

## Supplementary materials

### Extent of the Muscimol Injections

In order to assess the extent of the muscimol injection on the GPi, an electrode was implanted into the right GPi of monkey F under general anaesthesia [intramuscular ketamine hydrochloride 10–15 mg/kg (Panpharma, France) and intramuscular xylazine 1.5–2.5 mg/kg (Sigma, USA)]. Implantation was performed inside a stereotaxic frame (David Kopf Instrument, Tujunga, CA, USA) guided by radiography. A linear 16 channel multi-electrode array (Alpha-Omega Engineering, Nazareth-Illit, Israel) was lowered with a 35° lateral angle into the brain at slow speed up to locate the tip located 1.5mm from the tip of the cannula inserted in the left GPi. Extracellular single-unit activity was recorded with a wireless recording system (WS-16, Multichannel Systems, Reutlingen, BW, Germany). When a clear and stable GPi signal (for 15 minutes) from at least 3 contacts has been obtained with a signal to noise ratio above 3:1, we performed 10 minutes recording and then inject muscimol in the same manner as during the behavioural experiment. We recorded the firing rate of the neurons up to 10 minutes after the injection. For each neuron, we compute a mean firing rate and a threshold of significant variation ( $\pm 2.71 \times \text{SD}$  based on the assumption that firing rate follows a Poisson's distribution<sup>1</sup>) on the 10 minutes recording of baseline and assessed if muscimol injection induced a significant effect. Data are shown on **figure S1 B**. The 3 neurons we recorded show a significant decrease. It allows us to verify that the radius of effect of the muscimol is at least 1.5mm. It makes a volume of effect of at least  $14.1\text{mm}^3$  (under the assumption that this volume is roughly spherical) that, at least in the central part of the GPi where we injected (see **figure S1 A**), encompass both the central motor and the dorsal associative territories of the GPi<sup>2-7</sup>.

### Histology

After experiment, monkey Z was anesthetized with an overdose of pentobarbital sodium and perfused through the left ventricle with 4% paraformaldehyde. Its brain was equilibrated with 20% sucrose. Frozen sections were cut and stained with acetylcholine iodide. The anatomical location of the cannulae was reconstructed according to the dark lines of gliosis, which revealed their tracks (**figure S1 C**).

### Model description

The model is based on the model we have published in 2013<sup>8</sup> which itself derives from the competition principles introduced earlier<sup>9</sup>. This former model introduces an action selection mechanism that is based upon the competition between a positive feedback through the direct pathway and a negative feedback through the hyperdirect pathway. The model has been further extended<sup>8, 10</sup> and exploits the parallel organization of circuits between the basal ganglia and the cortex<sup>3, 4, 11</sup> using segregated loops: one for making the selection between the two presented cue shapes, and the other for making the selection between the two possible movement directions. However, to solve the task described previously, it is necessary for the model to first choose the cue shape and then (and only then) to select the right movement direction that depends upon the chosen cue. The model has been further refined in this study such as to have a competition mechanism within each cortical group. Using short-range

excitation and long-range inhibitions, this competition ensures that a unique cognitive (i.e. Value based) and motor decision eventually emerges, even if these decisions might be unrelated at this stage. The whole architecture of the model is described in **figure S2**. Learning occurs between the cognitive cortex and the cognitive striatum using a simple reinforcement learning where the values of the different cues are updated after each decision (see <sup>8</sup> for details). We added Hebbian learning (LTP) at the cortical level between the cognitive/motor cortical groups and the associative cortical group. This learning is enforced once per trial, at the time a move is made and independently of the actual reward (see **Table S1**).

Sources of the model are available from:

<https://github.com/rougier/Neurosciences/tree/master/basal-ganglia/topalidou-et-al-2014>.

## Results

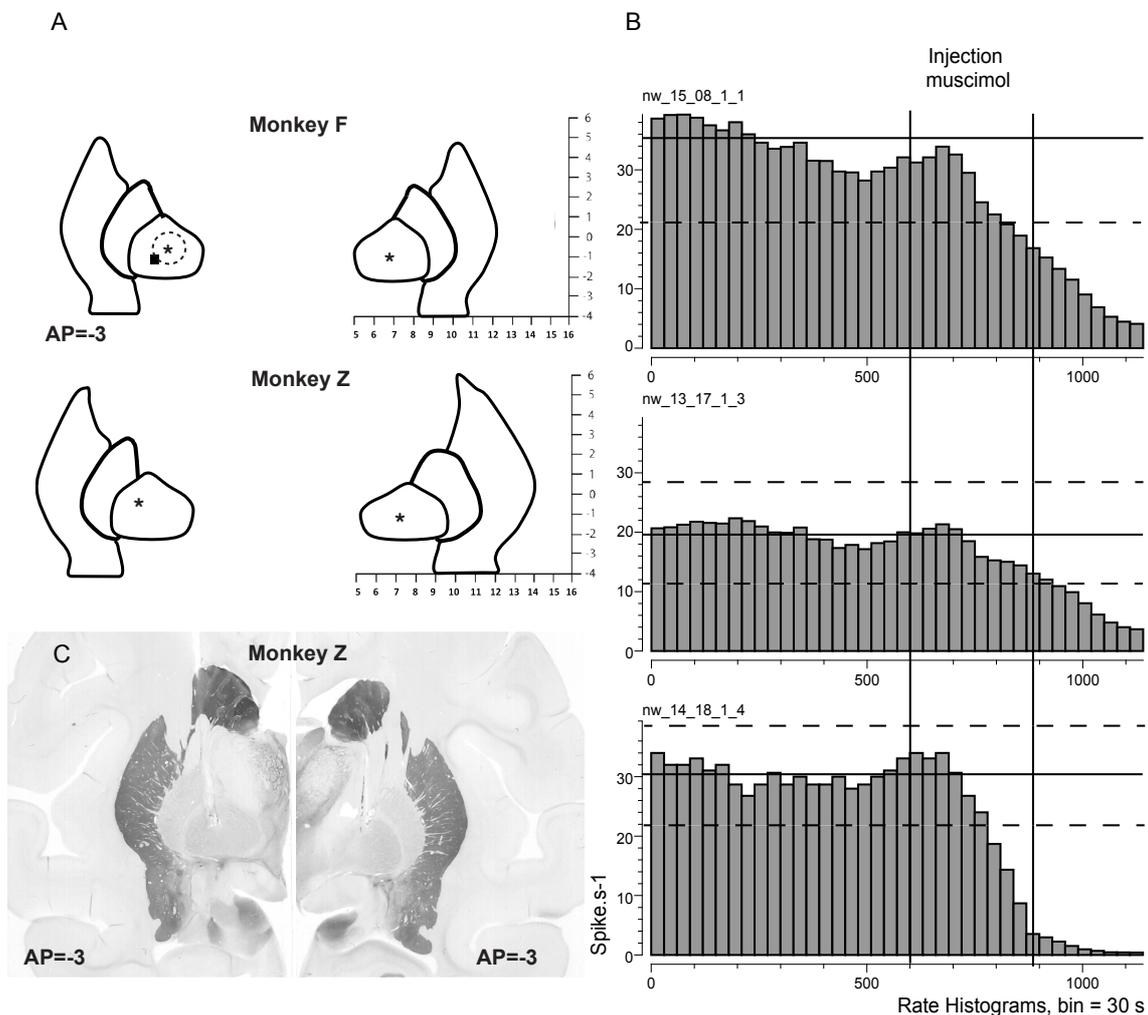
The model has been trained on cues 1 and 2 (cognitive cortex) that are presented simultaneously at random positions in the motor cortex. Cue 1 is associated with a reward probability of 75% while cue 2 is associated with a reward probability of 25%. The model is trained until it achieves a performance of 0.95, meaning it chooses cue 1 most of the time. This takes between 10 and 20 trials depending on the initial conditions (noise) and whether first cues are rewarded or not. In the meantime, this training impacts significantly Hebbian learning at the cortical level because cue 1 is chosen most of the time and consequently, the associative link relative to cue 1 is reinforced compared to associative link relative to cue 2 (while cues 3 and 4 are never reinforced since they are never presented). After this initial training phase, we tested the model using four different paradigms that corresponds to the experiments:

- RC/GPi (saline): Routine Condition using cues 1 & 2 with intact GPi
- NC/GPi (saline): Novelty Condition using cues 3 & 4 with intact GPi
- RC/NoGPi (muscimol): Routine Condition using cues 1 & 2 with lesioned GPi
- NC/NoGPi (muscimol): Novelty Condition using cues 3 & 4 with lesioned GPi

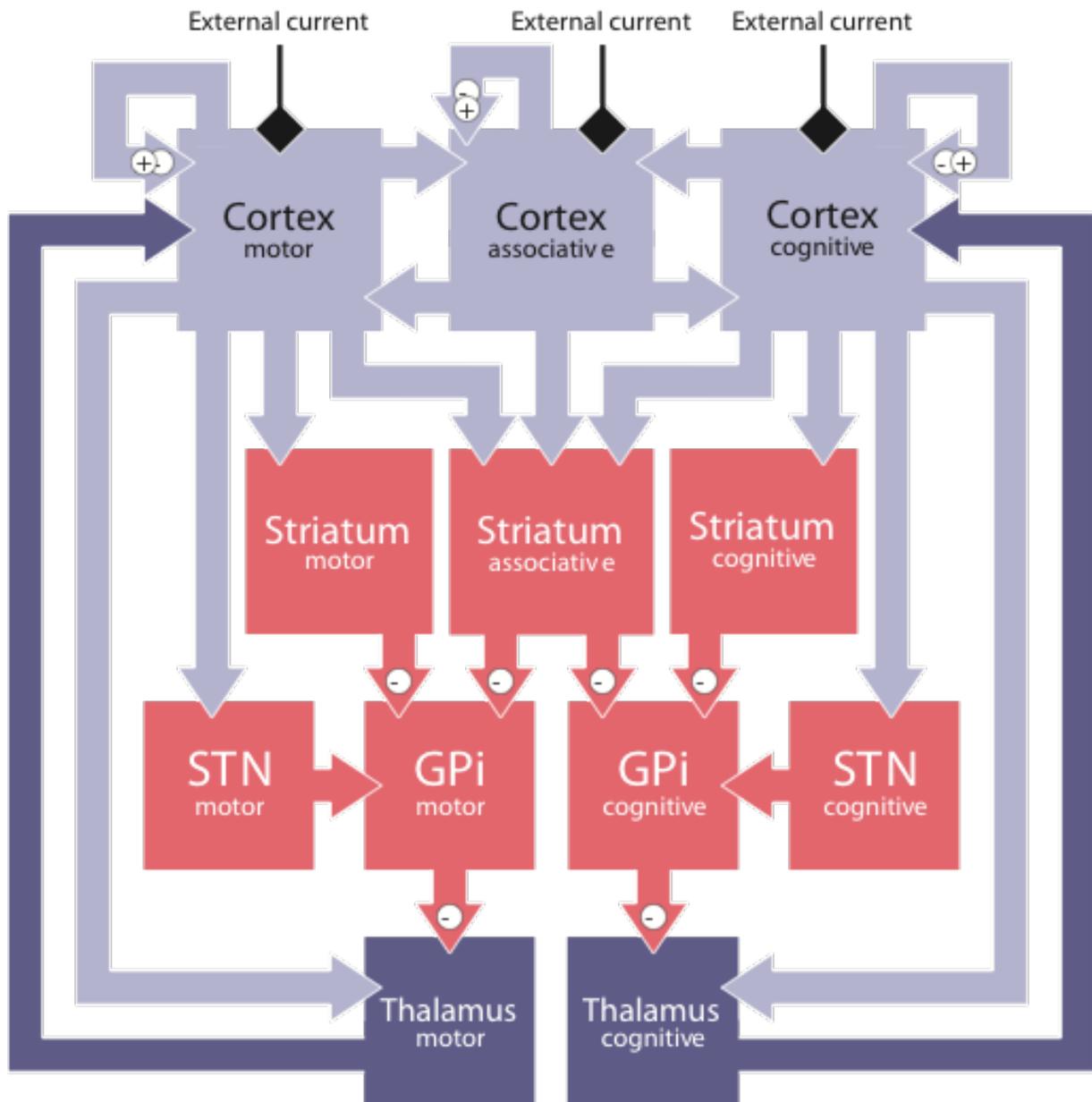
An experiment is made of 120 consecutive trials. Each trial starts with a settling period that last for 500ms until two cues are presented to the model at random position. Once a motor decision is made, the reward is computed according to the chosen cue, that is, the one that corresponds to the actual motor choice and not the cognitive one. Response time has been recorded as the time of the motor decision, that is, when the difference between the two greatest motor activations is greater than the decision threshold (40Hz). This time is relative to the stimulus onset. Each of the four conditions has been averaged over 250 experiments. Our results are in accordance with the experiments in monkeys. In the automatic condition (RC), performances are optimal with or without lesion, indicating the cortex is able to make the optimal decision without the help of the basal ganglia if it has been learned previously. In novel condition, performances of the intact model (NC/with GPi) are initially at chance level but after a few trials (around 15), it reaches a near-optimal performance, indicating the model has learned the respective reward probability associated with each novel cues. However, for the lesioned model (NC/without GPi), performances stay at chance level, indicating the cortex is unable to learn the new task without the help of the basal ganglia.

## References

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**Figure S1. Injection sites.** **A)** Theoretical injection sites for both monkeys in the right and left hemispheres have been reconstructed based on stereotaxic coordinates corrected for the position of the anterior and the posterior commissures obtained with X-ray ventriculography. On the right hemisphere of monkey F, we showed the position of the neurons recorded and displayed in B and the estimated radius of effect of the muscimol injection. The volume encompassed both the medial and the dorsal part of the GPi. Coordinates are provided according to the Anterior Commissure. **B)** Time histogram of the firing rate of three neurons recorded before and after muscimol injection in the right GPi of monkey F. The two vertical lines represent the beginning and the end of the injection. The horizontal lines represent the confidence limit of significant for  $p < 0.01$  (mean FR – solid – and  $2.71 \times \text{SD}$  – dotted – lines) under the assumption that the neuron fired according to a Poisson's process. The three neurons recorded were sensitive to the muscimol injection. The timescale is in ms. **C)** Histological display of the position of the cannulae in monkey Z.



**Figure S2. Architecture of the model.** Two cortico-basal ganglia loops are modelled, representing two levels of decision making: a cognitive loop (left, encoding value) and a motor loop (right). An Associative Cortex provides the representation of the on-going decision (i.e. which cue is presented in which position). Each loop consists of a focused, positive feedback, direct pathway loop [cortex - striatum - globus pallidus (GPI) - thalamus - cortex] and a divergent, negative feedback, hyperdirect pathway loop [cortex - subthalamic nucleus (STN) - GPI - thalamus - cortex]. Each cortical group has collaterals (short range excitation and long range inhibition) that promote competition between units. Cross talk between cortical modules is ensured through reciprocal links between the motor/cognitive group and the associative cortical group. For details, see Supplementary Materials.

**Table S1.** Detailed parameters of the model.

<b>A Model Summary</b>	
<b>Populations</b>	Twelve: Cortex (motor, associative & cognitive), Striatum (motor, associative & cognitive), GPi (motor & cognitive), STN (motor & cognitive), Thalamus (motor & cognitive)
<b>Topology</b>	—
<b>Connectivity</b>	one to one, one to many (divergent), many to one (convergent)
<b>Neuron model</b>	Dynamic rate model
<b>Channel model</b>	—
<b>Synapse model</b>	Linear synapse
<b>Plasticity</b>	Reinforcement & Hebbian learning rules
<b>Input</b>	External current in cortical areas (motor, associative & cognitive)
<b>Measurements</b>	Firing rate

<b>B Populations</b>					
<b>Name</b>	<b>Elements</b>	<b>Size</b>	<b>Threshold (h)</b>	<b>Noise</b>	<b>Initial state</b>
Cortex motor	Linear neuron	1×4	-3	1.0%	0.0
Cortex cognitive	Linear neuron	4×1	-3	1.0%	0.0
Cortex associative	Linear neuron	4×4	-3	1.0%	0.0
Striatum motor	Sigmoidal neuron	1×4	0	0.1%	0.0
Striatum cognitive	Sigmoidal neuron	4×1	0	0.1%	0.0
Striatum associative	Sigmoidal neuron	4×4	0	0.1%	0.0
GPi motor	Linear neuron	1×4	+10	3.0%	0.0
GPi cognitive	Linear neuron	4×1	+10	3.0%	0.0
STN motor	Linear neuron	1×4	-10	0.1%	0.0
STN cognitive	Linear neuron	4×1	-10	0.1%	0.0
Thalamus motor	Linear neuron	1×4	-40	0.1%	0.0
Thalamus cognitive	Linear neuron	4×1	-40	0.1%	0.0
Values ( $V_i$ )	Scalar	4	—	—	0.5

<b>C Connectivity</b>					
<b>Source</b>	<b>Target</b>	<b>Pattern</b>	<b>Weight (W)</b>	<b>Gain (G)</b>	<b>Plastic</b>
Cortex motor	Thalamus motor	$(1, i) \rightarrow (1, i)$	1.0	0.4	No
Cortex cognitive	Thalamus cognitive	$(i, 1) \rightarrow (i, 1)$	1.0	0.4	No
Cortex motor	STN motor	$(1, i) \rightarrow (1, i)$	1.0	1.0	No
Cortex cognitive	STN cognitive	$(i, 1) \rightarrow (i, 1)$	1.0	1.0	No
Cortex motor	Striatum motor	$(1, i) \rightarrow (1, i)$	$\mathcal{N}(0.5, 0.005)$	1.0	No
Cortex cognitive	Striatum cognitive	$(i, 1) \rightarrow (i, 1)$	$\mathcal{N}(0.5, 0.005)$	1.0	<b>Yes</b> (see F1)
Cortex motor	Striatum associative	$(1, i) \rightarrow (*, i)$	$\mathcal{N}(0.5, 0.005)$	0.2	No
Cortex cognitive	Striatum associative	$(i, 1) \rightarrow (i, *)$	$\mathcal{N}(0.5, 0.005)$	0.2	No
Cortex associative	Striatum associative	$(i, j) \rightarrow (i, j)$	$\mathcal{N}(0.5, 0.005)$	1.0	No
Thalamus motor	Cortex motor	$(1, i) \rightarrow (1, i)$	1.0	1.0	No
Thalamus cognitive	Cortex cognitive	$(i, 1) \rightarrow (i, 1)$	1.0	1.0	No
GPi motor	Thalamus motor	$(1, i) \rightarrow (1, i)$	1.0	-0.5	No
GPi cognitive	Thalamus cognitive	$(i, 1) \rightarrow (i, 1)$	1.0	-0.5	No
STN motor	GPi motor	$(1, i) \rightarrow (1, i)$	1.0	1.0	No
STN cognitive	GPi cognitive	$(i, 1) \rightarrow (i, 1)$	1.0	1.0	No
Striatum cognitive	GPi cognitive	$(i, 1) \rightarrow (i, 1)$	1.0	-2.0	No
Striatum motor	GPi motor	$(i, 1) \rightarrow (i, 1)$	1.0	-2.0	No
Striatum associative	GPi motor	$(* , i) \rightarrow (1, i)$	1.0	-2.0	No
Cortex cognitive	Cortex cognitive	$(i, 1) \rightarrow (i, 1)$	1.0	+0.5	No
Cortex cognitive	Cortex cognitive	$(i, 1) \rightarrow (-i, 1)$	1.0	-0.5	No
Cortex cognitive	Cortex associative	$(i, 1) \rightarrow (i, *)$	1.0	-0.5	<b>Yes</b> (see F2)
Cortex associative	Cortex cognitive	$(i, *) \rightarrow (i, 1)$	1.0	+0.1	No
Cortex motor	Cortex motor	$(1, i) \rightarrow (1, -i)$	1.0	+0.5	No
Cortex motor	Cortex motor	$(1, i) \rightarrow (1, i)$	1.0	+0.5	No
Cortex motor	Cortex associative	$(* , i) \rightarrow (* , i)$	1.0	+0.5	<b>Yes</b> (see F2)
Cortex associative	Cortex motor	$(* , i) \rightarrow (i, 1)$	1.0	+0.1	No

D1 Neuron model	
<b>Name</b>	Linear neuron
<b>Type</b>	Rate model
<b>Membrane Potential</b>	$\tau \frac{dV}{dt} = -V + I_{syn} + I_{ext} - h$ $U = \max(V, 0)$

D2 Neuron model	
<b>Name</b>	Sigmoidal neuron
<b>Type</b>	Rate model
<b>Membrane Potential</b>	$\tau \frac{dV}{dt} = -V + I_{syn} + I_{ext} - h$ $U = V_{min} - (V_{max} - V_{min}) / (1 + e^{\frac{V_h - V}{V_c}})$

E Synapse	
<b>Name</b>	Linear synapse
<b>Type</b>	Weighted sum
<b>Output</b>	$I_{syn}^B = \sum_{A \in sources} (G_{A \rightarrow B} \cdot W_{A \rightarrow B} \cdot U_A)$

F1 Plasticity	
<b>Name</b>	Reinforcement learning
<b>Type</b>	Delta rule
<b>Output</b>	$\Delta W_{A \rightarrow B} = \alpha \cdot PE \cdot U_B$ $PE = Reward - V_i$ $\alpha = 0.01 \text{ if } PE < 0 \text{ (LTD)}, \alpha = 0.02 \text{ if } PE > 0 \text{ (LTP)}$

F2 Plasticity	
<b>Name</b>	Hebbian learning
<b>Type</b>	Delta rule
<b>Output</b>	$\Delta W_{A \rightarrow B} = \alpha \cdot U_A \cdot U_B$ $\alpha = 0.01 \text{ (LTP)}$

G Input	
<b>Type</b>	Cortical input
<b>Description</b>	A trial is preceded by a settling period (500ms) and followed by a reset period. At time $t = 0$ , two shapes are presented in cortical cognitive area ( $I_{ext} = 7$ at $\{i_1, i_2\}$ ) at two different locations in cortical motor area ( $I_{ext} = 7$ at $\{j_1, j_2\}$ ) and the cortical associate area is updated accordingly ( $I_{ext} = 7$ at $\{i_1, i_2\} \times \{j_1, j_2\}$ ).
<b>Timing</b>	<p>Timeline: Trial start (-500ms), Stimulus onset (0), Stimulus onset (2500 ms), Reset (3000 ms)</p>

H Measurements	
<b>Site</b>	Cortical areas
<b>Data</b>	Activity in cognitive and motor cortex Cortico-striatal weights

I Environment	
<b>OS</b>	Cortical areas
<b>Language</b>	Python 2.7.6 (brew installation)
<b>Libraries</b>	Numpy 1.8.1 (pip installation) Scipy 0.13.3 (pip installation) IPython 1.2.1 (pip installation)

**Tools**

Matplotlib 1.3.0 (pip installation)

DANA 0.5.0 (pip installation)

Safari browser (native)