Data for Brain Reference Architecture of TM25CILsSpiralingHypothesis

The Spiraling Hypothesis of Habit Formation in the Basal Ganglia

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Abstract

This dataset describes the "Spiraling Hypothesis," the neural basis for habit formation in the basal ganglia. The data is structured in the Brain Reference Architecture (BRA) format. The content was constructed based on foundational literature (e.g., Haber, Fudge, and McFarland (2000); Yin and Knowlton (2006)) and recent anatomical evidence from Ambrosi and Lerner (2022). Specifically, the monosynaptic "Striatonigrostriatal (SNS) pathways," which mediate the transition from goal-directed (DMS) to habitual (DLS) behavior, are implemented as BIF. This dataset is reusable for computational modeling of habit formation and related disorder research.

Keywords: Brain Reference Architecture; Basal Ganglia; Habit Formation

Author roles:

Tatsuya Miyamoto Data curation, Methodology, Visualization, Writing & Investigation

Yoshimasa Tawatsuji Supervision, Validation, Writing, editing &Project administration

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1 Context

Brain Reference Architecture (BRA) is the reference architecture for software that realizes cognitive and behavioral functions in a brain-like manner. The architecture primarily consists of the mesoscopic-level anatomical data of the brain and the data of one or more functional mechanisms that are consistent with that knowledge(Yamakawa, 2021). BRA consists of Brain Information Flow (BIF), which represents structural knowledge of the brain, and Hypothetical Component Diagram (HCD)/Function Realization Graph (FRG), which represent brain functionality.

The basal ganglia, the subject of this dataset, play a central role in various forms of behavioral control and are particularly critical as the neural basis for "habit formation". Many of our behaviors are initially learned as conscious "goal-directed actions," but with repeated training, they transition into "habitual responses" that are automatically triggered by external stimuli.

A prominent neural circuit model explaining this transition process from goal-directed action to habit is the "Spiraling Hypothesis," as discussed in Yin and Knowlton (2006) and others. The anatomical basis for this hypothesis lies in the characteristic connectivity within the cortico-striatal loops, as demonstrated by (Haber et al., 2000). Specifically, it is suggested that the "Striatonigrostriatal (SNS)" pathways—which connect the striatum with the dopaminergic cells of the midbrain (such as the substantia nigra)—form an "ascending spiral" that transmits information between functionally distinct loops.

This spiral structure is thought to provide the neural substrate for a gradual shift in information processing: from the ventral striatum (limbic loop), which is associated with reward and emotion, to the central striatum (associative loop) for cognition and learning, and finally to the dorsolateral striatum (sensorimotor loop), which is involved in behavioral automation. Habit formation is thus conceptualized as the process by which the locus of this information processing shifts from the associative loop to the sensorimotor loop.

This dataset, TM25CILs-Spiraling-Hypothesis targets the neural circuit architecture involved in habit formation as described by the Spiraling Hypothesis of the basal ganglia. We have collected and integrated relevant anatomical and physiological findings (e.g., Yin and Knowlton (2006); Haber et al. (2000)) to construct the neural circuitry connections based on this hypothesis as BIF, and the functions of each component in habit formation as HCD/FRG. This dataset aims to provide a standardized reference model that contributes to the computational understanding of habit formation and the elucidation of mechanisms underlying related psychiatric disorders (such as addiction).

2 Method

SCID method/Function-oriented SCID method The creation of this dataset was conducted following the structure-constrained interface decomposition (SCID) method (Yamakawa, 2021) or the function-oriented SCID method (Yamakawa et al., 2023). This study focused on collecting literature-based knowledge regarding the neural circuit model of habit formation in the basal ganglia, particularly the "Spiraling Hypothesis," and systematizing this knowledge into Brain Information Flow (BIF) and Function Realization Graph (FRG) formats.

Sampling strategy The anatomical and functional knowledge used to construct the BIF and FRG in this dataset was primarily collected and integrated from the following key literature reviews and experimental studies:

- Haber et al. (2000): Based on anatomical studies in primates, this research proposed the existence of "Striatonigrostriatal (SNS) pathways" that form the basis of the "Spiraling Hypothesis." It was used to define the macro-scale circuit connections (information flow from ventral to dorsal) in this dataset.
- Yin and Knowlton (2006): This review provided the functional framework asserting that habit formation is a process involving a shift in the locus of behavioral control from the dorsomedial striatum (DMS; goal-directed) to the dorsolateral striatum (DLS; habitual). It was used to define the functional components in the HCD/FRG of this dataset.
- Ambrosi and Lerner (2022): A recent viral tracing study in mice, which was used to validate the connectivity implemented in the BIF of this dataset.

The study by Ambrosi and Lerner (2022) is particularly important. In this research, the large-scale functional information flow (i.e., the "Spiraling") from the DMS (associative loop) to the DLS (sensorimotor loop), as hypothesized by the Spiraling Hypothesis, was not explicitly demonstrated. However, it provided anatomical evidence at the micro-level, showing that DMS neurons form monosynaptic connections onto DLS neurons via dopaminergic neurons in the substantia nigra pars compacta (SNc).

Therefore, this dataset adopts the "monosynaptic SNS connections," which were anatomically demonstrated by Ambrosi and Lerner (2022), as the evidence base for the edges (connections) within the BIF.

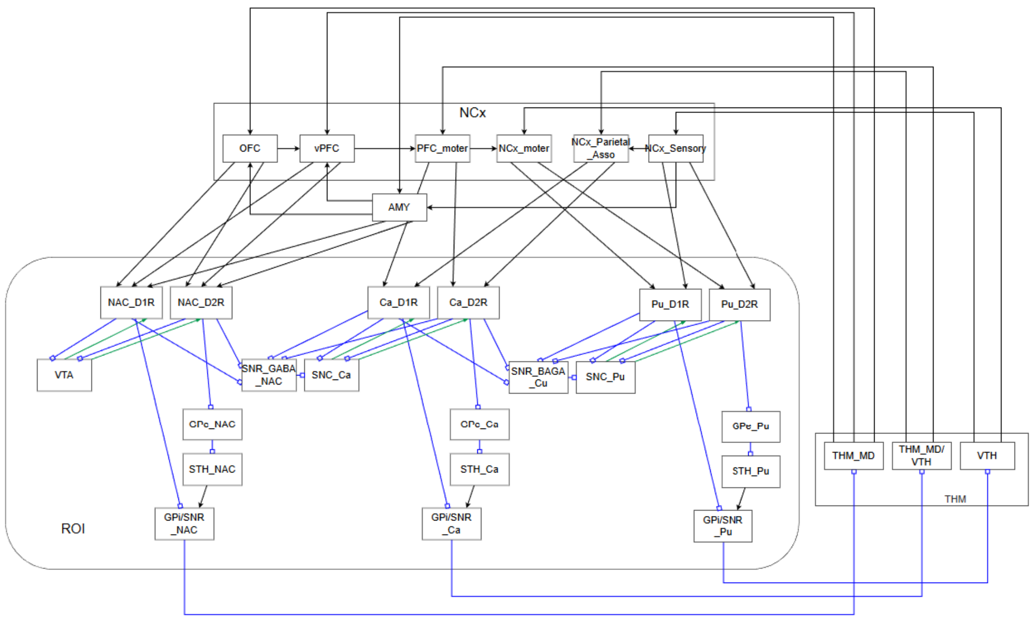

Figure 1: Brain Information Flow diagram of TM25CILs-Spiraling-Hypothesis

Construction of HCD from BIF The Hypothetical Component Diagram (HCD) was derived from the BIF through a process of functional abstraction and simplification, guided by the SCID method principles. This involved grouping anatomical regions into functional components based on their roles in the Spiraling Hypothesis, while maintaining consistency with the structural constraints in the BIF. Specific criteria for summarization and adoption/exclusion were as follows:

- D1R and D2R pathways were summarized into unified components to focus on their shared functional roles in dopaminergic modulation, reducing complexity while preserving the core mechanism of plasticity modulation.
- Output nodes such as GPe, STH, and GPi were consolidated into a single functional output node, as they collectively represent downstream inhibitory/effector pathways in the basal ganglia loops relevant to habit automation.
- The BIF includes three loops: the NAC (limbic) loop, Putamen (sensorimotor) loop, and Caudate (associative) loop. However, to emphasize the transition from goal-directed to habitual behavior, components related to the NAC loop were excluded from the HCD, as this dataset prioritizes the associative-to-sensorimotor shift supported by evidence from Yin and Knowlton (2006).

These decisions were made to maintain focus on the essential mechanisms of habit formation, ensuring the HCD remains computationally tractable and aligned with the hypothesis's core motifs.

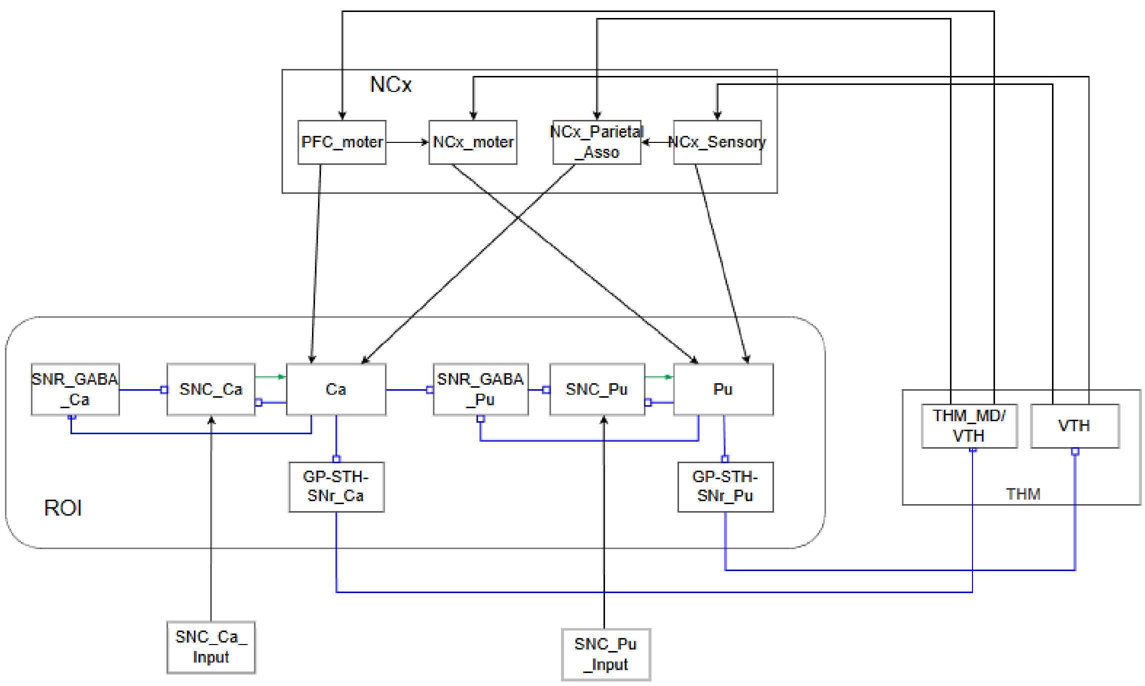

Figure 2: Hypothetical Component Diagram of TM25CILs-Spiraling-Hypothesis

The FRG is intentionally simplified, with the top-level function (TLF) node branching directly to eight uniform circuits from the HCD. This minimalistic design highlights the core spiraling motif of the hypothesis, facilitating initial computational modeling and reusability. Detailed hierarchical functional structures, including more nuanced sub-motifs and feedback loops, represent future challenges for refinement and extension of this dataset.

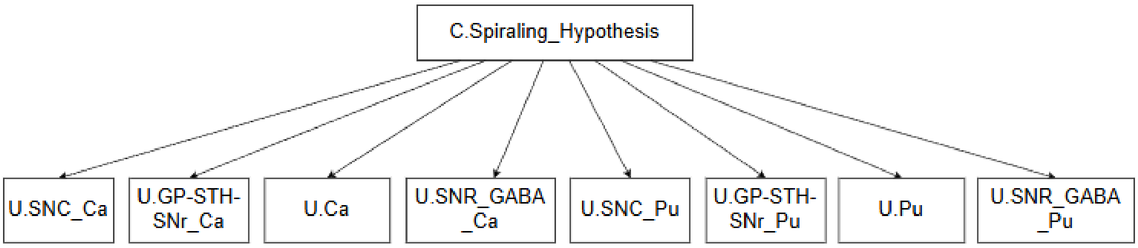

Figure 3: Function Realization Graph of TM25CILs-Spiraling-Hypothesis

3 Dataset Description

Repository location BRA Editorial System (BRAES) https://sites.google.com/wba-initiative.org/braes/data

Object name and versions Please refer to the "Project" sheet in the BRA data for the more detail of data summary.

Table 1: BRA DATA SUMMARY

BRA Data			
Object Name	Template	Including Content(s)	
		BIF	HCD/FRG
TM25CILs-Spiraling-Hypothesis.bra	*version 2.1*	√	√

Table 2: BRA IMAGE SUMMARY

Graphic Files: BIF Image, HCD Image, FRG Image	
File Type	Object Name
BIF Image	TM25CILs-Spiraling-HypothesisBI.png
HCD Image	TM25CILs-Spiraling-HypothesisHCD.png
FRG Image	TM25CILs-Spiraling-HypothesisFRG.png

Creation dates The start and end dates of when the data was created (2024-10-18 to 2025-01-24).

Language English.

License The open license under which the data has been deposited (CC-BY 4.0).

Publication date The date in which the dataset was published in the repository (2025-11-04).

Competing interests

Yoshimasa Tawatsuji and Hiroshi Yamakawa are managers of BRAES but did not take part in the editorial process or decisions pertaining to this manuscript.

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