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Topological Considerations of Memory Structure

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Abstract
The human memory system is an integration of three distributed memory systems associated with respective autonomous organic systems; the perceptual system that takes care of sensory input from the environment, the conscious system that performs deliberate decision making, and the unconscious system that carries out action selections in the environment. The memory system works as a memory component in the comprehensive brain model, MHP/RT [3], which is capable of simulating human daily behavior considering the real time constraints that should define strong mutual dependencies among the three systems. This paper reconsiders MHP/RT's memory system by mapping it on the real interconnections between the cranial nerves and the spinal nerves to obtain a topological representation of the distributed memory system.

Keywords: Human memory system, topological representation, MHP/RT

1 Two views of memory structure

1.1 Memory as a conceptual construct

In the diagram of Two Minds depicted by [1], the memory module is placed independently from System 1 and System 2. MHP/RT extends Two Minds by specifying the role of memory when System 1 and System 2 work [2]. This is critical because the contents stored in memory determine what System 1 and System 2 would do in the ever-changing environment, and we are interested in interactions between the two systems with different characteristic times, i.e., very fast System 1 and very slow System 2.

In [3], the human memory structure is modeled conceptually as shown by Figure 1: MHP/RT assumes that memory is organized by "Multi-Dimensional Frame (MD-Frame)" for storing information. MD-frame is a conceptual extension of Minsky's frame [5]. It is a primitive cognitive unit that conveys information that can be manipulated by brain under various constraints, similar to the concept in the ICM (Idealized Cognitive Model) theory by [4], the schema theory by [6], and so on. There are a number of MD-frame in MHP/RT, which will be explained in the next section.

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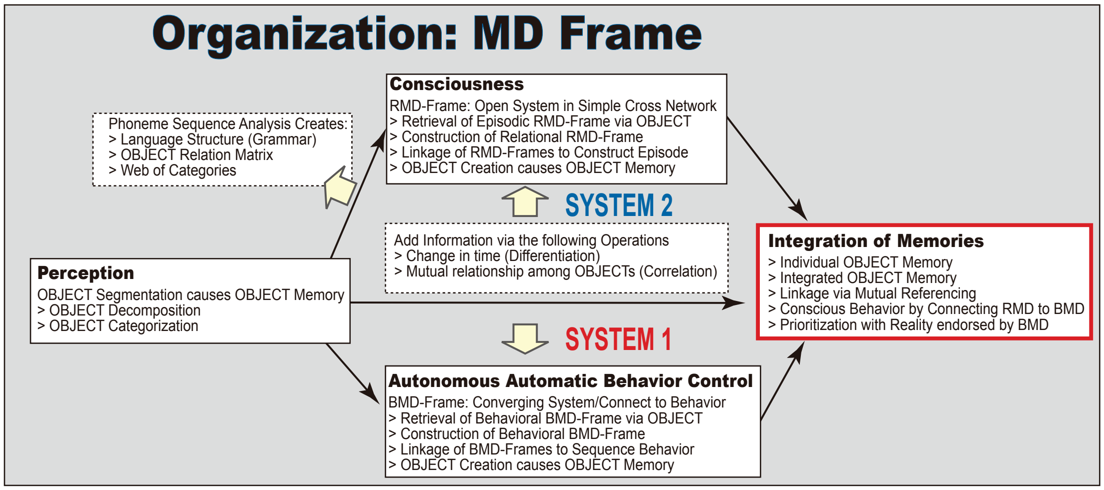

Figure 1: frame relations (Figure 7, [3]).

1.2 Memory as a nervous system

On the other hand, in reality, memory is a structured record of the activities of the nervous system to internal and external stimuli. The nervous system consists of three sub-systems (see, for example, [7]);

1. the sensory nervous system that is responsible for processing sensory information,
2. the somatic nervous system that is associated with the voluntary control of body movements via skeletal muscles, and
3. a system of interneurons that connect these systems.

Each nervous system is functionally different from each other in terms of its input-output structure, and therefore each is associated with its own memory structure, that develops and organizes differently from the other memory structures. Each memory structure interconnects hierarchically as the nervous system develops, topologically forming an evolving cyclic network structure with the somatic nervous system being the core of the network.

Integration of these two views should provide a deeper understanding of human memory. The goal of this paper is to reconsider MHP/RT's memory system by mapping it on the real interconnections between the cranial nerves and the spinal nerves. This results in a topological representation of the distributed memory system.

2 Memory formation and activation

2.1 Chain-firing in the nervous system

Since one's birth, one continuously carries out physical behavior without any pause. This reflects on the construction of the respective memories: each constitutes a continuous cyclic

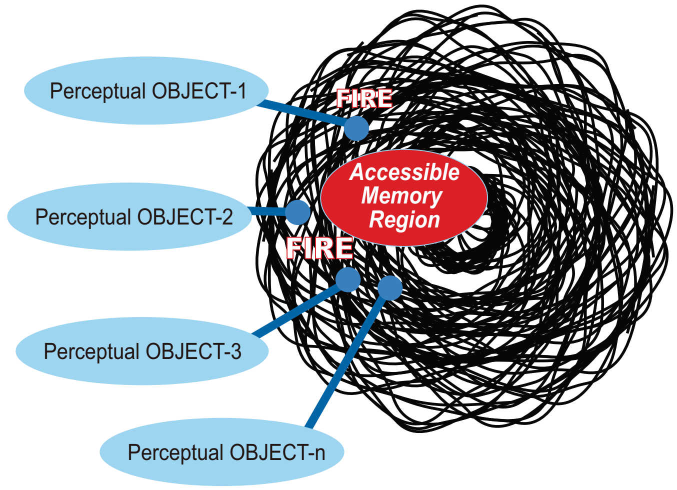

Figure 2: Chain-firing triggered by perceptual stimuli in a cross-networked memory structure.

network that reflects day-by-day cyclic events. Perception plays an important role for the development of the cyclic memory network. The memories are cross-connected each other and perceptual objects reside at the center of the cross connections. The perceptual system continuously monitors changes in the environment, and starting from the perceptual objects that are created while processing the environment, it fires the cyclic memory network. The firing continues and spreads in the network, i.e., chain-firing, as long as the perceptual objects last in the environment. The activated region of the network finally obtained as the result of the chain-firing is "the accessible memory region" at the moment. What this process actually does is to preprocess the situation for the future by activating related memory regions beforehand.

Figure 2 illustrates schematically the process of chain-firing triggered by perceptual objects. The accessible memory region, depicted in the red oval in the figure, corresponds to the region where the activation levels are kept above certain threshold values necessary for maintaining a chain-firing by using primarily perceptual stimuli related to the current behavioral purpose. The origins of the chain-firing are continuous input from the current environment. In the situation with severe realtime constraints, the activated region would be used with a high priority.

In summary, specific input stimuli, which could be internal or external, selectively activate part of memory, and it then triggers activation of another part of memory. This continues as long as input stimuli exist. Since the sensory nervous system reacts to the rapidly-changing external environment with shorter reaction times, the activated part of memory tends to be related with the current state of the environment.

3 Multidimensional frame as a distributed memory system

Object cognition occurs as follows [3]: collecting information from the environment via perceptual sensors; integrating and segmenting the collected information, centering on visually

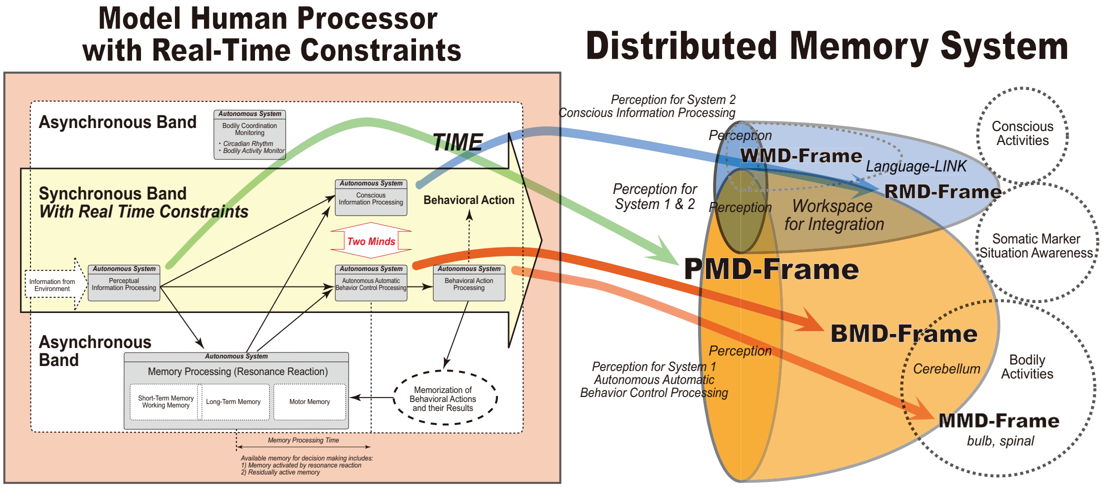

Figure 3: MHP/RT (Figure 3, [3]) and the distributed memory system.

collected objects; and continuing these processes until the necessary objects to live in the environment are obtained. These objects are then used independently in Systems 1 and System 2 of Two Minds, and memorized after integrating related entities associated with each system. Due to the limitation of the brain's processing capability, the range of integration is limited; therefore, System 1 memory and System 2 memory should differ. However, they could share objects originating from perceptual sensors. Thus, when objects that are the result of the just-finished integration and segmentation process are processed in the next cycle, representation of the objects may serve as the common elements to combine the System 1 memory and the System 2 memory to form an inter-system memory. We call this memory the Multi-Dimensional (MD) -frame. There are five kinds of MD-frame in MHP/RT[1].

3.1 Integration of MHP/RT's definition of memory with neuronal activities

Figure 3 illustrates how each MD-frame is created as the result of working of autonomous processes in MHP/RT and how MD-frames are mutually interrelated. This essentially details the process "Memorization of Behavioral Actions and their Results" shown by the dotted oval in the diagram of MHP/RT by considering neuronal activities that actually happen. The basic idea is that each autonomous system has its own memory.

The five MD-frames are defines as follows:

1) *PMD (Perceptual Multi-Dimensional) -frame* constitutes perceptual memory as a relational matrix structure. It collects information from external objects followed by separating it into a variety of perceptual information, and re-collects the same information in the other situations, accumulating the information from the objects via a variety of different processes. PMD-frame incrementally grows as it creates memory from the input information and matches it against the past memory in parallel.

[1]In [3], three kinds of MD-Frame, i.e., PMD-frame, BMD-frame, and RMD-frame are defined. But now we have five as the result of the advance of the study.

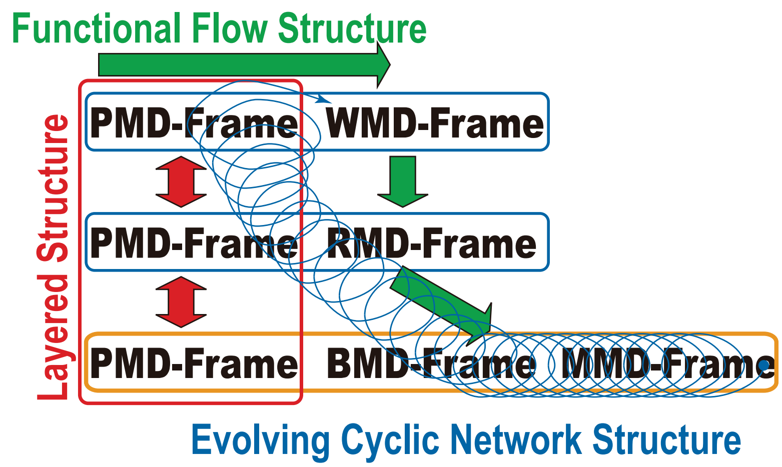

Figure 4: Functional flow structure, layered structure, and evolving cyclic network structure.

2) *MMD (Motion Multi-Dimensional) -frame* constitutes behavioral memory as a matrix structure. The behavioral action processing starts when unconscious autonomous behavior shows after one's birth. It gathers a variety of perceptual information as well to connect muscles with nerves using spinals as a reflection point. In accordance with one's physical growth, it widens the range of activities the behavioral action processing can cover autonomously.

3) *BMD (Behavior Multi-Dimensional) -frame* is the memory structure associated with the autonomous automatic behavior control processing. It combines a set of MMD-frames into a manipulable unit.

4) *RMD (Relation Multi-Dimensional) -frame* is the memory structure associated with the conscious information processing. It combines a set of BMD-frames into a manipulable unit. The role BMD-frames play for RMD-frame is equivalent to the role MMD-frames play for BMD-frame.

5) *WMD (Word Multi-Dimensional) -frame* is the memory structure for language. It is constructed on a very simple one-dimensional array.

4 Summary: Functional flow structure, layered structure, and evolving cyclic network structure

Figure 4 illustrates how the MD-frames are interrelated by introducing three structures representing different view points.

The functional flow structure describes memory activation paths starting from PMD-frames to WMD-frame, RMD-frame, or BMD-frame to MMD-frame, which describes how perception triggers motions. Notice that MMD-frame is the terminal MD-frame and therefore the paths from WMD-frame to RMD-frame, and RMD-frame to BMD-frame exist.

The layered structure consists of the following three layers:

1) *PMD-frame – WMD-frame layer* is the top layer controlled by words. It consists of sim-

ple one-dimensional array of symbols, logically constructed language, grammars that specify language use, etc.

2) *PMD-frame – RMD-frame layer* is the middle layer that resides on the behavioral econetwork for the individual. In this layer, one acquires the meaning of behavior in the social ecology.

3) *PMD-frame – BMD/MMD-frame layer* is the bottom layer that creates a behavioral econetwork for the individual. This is a cyclic network starting from PMD-frame towards MMD-frame, and returning to PMD-frame.

The evolving cyclic network structure depicted by a blue spiral refers to the fact that respective autonomous systems generate distributed memories for their use, and the memories are cyclically related and in effect topological.

These three features enable pipelining the processes. This cyclic connection is critical to understand the relationship between behavior and memory, which is not appropriately dealt with in the neuroscience researches.

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