Assessing the need for biological plausibility in cognitive modelling: a focus on basal ganglia without segregated pathways

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Abstract

Both old and new anatomical findings challenge mainstream theory of the basal ganglia circuitry and of how this structure performs action selection. A new biologically plausible model of basal ganglia takes into account these findings. Here I propose to compare this model with a simpler one which is in accordance with the mainstream theory. Both models will be used within an existing cognitive architecture to perform a well-known naturalistic task, the Tower of Hanoi, and be evaluated according to behavioural data from human studies. I believe it will be a good way to assess the functional performance of both models and the need for biological plausibility in cognitive modelling. The cognitive architecture will also provide a good framework for studying the relations between basal ganglia, high level cognition and movement disorders like Parkinson's disease.

Keywords: Computational neuroscience, Cognitive modelling, Basal ganglia, Parkinson's disease

1. Project description

Drawing inspiration from neuroscience has led to great progresses in artificial intelligence (AI). However, it is not yet clear to what extent biological plausibility is needed for human-level AI. Basal ganglia (BG) have been studied extensively and can serve as a case study to assess the need for biological plausibility. These brain nuclei have been modelled at different scales and with various levels of complexity. In Section 1.1.1, the traditional theory of how BG work will be presented and criticised, with neuroscientific studies suggesting that this theory is too simplistic. A BG model in accordance with the traditional theory has previously been implemented within cognitive architectures to perform naturalistic tasks. Comparing the ability of the cognitive architectures to reproduce human behavioural data when using this model, along with a more detailed one, can shed light on the trade-off between complexity and performance. This project can also be derived as a general method for evaluating computational theories and models. Furthermore, the detailed model described in Section 1.1.2 can be simulated in Parkinsonian conditions. Hence, it could be used to study the impact of the disease on behaviour. Societal, technical and scientific relevance of this project will be discussed in more details in Section 3.

1.1. Background

1.1.1. Basal ganglia

Basal ganglia (BG) form a brain structure thought to be fundamental for learning and decision processes. These strongly interconnected subcortical nuclei are often assumed to perform action selection modulated by reinforcement learning. Their dysfunction results in a wide range of motor impairments such as Parkinson's disease.

An old but still very popular box-and-arrow model of BG, the aim of which was to explain these disorders, was proposed by Albin et al. [2]. In the motor areas of the cortex and in the BG, each motor command is represented as a discrete channel of neurons. With their model, Albin et al. [2] argue that BG are divided into a direct and an indirect pathway and that motor disorders result from an imbalance of the activity of these pathways. The direct pathway is commonly referred to as the facilitating pathway as it results in the selection of the action corresponding to the channel whose direct pathway is activated (i.e. results in the excitation of the corresponding neurons in the motor cortex). Conversely, the indirect pathway results in the inhibition of the competing motor commands in the cortex. In the striatum, medium spiny neurons (MSN) of the direct pathway target the internal globus pallidus (GPi) and express D1 dopamine receptor. MSN of the indirect pathway target the external globus pallidus (GPe) and express D2 receptor (see the solid lines in Figure 1).

Abbreviations used in the text

AI: Artificial intelligence
BG: Basal ganglia
MSN: Medium spiny neurons
GPi: Internal globus pallidus
GPe: External globus pallidus

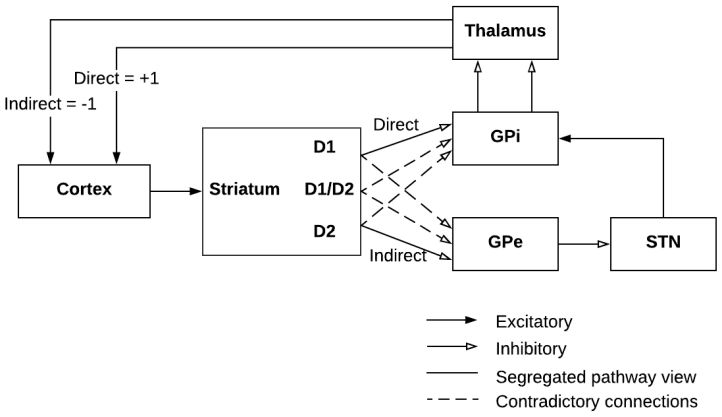

Figure 1: Direct and indirect pathways (solid lines) and contradictory connections (dashed lines). D1, D2 and D1/D2 refer to MSN populations of the striatum that express D1, D2 or both D1 and D2 dopamine receptor respectively. In the traditional view (solid lines), channels with D1 as most active MSN subpopulation receive a positive feedback via the direct pathway (+1). Channels with D2 as most active MSN receive a negative feedback via the indirect pathway which includes the STN (-1).

However, several findings suggest that the simple view in which the direct and indirect pathways are perfectly segregated is an over-simplification of the primates' and rats' BG connectivity. Almost every MSN projects to both GPi and GPe in primates [16, 12] and rats [11, 24]. Furthermore, up to 60% of MSN express both D1 and D2 dopamine receptors [3, 15, 1]. Figure 1 (dashed lines), summarises these findings that contradict the segregation view.

1.1.2. Biologically constrained model of basal ganglia

Liénard and Girard [13] have recently proposed a biologically constrained model of the primates' BG which takes into account the data that contradict the segregation view, as well as other anatomical and electrophysiological data. The parameters that are pretty well known, such as the number of neurons, the maximal discharge rates, or the axonal delays, were considered as fixed parameters. The other parameters such as the mean axonal varicosity counts, or the difference between the resting and threshold potential for each population, were optimized according to the fit of the models with available anatomical data, and with in vivo electrophysiological experiments. After optimisation, the authors found 15 solutions (i.e. configurations of the model) that matched their constraints. The overall architecture of the model is shown in Figure 2 (right).

The model can exhibit emergent action selection properties [13] and plausible Parkinson-like dynamics [14] although it was not optimized for these purposes. Even more recently, the model has been implemented with spiking neurons by Girard et al. [8]. When it is simulated in Parkinsonian conditions, this implementation exhibits dynamics that are less stereotypical than those exhibited with the non-spiking model [5, 9].

1.1.3. Nengo

Nengo is a software tool that can be used to simulate large-scale neural models. Its aim is to bridge the gap between low-level biological details and high-level modelling of cognitive functions such as sensory processing, memory formation, reasoning, and motor control [4]. Nengo has been used to implement Spaun, a model of multiple brain areas capable of performing eight different tasks[1] [19]. Spaun, among other projects developed with Nengo, make extensive use of BG as a program sequencer.

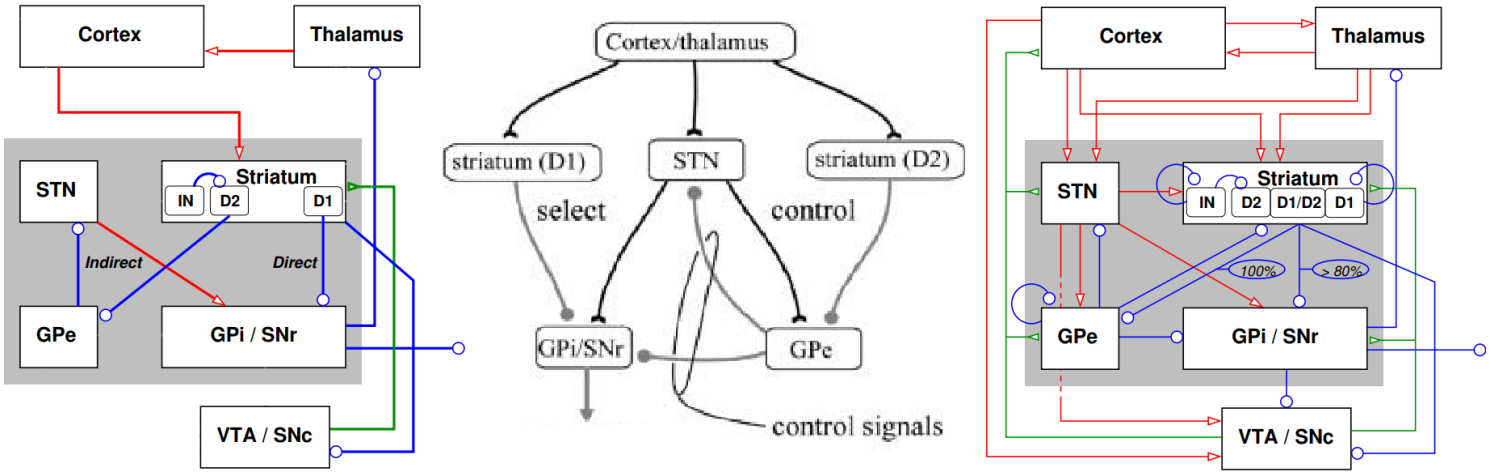

Figure 2: Comparison of the architecture of three models: the canonical model proposed by Albin et al. [2] (left), the model of Gurney et al. [10] on which Nengo's default action selection module is based upon (center), and the most biologically accurate model proposed by Liénard and Girard [13] which does not include segregated pathways (right). Adapted from [9] and [10].

[1]Description and examples for each task are available on `https://xchoo.github.io/spaun2.0/videos.html`

All of the projects that use a BG [6, 20, 19, 21, 18] used a spiking implementation of the model described by Gurney et al. [10] which includes segregated pathways. An explicit reference to the canonical model of Albin et al. [2] is made in the supplementary material of the report of Spaun [7]. As detailed above, these models inaccurately describe primates' and rats' BG. In his thesis, Tripp [22] does mention the results of Aizman et al. [1], Lévesque and Parent [12] while discussing the limitations of Albin et al. [2] but does not take them into account later in his work with Nengo. Aside from the segregation of projections of the striatum, the models of Albin et al. [2] and Gurney et al. [10] omit a lot of connections captured by the model of Liénard and Girard [13] (see Figure 2 for a comparison).

1.1.4. Cognitive architecture of the Tower of Hanoi task

Stewart and Eliasmith [21] have developed a neural cognitive architecture capable of solving arbitrary Tower of Hanoi problems in a human-like way in Nengo. This task involves three pegs and a fixed number of disks of different sizes. A disk can be moved from the top of a peg to the top of another peg if there is not a smaller disk in the new peg. Given an initial configuration, the goal is to move the disks to a goal configuration (typically, to move all disks from one peg to another). Figure 3 shows the optimal series of steps needed to solve the four-disk Tower of Hanoi when all disks start on one peg and have to be moved onto a different peg. Non-neural symbolic cognitive models of this task already exist and match empirical data extremely well. However, the neural cognitive architecture developed by Stewart and Eliasmith [21] also provides insights on how this task can be solved with spiking neurons and an architecture inspired by the human brain.

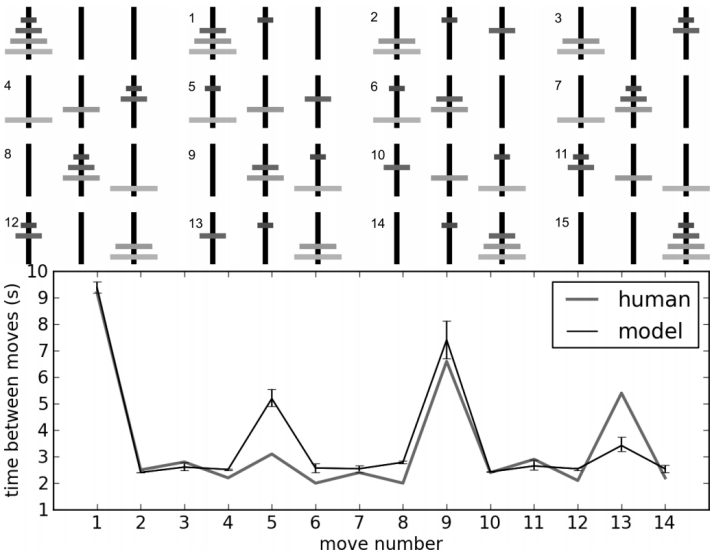

Figure 3: The sequence of moves to ideally solve the fourdisk Tower of Hanoi (top). Time delay for expert human performance and the neural model (bottom). Taken from [21].

The cognitive architecture is composed of cortical states, an action selection module based on the BG model proposed by Gurney et al. [10], a thalamus, a motor output and a visual input (see Figure 4). There is only one free parameter, namely the synaptic connection weights of the input to the short-term memory which controls how quickly the memory will store new inputs and forget old information. Nevertheless, the model is able to successfully solve the Tower of Hanoi, given any initial/goal configuration. The time delay at each move were compared with expert human players (see Figure 3).

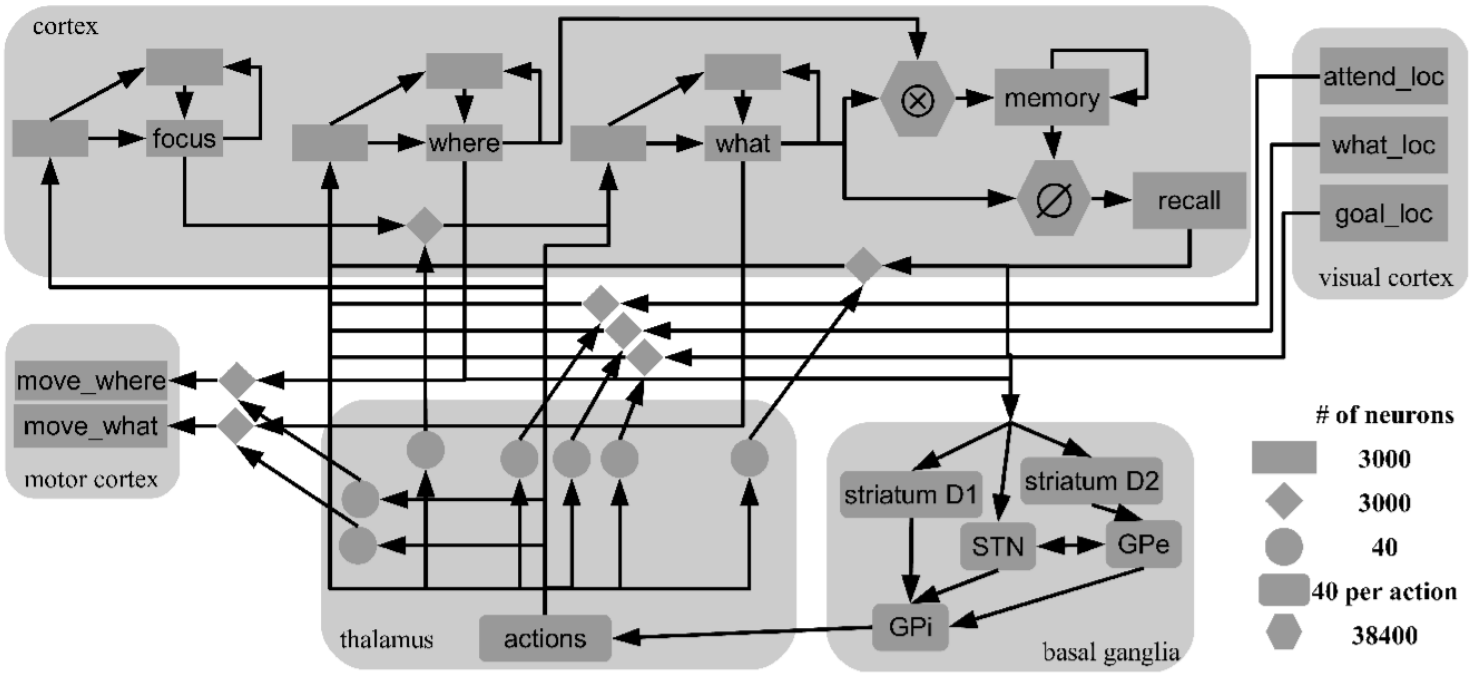

Figure 4: The Tower of Hanoi model. Total # neurons: 150,640. Taken from [21].

1.2. Aim of the project

During this project, the new model of BG described in section 1.1.2 will be used as a replacement of the action selection module of the Tower of Hanoi cognitive architecture. Action selection properties of BG models are usually tested with dummy inputs that do not explicitly represent a command, making the results hard to interpret. The Tower of Hanoi architecture provides the opportunity to assess the functional performance of models in a naturalistic context with a meaningful task. It is possible to directly compare the motor output of the architecture with the results of behavioural studies implying the Tower of Hanoi task. Stewart and Eliasmith [21] used the delay between moves to evaluate the plausibility of their model's behaviour (see Figure 3). One can hypothesise that a more biologically detailed action selection module like the biologically constrained model of Liénard and Girard [13] will improve the human-likeliness of the architecture, and better fit these behavioural data.

Furthermore, the Tower of Hanoi cognitive architecture will serve as a framework to study the relations between high-level cognition and Parkinson's disease, characterised by dopamine depletion leading to beta-oscillations in BG. The Tower of Hanoi is widely used as a test of planning and problem solving abilities. It is therefore used for studying the impact of Parkinson's disease on planning and executive function (e.g. [17, 23]). It will be interesting to compare the ability of the architecture to reproduce known pathological behaviours with both models of BG. A detailed model of the functioning brain would permit to better understand the relations between biological processes and symptoms. Hopefully, this study will form a significant building block for this long-term objective.

Last but not least, it can turn out that the new model is more efficient from the algorithmic point of view. Stewart and Eliasmith [21] noticed that their Tower of Hanoi architecture sometimes makes mistakes they could not explain. As the human BG do not seem to include perfectly segregated pathways, the current BG model available by default in Nengo may not be an optimal action selection device. If this more biologically accurate bottom-up model performs better, it could be useful for possibly commercial applications in Artificial Intelligence. Incidentally, ABR, a company whose aim is to make commercially available neuromorphic applications using Nengo, was recently founded and probably makes extensive use of Nengo's model of BG as an action selection device.

1.3. Research plan

The new model was originally implemented using NEST, another simulator for spiking neural networks. By contrast with Nengo, NEST is not aimed to implement cognitive processes, but rather to study the dynamics of biological neural systems. The first thing to do will be to implement it in Nengo. With the latter, connections are usually automatically chosen in accordance with the computation that needs to be performed. However, Liénard and Girard [13] did not define their model on the functional level, but rather with specific connectivity and details of neural populations. Although Nengo was not originally designed to implement such bottom-up models, it is possible to specify direct connections and neuron characteristics. Implementing the model in Nengo will probably be the main difficulty of the project.

To check the validity of the implementation, action selection tests will be performed in both Nengo and NEST. Common approaches for evaluating action selection include using more or less noisy and similar inputs for commands, checking if the most active command is selected, and measuring the time necessary to perform this task. Both implementations should exhibit the same dynamics (in terms of timing and activation levels) with the same inputs. Comparisons between action selection performances of both the new model and Nengo's implementation of Gurney et al. [10] will also be made. Nengo's implementation of the new model will also need to exhibit the same oscillations as NEST's implementation when the effects of Parkinsonian dopamine depletion are simulated. The oscillation index has been used to quantify the oscillations in the range 15-30 Hz from the activity of the neural populations of the model in pathological conditions. It is defined as follows:

$$OI = \frac{\int_a^b S(f)\, df}{\int_0^{F_{max}} S(f)\, df} \tag{1}$$

with a and b the limits of the frequency range of interest, F_{max} the maximal frequency of the spectrum, and $S(f)$ the frequency power function. Oscillation index has been shown to increase when the dopamine depletion is simulated with NEST and will need to be reproduced in Nengo (see Figure 5).

If the implementation is made properly, it should not be hard to switch between action selection modules in the cognitive architecture for the Tower of Hanoi task. A qualitative examination of errors may provide preliminary indications on the human-likeness of the new architecture. Comparisons of the delays between moves with both the new and old models (e.g. with mean square error or plots like Figure 3) will then be carried. Lastly, the behaviour of the architecture in Parkinsonian conditions will be compared with behavioural results from Schneider, J. S. [17] and Vakil et al. [23].

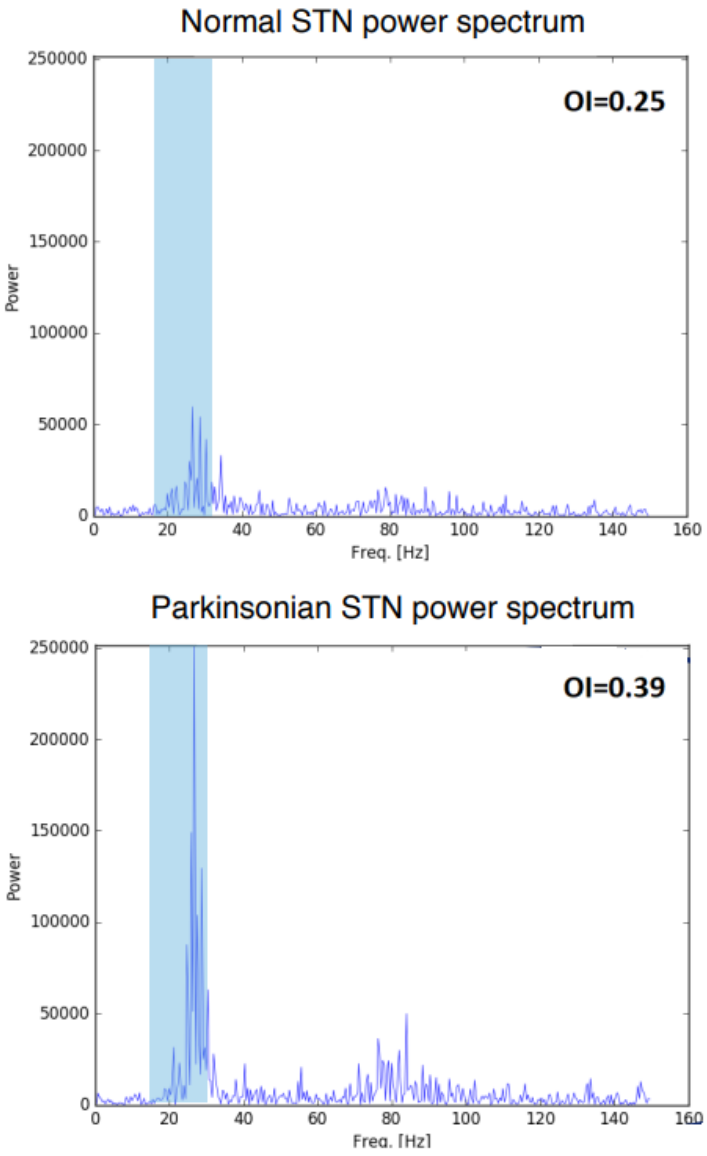

Figure 5: Parkinson-like oscillations (15-30 Hz) emerge in the STN when the dopamine depletion is simulated in the model. Adapted from [9].

Results of this study may provide insights to reduce the number of solutions of the model (see Section 1.1.2 for details about the 15 solutions resulting from the optimisation process).

2. Schedule

This research project will last approximately 21 weeks and will require a workload of 168 hours. It will be divided into three main phases, namely the setup, the implementation of the model in Nengo, and the use of the model within the architecture for solving the Tower of Hanoi (see Table 1). Project deliverables will be a report describing the study and the results, and the source code of the implementation of the biologically constrained model of the BG in Nengo. My supervisors, Serge Thill and Marcel van Gerven, will use these deliverables to evaluate my Capita Selecta of 6 EC.

#	Task	Start	Finish	Workload (h)
1	**Total**	**01/10/2018**	**25/02/2019**	**168**
2	**Setup**	**01/10/2018**	**21/10/2018**	
3	Install Nengo	01/10/2018	02/10/2018	1
4	Familiarise with Nengo	03/10/2018	21/10/2018	24
5	**sBCBG**	**22/10/2018**	**20/01/2019**	
6	Implement sBCBG in Nengo	22/10/2018	23/12/2018	71
7	Test action selection	24/12/2019	20/01/2019	16
8	Test PD oscillations	24/12/2019	20/01/2019	16
9	**sBCBG in TOH model**	**21/01/2019**	**25/02/2019**	
10	Get familiar with TOH model	21/01/2019	03/02/2019	16
11	Replace BG with sBCBG	04/02/2019	10/02/2019	8
12	Analyse results	11/02/2019	25/02/2019	16

Table 1: Dates of main tasks

3. Societal, technical, and scientific relevance

3.1. Treatments for Parkinson's disease

Parkinson's disease is the second most common neurodegenerative disease after Alzheimer's disease. Approximately 6 million men and women worldwide have it. The prevalence of the disease is expected to double in a lot of countries by the year of 2040, as a consequence of the increase of life expectancy. As it reduces movement control, Parkinson's disease impairs the individuals ability to function in daily life situations. Consequently, it affects the quality of life, social interactions, and the financial situation of these patients. Hence there is an urgent need to understand the biological underpinnings of this disease to better treat them.

3.2. Biological plausibility vs. explainable AI

Neuroscience-inspired artificial intelligence approaches such as deep learning currently have tremendous success. However, they face a big problem of interpretability. Evolution is obviously not constrained by explainability. As a matter of fact, the human brain contains approximately 6×10^{14} messy synaptic connections. The boundaries between what is needed for human-level intelligence, and what is just specific to the biological substrate are still far from being fully understood. Although the view that human action selection is performed with direct and indirect pathways can be appealing in its simplicity, it has been challenged by anatomical data (see Section 1.1.1). This study would provide an interesting framework to compare a simple and easily interpretable model, and a more accurate biologically constrained model of BG. I believe it could shed light on the necessity of biological plausibility for producing efficient artificial intelligent behaviour.

3.3. Interpretable and multidisciplinary evaluation of computational models

Researchers often regret the lack of bridges between disciplines. Although it is not always a trivial task, I believe that implementing computational models in cognitive architectures can provide useful and easily interpretable results. This method could permit the comparison of behavioural data from psychological studies and the dynamics of low-level models from

computational neuroscience. It can also be argued (for ethical, legal, and economic reasons) that simulations with cognitive architectures can be used as replacements for animal experiments.

4. Context and personal relevance

The present document is a research proposal for both AAPS and Capita Selecta courses (6 EC). The project is a follow-up to the internship I did at the Institute for Intelligent Systems and Robotics (ISIR) under the supervision of Benoit Girard in Paris. During this internship, I quantified the effect of dopamine depletion on the spiking version of the BG model proposed by Liénard and Girard [13]. I think this project will be a good approach for me to expand my knowledge on cognitive modelling with Nengo while using a model I am already familiar with.

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