Two Minds と行動選択・記憶
Two Minds and action selection/multi-dimensional memory frames*

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Abstract

We[1] have developed an architecture model, MHP/RT, that is capable of simulating people's daily action selection processes as an implementation of the dual-process theory [3]. MHP/RT describes people's daily behavior as a cyclic process of action selection and memory formation in the form of multi-dimensional memory frames. The cyclic process implies that the ways how people actually did should affect what would be memorized, and in turn the contents of memory should affect what people would do in the future. The purpose of this document is to provide a bird's-eye view of our project, development of a framework for considering the behavior of human-beings in the universe, NDHB-Model/RT, and a cognitive architecture, MHP/RT, that is capable of simulating human being's daily decision making and action selection under NDHB-Model/RT, with its complement memory structure, multi-dimensional memory frames.

Keywords — Two Minds, action selection, multi-dimensional memory frames

1. O-SCFT

To begin with, I start by describing the key idea, Organic Self-Consistent Field Theory (O-SCFT), that leads to the development of the theory of action selection and multidimensional memory frames.

1.1 SCFT in Physics

In physics and probability theory, Self-Consistent Field Theory (SCFT) studies the behavior of large and complex stochastic models by studying a simpler model. Such models consider a large number of small interacting individual components which interact with each other. The effect of all the other individuals on any given individual is approximated by a single averaged effect, thus reducing a many-body problem to a one-body problem.

In field theory, the Hamiltonian may be expanded in terms of the magnitude of fluctuations around the mean of the field. In this context, SCFT can be viewed as the zeroth-order expansion of the Hamiltonian in fluctuations. Physically, this means an SCFT system has no fluctuations, but this coincides with the idea that one is replacing all interactions with a self-consistent field. Quite often, in the formalism of fluctuations, SCFT provides a convenient launch-point to studying first or second order fluctuations.

1.2 O-SCFT

We applied SCFT in physics to organic systems. Organic systems are those comprised of human beings as their components. Any organic system can be represented as a model that considers a large number of interacting individual human beings which interact with each other. In addition, individual "organic" human beings interact with "inorganic" physical environment as well, which is modeled by SCFT. We prefixed the word "organic" to SCFT in order to explicitly indicate that the application domain of SCFT is extended to organic systems. We consider that the behavior of human beings in the universe is quasi-stable, which means that it is not stable but develop or evolve triggered by some fluctuations, a feature of dissipative system – a fluctuation of the system caused

*The contents of this document are from our papers including [1, 2, 3, 4, 5, 6].
[1] "We" refer to Makoto Toyota and Muneo Kitajima.

by an environmental change would trigger creation of a new order or catastrophe [7].

1.2.1 Human beings considered in O-SCFT

At the zeroth-order approximation implied by O-SCFT, each human being interacts with the integrated environment consisting of inorganic components and organic components. Each human being is considered as *autonomous system*, and interaction is best represented by *information flow* from the view point of human being. Figure 1 shows three nonlinear constructs, MSA, BIH, and SMT that correspond to human being, inorganic SCFT components, and organic O-SCFT components, respectively.

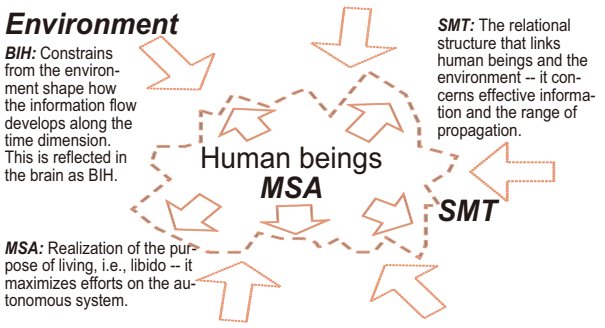

Figure 1 Three fundamental constructs of O-SCFT: MSA, BIH, and SMT.

1.3 Scale Mix

O-SCFT provides a macroscopic viewpoint and considers the system in question stable and it obeys the law of increase in entropy (second law of thermodynamics), whereas BIH provides a microscopic viewpoint where the universe is essentially a dissipative structure of a complex system that self-organizes as a hierarchical structure [7].

Gaia, the environment of the earth as a whole, is an extremely developed world of a complex hierarchical structure. Any phenomena in Gaia appear as the results of scale-mixed compound of individual phenomena, that coexist at different hierarchies characterized by their own scales in time and space. And therefore any entities in the complex hierarchical structure that live across the multiple hierarchies should exist under a certain balance in the scale-mix.

2. Development of Brain Architecture Model under NDHB-Model/RT

We are interested in not only how individual human being's brain processes information originated either from the external or the internal environment but also how it develops from his/her birth chronologically. We challenge this problem under the concept of MSA, BIH, and SMT shown in Figure 1.

2.1 O-PDP

We focus on information flow in the brain. We considered that Parallel Distributed Processing (PDP) is the fundamental mechanism for developing brain architecture [8]. Since PDP is considered under O-SCFT, we prefixed "O (organic)" to PDP, O-PDP, to indicate it explicitly.

O-PDP develops cross-networks of neurons in the brain as it accumulates experience of interactions in the environment. The neural network development process is *circular*, which means that any experience at a particular moment should reflect somehow the experience of the past interactions that have been recorded in the shape of current neural networks, i.e., memory. In this way, a PDP system is organized evolutionally, and realized as a neural network system, including the brain, the spinal nerves, and the peripheral nerves.

2.2 Architecture Selection

O-PDP represents the working of the entire organic system as a whole, in which a number of autonomous systems function in the real ever-changing environment. The strong constraint is that O-PDP evolves over time for millions of years in the largest scope, and develops from one's birth in the one-generation scope in the environment of Gaia. It is likely that a number of architectures could explain the behavior of human beings in the current status of Gaia.

However, we aimed at constructing one that should be consistent with the evolution history of human beings as well. This is the guideline we adopted for constructing an architecture. Figure 2 depicts it schematically.

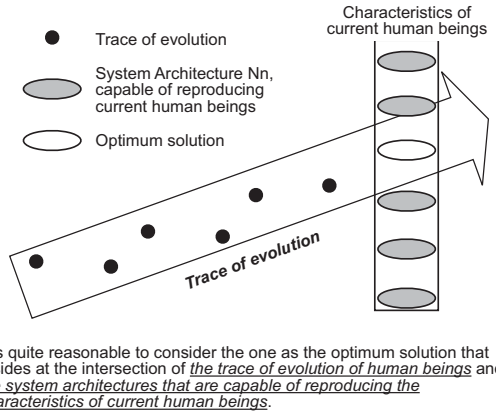

Figure 2 The guideline we adopted for selecting architecture.

2.3 Evolutional consideration

2.3.1 Three-layered structure of interneurons system

Cross-networks of neurons in the brain develop in a systematic way to show three-layered structure of interneurons system [9]. As shown by Figure 3, *interneurons* intervene the *sensory nervous system* that is responsible for processing sensory information and the *somatic nervous system* that is associated with the voluntary control of body movements via skeletal muscles to form complex paired structure of perception and motion. They consist of direct feedforward connections from perception to motion, and more complex connections with feedback loops using the interneurons to form three distinguishable layers.

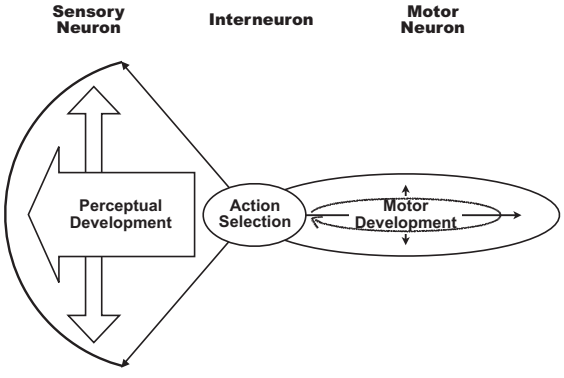

Figure 3 Development of the sensory nervous system and the somatic nervous system, and interneurons connecting them with action selection process.

Body movement is constructed by selecting executable motions and sequencing them in such a way that it adapts to the current environmental under environmental constraints. A motion is executable when it is exerted with stable postures, which are realized as a musculoskeletal system that has been formed via the developmental and experiential processes according to DNA's body plan. A body movement could be associated with multiple different purposes. Therefore, a meaning of particular body movement is given *consciously* as a compound social ecology. In this way, PDP [8] is naturally integrated with evolutional view [9].

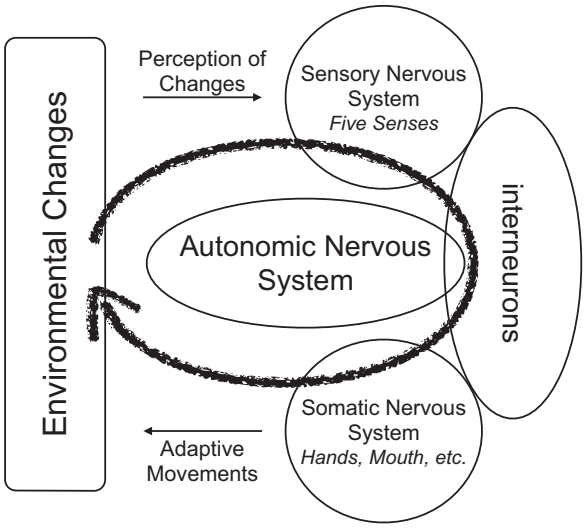

Figure 4 Continuous cyclic loop of perception and movement.

2.3.2 Development of neural network

According to [10], a vertebrate animal develops its neural network system in the following way. It starts with the development of the paired structure consisting of the sense of touch and reflexive movements associated with it. Then the sense of smell and the sense of taste, and finally, the sense of seeing and the sense of hearing develop their associations with reflexive movements. From the beginning, the perceptual stimuli from the five senses form a paired structure with their associated reflexive movements. In addition, the association tends to become bidirectional for the purpose of establishing selective sensing, which is a paired structure with feedback between perception and movement. For example, the sense of hearing and

the sense of vocalization establish a feedback loop between them immediately after one acquires the function of voicing.

The neural network system forms at first the autonomic nervous system of respective autonomous organs as a genetic fundamental structure, then crosses it with the somatic nervous system that controls reflexive movements associated with the perceptual stimuli from the five senses, and develops the feedback loops with a system of interneurons that connect these systems. Figure 4 depicts this loop schematically.

By pushing this further, we have developed NDHB-Model/RT as an architecture model that consists of a number of autonomous systems; including perceptual system, conscious system (System 2), unconscious system (System 1), memory system, behavior control system, and so on.

3. Two Minds and Memory

This section introduces Model Human Processor with realtime constraints (MHP/RT) as an implementation of Two Minds and autonomous memory systems.

3.1 Two Minds in Action Selection

Processes under O-PDP can be divided into conscious processes and unconscious processes. This has been studied in the domain of decision making for years. Kahneman, winner of the Nobel Prize in economics in 2002, introduced behavioral economics, which stems from the claim that decision-making is governed by the so-called "Two Minds" [11, 12, 13], a version of dual processing theory, consisting of System 1 and System 2. Figure 5 illustrates the workings of the two systems.

- **System 1:** The first type of process is a fast feedforward control process driven by the cerebellum and oriented toward immediate action. Experiential processing is experienced passively, outside of conscious awareness (one is seized by one's emotions).
- **System 2:** In contrast, the second type of process is a slow feedback control process driven by the cerebrum and oriented toward future action. It is experienced actively and consciously (one intentionally follows the rules of inductive and deductive reasoning).

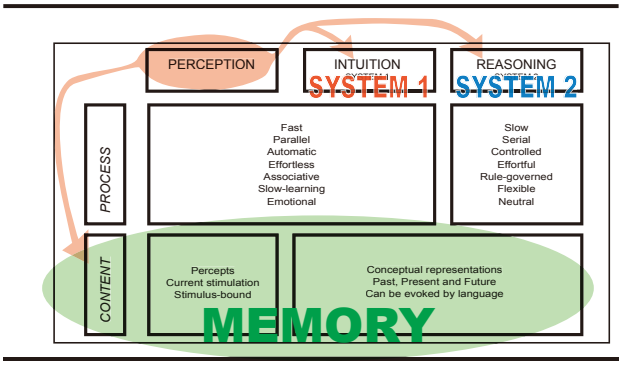

Figure 5 Two Minds (adapted from [11], shades are added by us)

3.2 Autonomous Memory System

Recent studies suggest that the memory system, shaded in green in Figure 5, should be considered as autonomous. As [14] write, unconscious memory establishes links to amygdala and is able to generate emotional response towards particular perceptual stimuli. This results in a great deal of strong active regions of memory, and therefore it is adequate to consider memory as a distinctive system.

3.3 MHP/RT: Integration of Two Minds and Memory

By integrating autonomous memory system and Two Minds, we have developed an architecture model, Model Human Processor with Realtime Constraints (MHP/RT), that is capable of simulating decision making and action selection in daily life, consisting of Two Minds, i.e., conscious processes, System 2, and unconscious processes, System 1, and an autonomous memory system. MHP/RT focuses on synchronization between System 1 and System 2 in the information flow under O-PDP. In other words, MHP/RT deals with one aspect of working of NDHB-Model/RT, which is synchronization between conscious system and unconscious system in the ever-changing environment where human beings make decisions and action selections to behave properly.

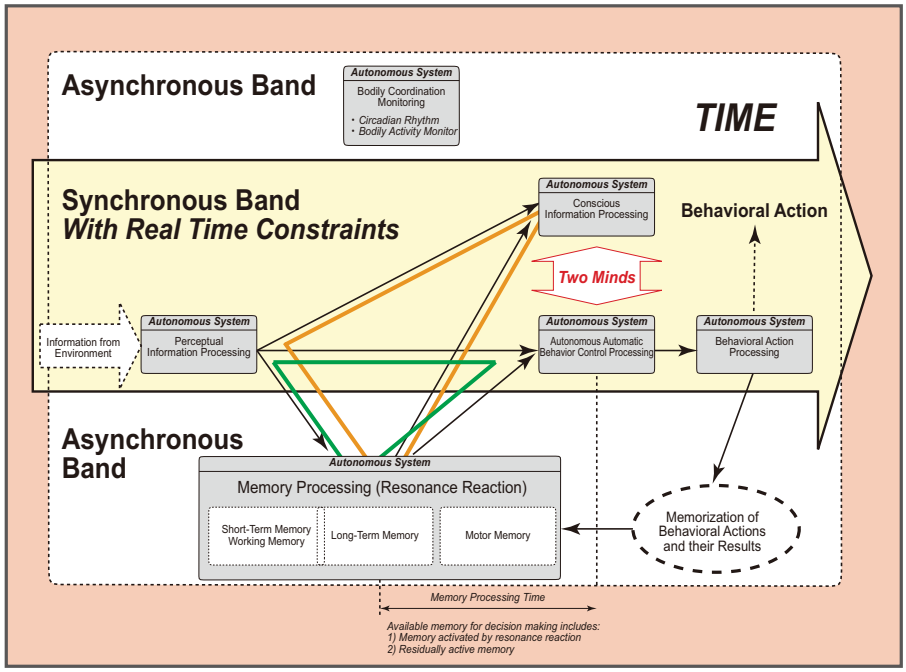

Figure 6 Outline of MHP/RT. Green lines indicates information for System 1 based processing and orange lines for System 2 based one. These two flows are synchronized before carrying out some behavior.

Figure 6 depicts the outline of MHP/RT. It is a *real* brain model comprising of System 1's unconscious processes and System 2's conscious processes at the *same* level. There are two distinctive information flows; System 1 and System 2 receive input from the Perceptual Information Processing System in one way, and from the Memory Processing System in another way. *System 1 and System 2 work autonomously and synchronously without any superordinate-subordinate hierarchical relationships but interact with each other when necessary.* In Figure 6, green lines and orange lines indicate the path associated with System 1 and the one associated with System 2, respectively.

3.4 Basic Operations of MHP/RT

At a given time, T, MHP/RT's state is considered from the viewpoint "which part of MHP/RT is working" or "how MHP/RT is working."

3.4.1 Four *Operation* Modes of MHP/RT

In MHP/RT as illustrated by Figure 6, behavior is the outcome of activities in System 1 and System 2 both of which use working memory to prepare for the next action. Depending on the situation, behavior is driven mainly by either System 1 or System 2. Both systems work *synchronously* by sharing working memory. The former is called Mode 1, and the latter, Mode 2. However, in some situations, both work *asynchronously*, Mode 3, or independently, Mode 4; working memory may be shared weakly or used solely for one of these layers.

Mode 1 (System 1 controls behavior): When System 1 governs behavior, the updating rate of the cognitive frame is the fastest, and the system behaves unconsciously. The system refers to the memory that is activated via the resonance reaction, and the outcome of behavior is consciously monitored, which is System 2's mission in this mode. As long as the output of behavior is consistent with the representation of the contents of activated memory, or prediction, no feedback control is applied. No serious decision-making is required but a series of unconscious action selections would result in smooth behavior. An example of this behavior mode is riding a bicycle on a familiar road.

Mode 3 (System 1 and System 2 are weakly coupled): In some cases, it is not necessary to monitor the behavior with high frequency. As a result,

System 2 may initiate tasks that are not directly relevant to unconscious behavior. In such a situation, consciousness is free from behavior that is tightly embedded in the environment. For example, while waiting for his/her name called in a lobby of a hospital, he/she may read a book. In this case, at the time when his/her name is called, he/she would be able to stand up immediately to start walking to the consultation room. In his/her working memory, the pointer to the action would be kept active while reading a book and waiting for the announcement.

This mode is characterized by weak coupling of System 1 and System 2, which means that pieces of information that reside in working memory are shared by System 1 and System 2, and therefore they could trigger the processes carried out by System 1 and System 2. And then, Mode 1 or Mode 2 takes over the operation. The shared information originates from perceptual encodings of the environment.

Mode 4 (System 1 and System 2 are isolated): In other cases, System 2 would initiate an independent process than System 1 is currently engaging. For example, he/she may use a mobile phone to talk with a friend while riding a bicycle, in which he/she might think deliberately to provide topics to enjoy conversation. In this case, his working memory would be used for two independent processes; talking with the friend over phone and riding bicycle safely. When encountering a dangerous situation, the system needs to take care of it primarily, which means that he/she needs to quit the phone conversation and uses his/her working memory for controlling bicycle. Switching the part of memory used for the phone call to the bicycle ride would cause a certain amount of delay in action.

This mode is characterized by isolation of System 1 from System 2, which means that each uses different portion of working-memory for the respective processes. System 2 could be either totally detached from System 1, e.g., daydreaming, or in the deliberate thinking mode like Mode 2, in which System 2 mainly controls behavior and System 1 works under the control of System 2 by using the area of working memory for this process. Mode 3 and Mode 4 are similar because the process System 1 takes control and the one initiated by System 2 are carried out quasi-independently, but they are different in terms of the

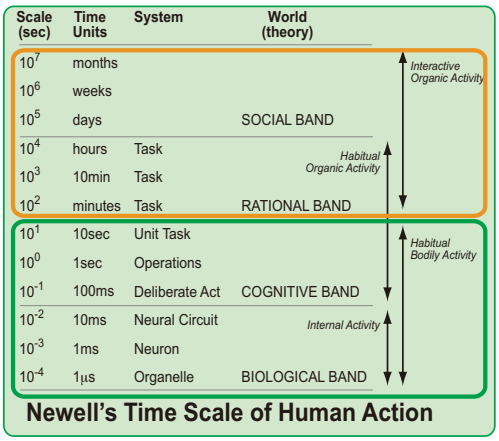

Figure 7 Newell's time scale of human action.

usage of working memory, i.e., Mode 3 has the area in working memory that hods information available to the two processes but Mode 4 does not.

Mode 2 (System 2 controls behavior): When System 2 governs behavior, the systems try to behave according to the image System 2 created, or meditate with no bodily movement. The least resources are allocated for initiating behavior according to input from the environment. This corresponds to a situation in which the amount of flow of information in System 1 is small. Working memory is occupied by activities related to System 2. However, the sensory-information filter functions so that the system can react to a sudden interruption from the environment, e.g., a phone call.

Mode 1 (System 1 control mode) would require least cognitive resources for stringing pieces of behavior in the ever-changing environment. On the other hand, Mode 2 (System 2 control mode) would consist of resource consuming activities including reasoning, recalling weak memory, etc. System 1 control may break down due to unexpected change in the environment, which would be detected by System 2's monitoring activity, leading to System 2 control mode for searching for procedures for escaping from the undesirable situation. Note that, in daily life, human beings are normally in System 1 control mode because human beings normally prefer effortless behavior, but occasionally forced to operate in System 2 control mode for the purpose of resuming to "normal" System 1 control mode as soon and easily as possible.

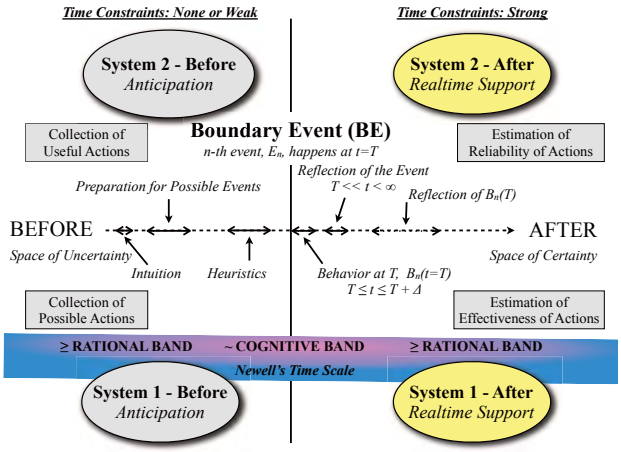

Figure 8 How the Four Processing Modes work

3.4.2 Four *Processing* Modes of MHP/RT

Event: It is important to introduce the concept of *event* for considering basic operations of MHP/RT in the multi-layered networks. For MHP/RT, an event corresponds to a point on the time dimension where it can select an action from the alternatives under a specific environmental condition. The environment makes chaotic changes, and human beings, modeled by MHP/RT, are requited to develop an adaptive system that is capable of dealing with a set of events that happen in such an environment.

4-Process: At a particular time *before the event*, say T_{before}, one engages in conscious processes and unconscious processes concerning the event. At a particular time *after the event*, one engages in conscious processes and unconscious processes. What one can do before and after the event is strongly constrained by the Newell's time scale of human action (see Figure 7). System 2 carries out the processes surrounded by an orange round-cornered rectangle, whereas System 1 does those surrounded by a green one.

There are four processing modes:

- **System 2 Before Mode:** Conscious use of long-term memory before the event, i.e., System 2's operation for anticipating the future event, or decision-making.
- **System 1 Before Mode:** Unconscious use of long-term memory before the event, i.e., System 1's operation for automatic preparation for the future event, or action selection.
- **System 1 After Mode:** Unconscious use of long-term memory after the event, i.e., System 1's operation for automatic tuning of long-term memory related with the past event.
- **System 2 After Mode:** Conscious use of long-term memory after the event, i.e., System 2's operation for reflecting on the past event.

Figure 8 illustrates the Four Processing Modes along the time dimension expanding before and after the event, which is shown as "boundary event" in the figure. At each moment along the time dimension human behaves in one of the four processing modes and he/she switches among them depending on the internal and external states.

4. Memory: Muti-Dimensional Frame

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, which is capable of simulating human daily behavior considering the real time constraints that should define strong mutual dependencies among the three systems.

4.1 Memory under O-PDP

The question is how memory is created under O-PDP with the cognitive architecture, MHP/RT. The simple answer is that memory is created via working of autonomous nervous system shown in Figure 4 that operates along the information flow from the sensory nervous system to somatic nervous system via interneurons under the time constraints reflecting the environmental conditions at the time of operation.

To begin with, we can derive structural features by considering the fact that each autonomous system in MHP/RT has its own memory; each memory system records the traces of its working over time. Therefore, the human memory structure is modeled conceptually as shown by Figure 9. MHP/RT assumes that memory is organized by Multi-Dimensional Frame (MD-Frame) for storing information. As the main

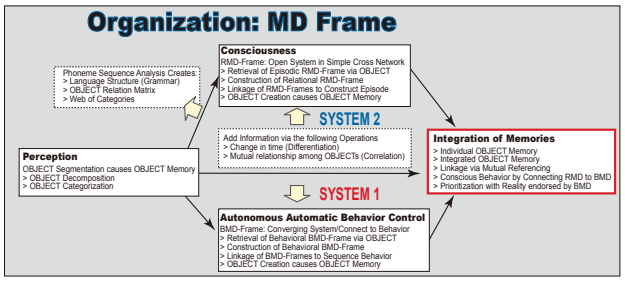

Figure 9 Multi-dimensional memory frame.

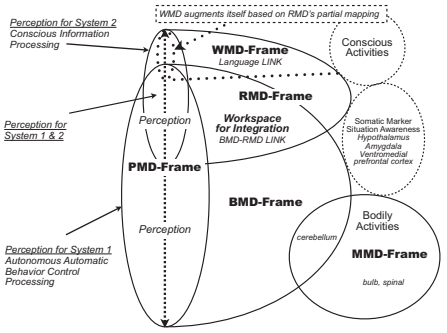

Figure 10 Distributed memory system

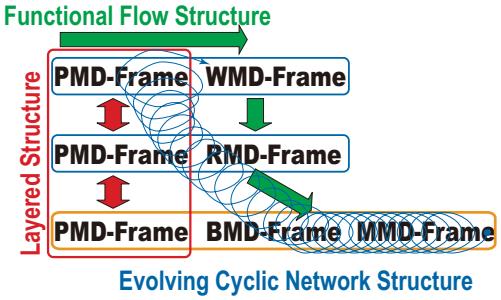

Figure 11 Functional flow structure, layered structure, and evolving cyclic network structure.

modules, MHP/RT consists of perceptual system, conscious processing system, and unconscious (autonomous automatic behavior control) processing system. Figure 9 illustrates memory systems associated with these main modules.

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

4.2 Five MD-Frames in MHP/RT

We call this memory the Multi-Dimensional (MD) -frame. There are five kinds of MD-frame in MHP/RT.

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.

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.

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.

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.

WMD (Word Multi-Dimensional) -frame is the

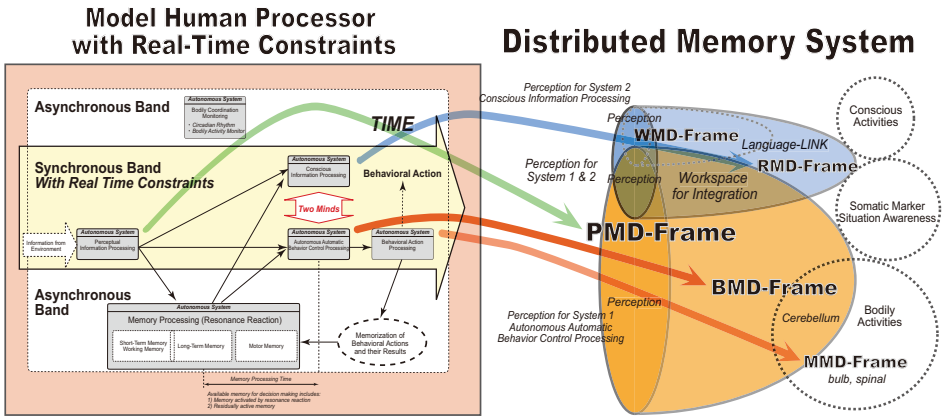

Figure 12 MHP/RT and the distributed memory system.

memory structure for language. It is constructed on a very simple one-dimensional array.

4.3 MHP/RT Processes and MD-Frames

Figure 12 shows that activity traces of autonomous systems of MHP/RT create respective memories as MD-Frames. If the area indicated as "Work space for integration" is used for creating memory, it integrates multiple MD-Frames. Later, this integration enables a set of MD-Frames to make chain-firing when provided with similar perceptual stimuli. As shown by the green arrows in Figure 11, chain-firing goes from PMD to MMD via WMD, RMD, and BMD.

The somatic nervous system that leads to BMD is created autonomously under the constraints defined by the mutual relationships between nerves, muscles and skeletons. This determines what is written in the memory. The entire memory system is topologically represented by Figure 10 and 11. This is used when reading information from memory, which determines actually read memory under the influence of reward (somatic marker) and status of short-term memory.

5. Summary

This final section explains the developmental paths of the neural networks as human beings grow through behave–memorize cycle as the function of their ages.

What we observe as each individual's physical behavior is the results of a multiple processing with a PDP system, not with a single unified system. This PDP system is organized evolutionally, and realized as a neural network system, including the brain, the spinal nerves, and the peripheral nerves.

Interneurons intervene the sensory nervous system that is responsible for processing sensory information and the somatic nervous system that is associated with the voluntary control of body movements via skeletal muscles to form complex paired structure of perception and motion. It consists of direct feedforward connections from perception to motion, and more complex connections with feedback loops using the interneurons to form three distinguishable layers.

There are two layers in the autonomous automatic behavior control processing, both of which are controlled by feedforward loops. *The first layer* is associated with reactive activities carried out by the spinal nerves characterized by automatic and simple reflexive movements. *The second layer* is associated with reactive activities carried out by the bulb or the cerebellum characterized by automatic and complex reflexive movements.

One layer is associated with the conscious information processing, controlled by feedback loops and the back propagation mechanism. *The third layer* is associated with activities carried out by the frontal lobe and the cerebrum characterized by deliberate movements.

Early stage (0 ∼ 6 years of age): In 0 ∼ 6 years of age, feedforward loops are the dominant control mechanism and they establish fundamental relationships between the layers by means of uplink. In the first half of this period, human beings establish inter-connections between Layer-1 and Layer-2 as integrated movements of bodily actions on the basis

of the relationships between the input from the perceptual system and the output expressed as reflexive movements, for example, simple utterances. In the latter half of this period, human beings acquire the skill of behaving in relation with the other persons and the methods for conversing with others such as explanation formation via simple syntax.

Middle stage ($7 \sim 12$ years of age): Later, human beings acquire the skill of logical thinking by means of the first order logic by using letters or symbols and that of cooperation with the other persons. These activities facilitate the development of interconnections among the three layers, resulting in very complex networks. The key is the existence of symbols that intervene various connections between input and output.

Later stage (13∼18 years of age): Lastly, in $13 \sim 18$ years of age, feedback loops come into play, which are used to form language processing circuits in a single layer, Layer 3, by means of the learning mechanism such as the back propagation.

In $13 \sim 18$ years of age, the interconnections of the neural networks evolve among the three layers. In this period, the ability of logical writing by using an ordinary language affects significantly the evolving process. Without language, structural recognition is formed dominantly via visual information. On the other hand, when accompanied with language, it makes possible to represent the visual information in a highly logical way, the vision-based structural recognition is significantly augmented to become a structure that can be dealt with a language-based logic system.

Final stage ($18 \sim$ years of age): Finally, in $18 \sim$ years of age, feedback loops become dominant, which make possible to form a compound language processing circuits by means of the learning mechanism such as the back propagation mechanism.

A final note – Role of language: It is important to notice that the "language" each individual is doomed to use should affect the course of development of the individual. There are obvious differences in the syntax of languages among, for example, Japanese, English, French, and so on. Therefore, Japanese people, for example, tend to acquire the skill of visual perception to compensate for the weakness of their language. It is because their language is not good at representing logical relationships. Conscious processing of System 2 comes at the later stage of the one's life. However, it poses strong constraints on the individual's developmental path, because it is language-bound. This consideration provides a new light on how the hierarchy of the neural networks should develop in the circumstances where we live.

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