A computational model for the effect of dopamine on action selection during Stroop test

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Abstract. Based on a connectionist model of cortex-basal ganglia-thalamus loop recently proposed by authors a simple connectionist model realizing the Stroop effect is established. The connectionist model of cortex-basal ganglia-thalamus loop is a nonlinear dynamical system and the model is not only capable of revealing the action selection property of basal ganglia but also is capable of modelling the effect of dopamine on action selection. While the interpretation of action selection function is based on solutions of nonlinear dynamical system, the effect of dopamine is modelled by a parameter. The effect of dopamine in inhibiting the habitual behaviour corresponding to word reading in Stroop test and letting the novel one occur corresponding to colour naming is investigated using the model established in this work.

1 Introduction

Computational modelling of cognitive processes began to attract more attention as benefits of these models in different disciplines are recognized [1-3]. There are different approaches in computational modelling, while some consider the problem of modelling at cell level and develop models considering biophysics, others, as those using symbolic AI techniques, intend to model only behaviours. There are other models not as complex as realistic models of cell level and not as far away from the neural validity as symbolic AI techniques; these focuses not only on how to get a system behaving as expected, but also aims to use the model in understanding the ongoing processes. These are models at behavioural level and while developing these models neural substrates related with the involved behaviour and their interrelations have to be considered. Thus these models are capable of explaining how the neural substrates provoke the behaviour without dealing with structures at physiological level [2, 4, 5].

Modelling at behavioural level is not only beneficial at explaining the whys' of cognitive processes but also is capable in providing tools for investigating the reasons behind the abnormal behaviour. This characteristic of behavioural models makes them especially important in pharmacological studies. As animal models are not sufficient, and these models provide more flexible applications they are advantageous over models used nowadays in pharmacology [6]. Still another advantage of behavioural mod-

els is they can be used in engineering applications as designing robots and intelligent systems [3].

In this work behavioural approach in modelling will be considered, and previously proposed model [7] of cortex-basal ganglia-thalamus (C-BG-TH) loop for action selection will be expanded to model the Stroop task. As the model of C-BG-TH loop is capable of explaining the effect of neurotransmitter on action selection, the expansion of this model will also exploit the effect of dopamine on Stroop task.

First computational model for C-BG-TH loop will be reviewed, then expanded model of C-BG-TH loop will be established and the effect of dopamine on Stroop effect will be shown. The simulation results will reveal the effect of dysfunctioning dopamine system on action selection. On the last section, the model will be discussed considering the other similar models given in the literature.

2 Computational Model for Cortex-Basal Ganglia-Thalamus Loop

The basal ganglia once known for their role in motor movement control, now are also considered for their part in high order cognitive processes and motivation related acts as temporal sequence storage and generation, behavioural switching, reward evaluation, goal-directed behaviour, reinforcement learning. These behavioural functions are possible only through the interrelations of basal ganglia with cortex and thalamus and these interrelations have been investigated in [8] by means of five basal ganglia-thalamocortical circuits, which are responsible for generating different behavioural functions. Different substructures of cortex, basal ganglia, thalamus take part in each of these circuits. On the other hand dopamine systems as mesolimbic, mesocortical and nigrostriatal systems provide regulation of information transfer through these neural circuits [9] and dysfunctions of these dopamine systems cause deficits in behavioural functions. To obtain a biologically plausible computational model of basal ganglia revealing modulating effect of dopamine, the interrelations of basal ganglia with related neural structures as cortex and thalamus has to be considered. These interrelations are considered keeping in mind that our intention is to focus on a specific cognitive process, action selection, rather than modelling all aspects of basal ganglia-thalamocortical circuits described in [8] and the model obtained will be a behavioural one.

In this section, first a simple neural structure of C-BG-TH loop will be investigated and a mathematical model of this structure will be restated. This model was inspired from [5] and proposed previously in [7]. Then how this mathematical model is used for modelling action selection will be introduced. The modification of the mathematical model for action selection was again previously given in [7] and it was inspired from [4].

2.1 Neural Substrates and Related Mathematical Model

As a cognitive process, it has been expressed that action selection is a major function of basal ganglia and is crucial in understanding human behaviour [4]. Action selec-

tion, like other cognitive processes, is initiated at cortex, where anterior cingulate system responsible for attention takes part in generating a salience signal which initiates the action selection process. Action is also terminated at cortex when the motor circuits trigger action. The salience signal causes an activation in basal ganglia, which then via thalamus initiates in cortex relevant structures for action. Thus a feedback structure, which incorporates cortex, basal ganglia and thalamus, is necessary and so a loop composed of cortex, basal ganglia and thalamus is formed. This feedback structure can be expressed as a non-linear dynamical system. The equations of the non-linear dynamical system corresponding to basic connections of cortex, basal ganglia and thalamus besides the connections within basal ganglia, which are shown in Fig. 1, are given in Eq. 1.

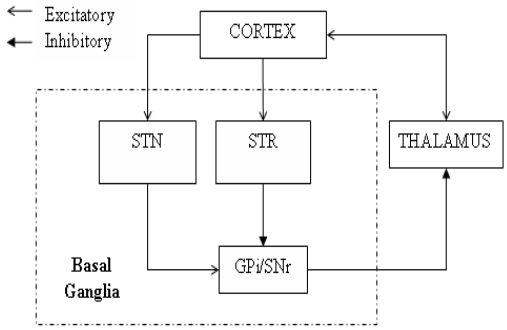

Fig. 1. Cortex-basal ganglia-thalamus (C-BG-TH) loop

$$\begin{aligned} p(k+1) &= \lambda \cdot p(k) + f(m(k)) \\ m(k+1) &= f(p(k)) - f(d(k)) \\ r(k+1) &= g(p(k), \theta_{att}) \\ n(k+1) &= f(p(k)) \\ d(k+1) &= -g(r(k), \theta_{sel}) + f(n(k)) \end{aligned} \tag{1}$$

In Eq. 1 $g(x,\theta) = 0.5 \cdot (1+\tanh(3 \cdot (x+\theta-1.5)))$ and $f(x) = g(x,1)$. θ_{att} stands for the effect of attention and is set to "1" throughout this section. The subsystem given by the Eq. (1) is rewritten in compact form as follows:

$$\Sigma_1: \ \mathbf{x}(k+1) = \mathbf{F}(\mathbf{x}(k), \theta_{att}, \theta_{sel}). \tag{2}$$

Striatum and subthalamic nucleus (STN) are initiated by cortex with excitatory glutamatergic projections, these are the inputs of basal ganglia and main outputs are globus pallidus internia (GP_i) and substantia nigra pars reticulata (SN_r). The output structures then project inhibitory GABAergic projections to thalamus. Thalamus completes the loop by excitatory glutamatergic projections to cortex. All these connections are exploited in Eq. 1, where cortex, thalamus and the substructures in BG, namely, STR, STN and GPi/SNr are denoted by $p(k)$, $m(k)$, $r(k)$, $n(k)$, and $d(k)$, respectively. While

mainly GABAergic and glutamatergic projections convey this information transfer, dopamine modulates this process [10] and in Eq. 1 the parameter θ_{sel} represents the effect of dopamine while the inhibitory and excitatory effects of GABAergic and glutamatergic projections are denoted by negative and positive coefficients in the matrix.

Even though two pathways exist in C-BG-TH loop, only the one named "direct pathway" is considered in Figure 1 as for the modelling purpose of this work the role of basal ganglia can be expressed through this simple structure [8]. In this model, as can be followed from Eq. 1 each substructure is modelled by a single variable. These variables can be thought to denote a group of neurons that take part during the process. It is shown in [7] that this basic model of C-BG-TH loop is capable of originating two stable fixed points. These two fixed points are named "active" and "passive" points and they are interpreted as an action took place or did not take place, respectively. The attraction domains and how they depend on parameter θ_{sel}, so on neurotransmitter dopamine, are investigated in [7].

2.2 Computational Model for Action Selection

Action selection depends on competition; to construct this competition using the C-BG-TH loop model given by system Σ_1 coupling of Σ_1 systems is needed. Each Σ_1 system will correspond to a competing action. The coupling done is biologically plausible, as diffusive, excitatory connections from STN to GPi/SNr, which have disinhibition effect on the other loops as an overall effect, are used as shown in Fig. 2. The model for action selection is obtained connecting two Σ_1 subsystems as given in Eq. 3.

$$\Sigma_2: \begin{aligned} \mathbf{x_1}(k+1) &= \mathbf{F}(\mathbf{x_1}(k), \theta_{att}, \theta_{sel}) + \mathbf{G}(\mathbf{x_2}(k)) \\ \mathbf{x_2}(k+1) &= \mathbf{F}(\mathbf{x_2}(k), \theta_{att}, \theta_{sel}) + \mathbf{G}(\mathbf{x_1}(k)) \end{aligned} \quad . \tag{3}$$

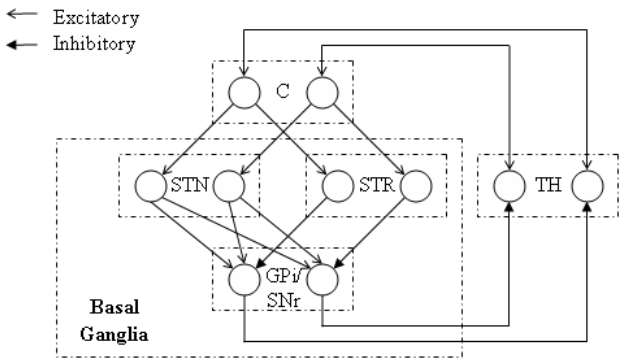

Fig. 2. Model for action selection

Here, coupling function is $\mathbf{G}(\boldsymbol{x}) = (0\ 0\ 0\ 0\ f(x_4)/2)^T$ and stands for the abovementioned connection between Σ_1 subsystems. Due to coupling two loops, the maximum number of the fixed points increases from two to four as shown in Fig. 3. These fixed points are denoted by x_1^*, x_2^*, x_3^* and x_4^* and these respectively correspond to the following behaviours: both subsystems are passive, only first subsystem is active, only second subsystem is active and both subsystems are active.

Attraction domains of the fixed points are named A for x_1^*, B for x_2^*, C for x_3^* and D for x_4^* and they are illustrated in Fig. 3. For different initial conditions the system Σ_2 converges to different fixed points. For example, if the initial condition is $p_1 = 0.5$, $p_2 = 1$, it converges to x_3^*. Thus the second action is selected. If the initial state of the system is in region A or D, the system cannot discriminate competing actions. In the first case none of the actions and in the second case both actions are generated. If there exist all of these regions A, B, C and D like in Fig. 3, the system cannot be considered suitable for action selection. In order to realize action selection properly, Σ_2 should have larger domains of type B and C. For some values of parameter θ_{sel} this objective can be fulfilled [7]. The system with such parameter value is regarded as exploiting normal action selection behaviour, whereas occurrence of the region D and enlarging of the domain A correspond to abnormalities in action selection. These abnormalities occur due to dopamine level. Dopamine excess/depletion causes both competing subsystems to get activated/inhibited for a large area of initial conditions. Thus action selection fails for these salience values.

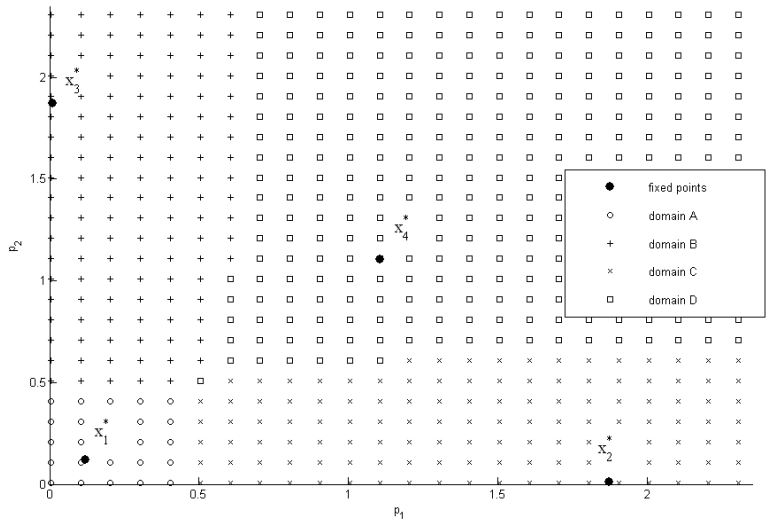

Fig. 3. Attraction domains of Σ_2 for $\theta_{sel} = 1.05$

3 The Effect of Dopamine on Stroop Test

Stroop test is mostly used as a measure of selective attention. During the test the subjects has to inhibit word reading tendency, which is an automatic process so fast and do not require attention and follow the novel task of colour naming, which is a controlled process, slow and requires attention [2]. So, while word reading process takes less time, colour naming takes prolonged time as some time is used for inhibiting the habitual behaviour. Since Stroop test is considered as a measure of focused attention, dysfunction of attentional system, i.e., anterior cingulate system is investigated in most computational models [2, 11]. Unlike previous works, in this work, effect of nigrostriatal dopamine system on Stroop test rather than mesocortical dopamine system will be investigated. This investigation has a value since behavioural consequences of nigrostriatal dopamine system in case of occurrence of salient stimuli has also been investigated [12].

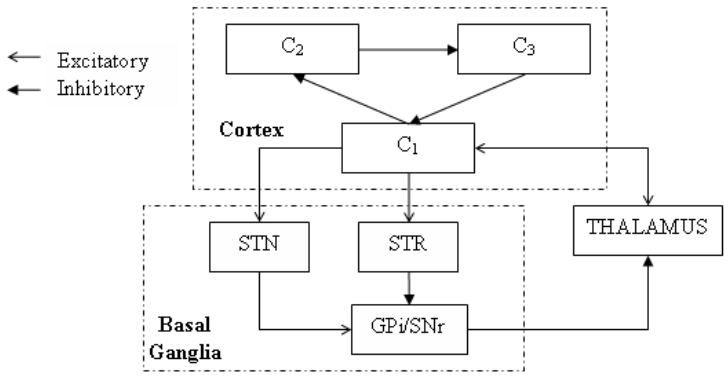

Fig. 4. Proposed model for stroop test

In order to obtain a model to investigate the effect of dopamine on Stroop test, besides the coupled C-BG-TH loops for action selection another loop, which is composed of simple representations of neural substrates responsible for attention and error detection is needed. Two structures, one the coupled C-BG-TH loops for action selection, the other cortico-cortico (C_1-C_2-C_3) loop for attention and error detection are used together but with different time scales. The model of coupled C-BG-TH loops given by system Σ_2 is utilised in this new structure after some modifications as shown in Fig. 4. To favour habit, one of the coupled loops in Σ_2, which is supposed to correspond to word reading task, is strengthened by changing weight of the connection from C to STR as "2", while the loop for novel task, i.e., colour naming remains same. This change of connection alters the attraction domains of Σ_2. Even for some initial values with large colour naming component, the word reading loop can win.

The error detector (C_2) and the attention block (C_3) are used to provide the inhibition of the habitual action and to support the generation of the task related action,

respectively. C_1 represents the part of cortex being in connection with other structures like BG and TH. The equations of C_1-C_2-C_3 loop are given as follows:

$$
\begin{aligned}
c_2(k) &= \begin{cases} t - f(c_1(k-5)) & , \quad k = 10,20,30,\ldots \\ c_2(k-1) & , \quad other \end{cases} \\
c_3(k) &= \begin{cases} A \cdot f(c_2(k-1)) & , \quad k = 11,21,31,\ldots \\ c_3(k-1) & , \quad other \end{cases} \\
\theta_{att}(k) &= \begin{cases} \theta_{att}(k-1) + 0.1 \cdot c_3(k-1) \cdot \left(2 - \min\left(\left| \theta_{att}(k-1) - \begin{pmatrix} 1 \\ 1 \end{pmatrix} \right| \right) \right) & , \quad k = 12,22,32,\ldots \\ \theta_{att}(k-1) & , \quad other \end{cases}
\end{aligned}
\tag{4}
$$

In Eq. 4, t represents the input for task and set to $(0\ 1)^T$ for colour naming task. The matrix A is a two by two matrix with "1"'s in diagonal, "-1"'s in other entries; its role is to realize both suppression of habitual behaviour and to drive attention to novel one. The initial values are taken as very small random numbers. These two loops, namely C-BG-TH and C_1-C_2-C_3, are combined at C_1 which corresponds to the variable p in Eq. 1, so c_1 is composed of p_1 and p_2. The nigrostriatal dopamine level is simulated by changing the parameter θ_{sel} in C-BG-TH loop. The activation of two cells in C1 corresponding to word reading and color naming salience signals are shown in Fig. 5 for a normal dopamine level. The activation of the task-irrelevant loop at the first time steps vanishes after a while and the task-relevant loop takes action. This result fits the phenomena called Stroop effect. To investigate the effect of θ_{sel} simulation results are shown in Table 1. These simulation results are obtained using the following criteria: If the value of a signal is greater than one plus the other's value during 100 time steps and during the following 100 steps it's value is never less than the other's value minus one, then the action corresponding to this signal is regarded to be generated at the end of this 200 time steps.

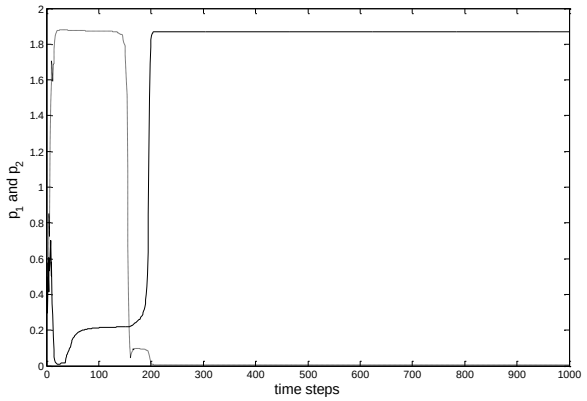

Fig. 5. Simulation result for normal dopamine level (θsel =1). Dotted line shows the activation of p_1 that corresponds to C_1 activation of word reading loop. Solid line shows the activation of p_2 that corresponds to C_1 activation of colour naming loop

Table 1. Simulation results for different θ_{sel} values

	Dopamine Level (θ_{sel})	Error	Time of the correct response
Dopamine excess ↑	2	no	> 30000
	1.6	no	1396
	1.4	no	1261
	1.2	no	1129
	1	no	396
Dopamine depletion ↓	0.8	no	390
	0.6	yes	405
	0.55	yes	440
	0.5	yes	> 30000

In the case of dopamine excess C-BG-TH loops let both actions get activated during the first time steps. As a result, error at C_2 is less than the error in the case when C-BG-TH loop select the habitual one. This slows down the correction process, i.e. the work of C_1-C_2-C_3 loops. On the other hand, the effect of dopamine depletion is mainly on errors rather than on the prolonged time used for correction. In this case C_1-C_2-C_3 loops work well but the activation of the task-related action occurs late because of the low dopamine level. This causes an error according to our abovementioned criteria.

Dopamine excess corresponds to dysfunction of BG where the subject can not suppress irrelevant action and dopamine depletion corresponds to the case where subject can not perform the action, due to akinesia.

4 Discussion and Conclusion

Quite a number of computational models of basal ganglia, which evaluate the neural substrates and related neurotransmitter systems responsible for the interested behaviour have been developed [4, 5, 7]. There are also connectionist models, exploring the effect of mesocortical dopamine system on frontal cortex following similar approach [2,13] and amongst these [2] considers Stroop task. The objective of this work is to develop a connectionist model to investigate the role of basal ganglia during Stroop task. Computational models investigating cognitive behaviour during Stroop task focuses on the dysfunction of attentional system and error detection system as Stroop task is well known as measure of selective attention. However, in this work, it is proposed that dysfunctioning of modulatory nigrostriatal dopamine system can impair the action selection property of basal ganglia and it shown by simulation results that this effects the performance of subjects during Stroop task.

In action network of Taylor & Taylor [5], the motivation is to propose a model of C-BG-TH-C especially to model the temporal sequence storage and generation process, which takes part in working memory tasks. Their model is a non-linear dynamical system, where a parameter denotes the effect of dopamine. In their model, excess

of dopamine corresponds to dynamical system solutions ending at only one high valued stable fixed point, which is proposed to correspond to Huntington disease case. When the parameter is changed and the case corresponds to dopamine depletion, the dynamical system solutions again attracted by a single stable fixed point but with low value and this case is interpreted as Parkinson disease as the low value of fixed point refers to case with no activation. Another value of the parameter corresponds to normal level of dopamine and in this case there exists two different stable fixed points, one with low value denoting no activation the other with high value denoting activation, so there is always the possibility of activation or no activation. In [7], while proposing a model for action selection property of C-BG-TH loop the mathematical model was inspired from [5]. So the interpretations of the solutions of the model in [7] have the similar properties as Taylor & Taylor's but this model is capable of action selection.

In [4] a model of C-BG-TH loop is given for action selection and the effect of dopamine is investigated by changing the weight of connections. Control and selection loops instead of direct and indirect pathways are utilized for action selection. They also interpreted their results considering dopamine depletion and excess in relation with Parkinson's disease and Huntington's disease, and discussed that dopamine depletion gives rise to failure in selection and dopamine excess causes inability in ignoring distractors. The competition mechanism of [4], that is the use of diffusive connections from STN to GPi/SNr, is utilized in [7].

One another work that has to be mentioned is the work of Servan-Schreiber [2]. This work focuses on mesocorical dopaminergic system, but they have not concerned with C-BG-TH loop. They are more concerned with attention than action selection in Stroop test as most work deal.

In this work, a recently proposed model [7] exploiting the action selection property of basal ganglia is utilized in a newly proposed neural structure where cortico-cortico loop is considered along with C-BG-TH loop. Even though the model of C-BG-TH loop is inspired from [4, 5], it is simpler than [4] and still able to model action selection.

The effect of dopamine is modeled similar to [5] and the simulation results obtained are consistent with the observed relationship between dopamine excess/depletion and behaviour. The investigation of basal ganglia dysfunction on Stroop test is valuable since the effect of nigrostriatal dopamine systems on behaviour other than motor actions are also investigated [12].

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