition with $\alpha = 0.15$ the maximal delay was 4 simulation steps. This is consistent with the idea that the inhibitory processing loop is slower in ADHD. The parameters in the other equations were held constant.

6.3 The Go/No-Go task

Börger and van der Meere (2000) reported normal error rates in a Go/No-Go task with inter-stimulus intervals of 2 and 6 seconds. At an 8 second ISI, however, responses were not as accurate. We interpret this as a discrimination task where the subjects have to discriminate between the Go stimulus Q and the No-Go stimulus O. When the ISI is shorter, the contextual representation needed to inhibit the generalized response to the No-Go stimulus is retained in the prefrontal system. When the ISI is longer, the context is not maintained between trials and the response inhibition arrives too late. The explanation for the errors with long ISI is thus similar to the explanation for the failure to respond to a stop signal as described above.

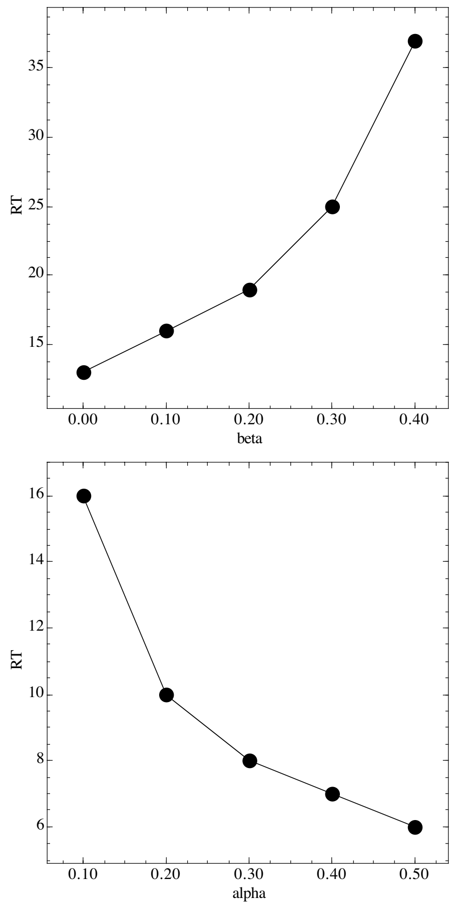

FIGURE 2: *Reaction time (in simulation steps) as function of α and β. Top: α=0.1, β is changed. Bottom: β=0.1, α is changed.*

6.4 Task-switching

The task switching task is perhaps the most interesting in the light of the present model. In this task there are two contexts that each determines the response selection for each task. When the same task is repeated the contextual representation is the same and so is the inhibition of the incorrect responses. When the task changes, a new contextual representation must be activated and this process is slower in persons with ADHD. As a consequence, incorrect behavior is selected immediately after each task-switch and it will take longer before the behavior changes. Figure 4 shows the task representation in the model.

In figure 5, the activation of the two contexts corresponding to the what number and how many tasks are shown over time for the ADHD condition. As can be seen, it takes several trials before the context switches.

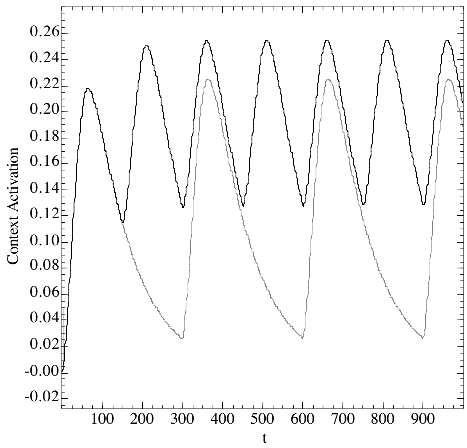

FIGURE 3: *A computer simulation of the Go/No-Go task. The graph shows the activation of the context-node used for discrimination between the Go and No-Go stimulus for long (dotted) and short (black). For the long ISI the context does not become sufficiently activated and discrimination becomes impossible.*

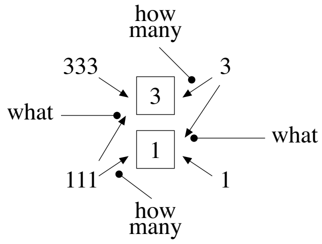

FIGURE 4: *The representation of the task-switching experiment. 333, 111, 3, and 1 are stimuli while "how many" and "what" are contexts. The context modulates the stimulus-response connections between stimuli and responses 3 and 1. This corresponds to the matrix M in equation 3.*

6.5 Latent inhibition

We have also simulated latent inhibition with the model (Lubow and Josman, 1993). The result of this simulation is similar to the simulation of habituation after prefrontal lesion presented in Balkenius (2000). In the ADHD condition, the contextual representation is less active and learning to inhibit responses thus becomes harder.

6.6 Discussion

The presented model is still in a very early form. Although it reproduces some of the experimental results of studies of persons with ADHD, there are many refinements that can be made. An important next step will be to set the parameters in such a way that the experiments are modeled in a quantitative way. In the simulations reported above, only qualitative results were obtained. Another development of the model will be to implement it on a robot with a visual system. By doing so it will become possible to test the model in a more realis-

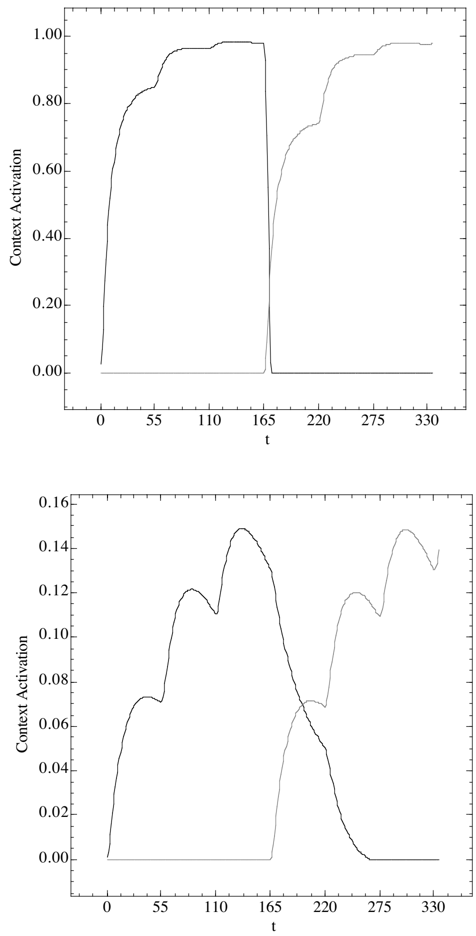

FIGURE 5: *A simulation of task-switching in the control (top) and ADHD condition (bottom). Each trial was 55 time steps.*

tic setting in a real-world situation to overcome the limitations of a simulated environment.

Despite these shortcomings the model makes a number of prediction that can be tested experimentally. It predicts that working memory in the form of context-memory is impaired in persons with ADHD, which influences the ability to sustain and switch cognitive set.

We have not yet simulated the selective attention task described above. A possible, though speculative, explanation for the effect of distracters can be given in the light of the present model. If we assume that sustained attention depends on the ability to inhibit reactions to stimuli that are not relevant to the current situation, then this would depend on an accurate contextual representation. If such representations are hard to activate in persons with ADHD, it would result in a less developed ability to select relevant stimuli. Although methylphenidate makes the activation of contextual representations easier, this does not help if the relevant stimuli in each context has not already been learned. We predict that with prolonged medication distactability will become increasingly context dependent. The model also predicts that the behavior in the task-switching task should depend on the inter-trail length.

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