Implementation of Structured Memes into Behavioral Ecology via GOMS

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***Abstract*— Our daily actions are executed to achieve desired states. Perceiving our own situation, we select actions that are expected to bring about the desired states, and execute them as a series. The memory used in this process is a representation in the brain of memes that are inherited from generation to generation. Memes are structured into three levels: action level, behavioral level, and cultural level, and are acquired through mimetic behavior. Memes at the higher levels are acquired as one gets older. This study is based on the Model Human Processor with Real-Time Constraints (MHP/RT), a cognitive architecture that includes Perceptual, Cognitive, and Motor (PCM) processes, and a memory system that is used during action selection by the PCM process and updated after action execution. We examine how the cognitive process of Two Minds utilizes memes structured in three layers, which is referred to as C-resonance in MHP/RT. It is known that knowledge built as a result of iterative actions toward a goal state is represented by a GOMS hierarchical structure whose elements are goals (G), operators (O), methods (M), and selection rules (S). This study shows that GOMS bundles memes belonging to different levels and combines goals and selection rules at the conscious level with methods and operators at the unconscious level to achieve effective and efficient goal-oriented action execution. The expressed behavior can be regarded as the result of crossing the syntax expressed by GOMS with the semantics expressed by memes, showing distinct characteristics depending on the balance of dominance between unconscious and conscious behavior in the behavioral ecology.**

Keywords*— *GOMS; Behavioral ecology; Meme; Resonance.

I. INTRODUCTION

In interacting with the environment for living, humans develop by selecting and executing actions and accumulating execution results while operating a cyclic loop of the Perceptual, Cognitive, and Motor (PCM) processes. The basis of action selection is imitation. The things – any cultural entity including objects and events that an observer might consider a replicator of a certain idea or set of ideas – to be imitated exist as memes; they are repeatedly imitated from generation to generation.

A. Meme Proposed by Dawkins [1]

The mechanism by which cultures and civilizations produced by humans are passed on from generation to generation was not clear. From the standpoint of cultural anthropology, Dawkins organized his research on the mechanisms of cultural inheritance. As a result, he argued that cultural inheritance cannot be explained solely in terms of the capability of memory on the part of humans, and that there must be a hypothetical existence on the part of culture that might convey information, such as genes. He coined the term "meme" for this indefinite virtual entity [1]. This idea itself received a lot of support, but the time passed without the mechanism being clarified [2].

When Dawkins proposed the meme, the function of genes was not yet understood. Therefore, Dawkins' explanation and others had many problems inherent in them due to misunderstandings about genes. Certainly, genes were replicators. However, they did not play the role of duplicating the blueprint of the finished product as conventionally thought, but rather, they played the role of plotting the process of growth that established the basic functional structure and its relationships. It was this role of the genes that enabled humans to be highly adaptable.

B. Redefining Memes through their Connection to the PCM Process

The memes proposed by Dawkins can be redefined by considering them as mappings of the individual's memory (which can be called *the individual ecological memes*), which is activated in the process of selecting and executing actions, onto *the collective ecology* that caries the culture. Memes are realized in the memory of each individual. They hold the relationships between events, which enable humans in an ever-changing environment to express effective behavior in each situation in generic forms that are valid across generations [3]. More specifically, the spatial coordinates and absolute times that characterize events occurring in the real world are *not* retained in the memes; they are dynamically determined according to the state of the environment when the behavior is expressed according to the representation of the memes.

Figure 1 shows a schematic representation of the action selection and execution process in the real environment as the PCM process. In the perceptual process, humans perceive the state of the real environment through parallel processing of

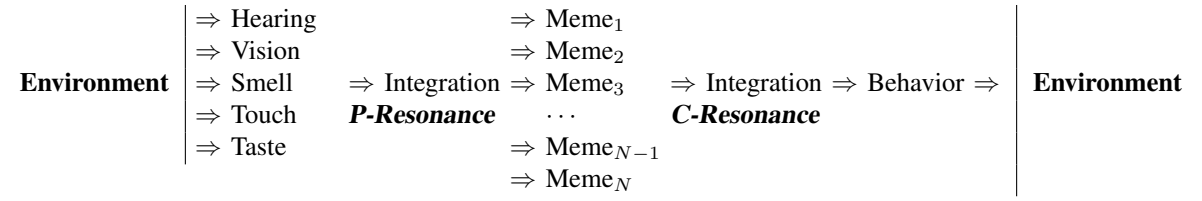

Figure 1. PCM process and memes

the five senses and integrate what they perceive individually by binding them. In the cognitive process, the memes related to the perceived information are activated in parallel, and they are integrated as a series of operators that can be executed as concrete actions in the environment. In the motor process, the operators are executed through feedforward processing, keeping pace and synchronizing with changes in the environment in an unconscious manner.

C. Problem Statement

The PCM process runs synchronously with the environment, whereas, the "memory system" used by the PCM process updates itself asynchronously with the environment to reflect the results of the PCM process. Supported by the PCM process and the memory system, each individual repeats action selections in an ever-changing environment without any breakdown. In this regard, it is important to clarify the interface between the PCM process, which operates synchronously with the environment, and the memory system, which is not required to synchronize with the environment but is connected to the PCM process. The mechanism for connecting what is perceived with memory has been described as P-resonance [4]. Within the memories, structured with memes as elements, activation propagates in parallel with the integrated perceptual information as the activation source. Connecting activated memories to the actions performed in the real world can be rephrased as "enabling the activated memes in the real world by integration." In Figure 1, this mechanism is shown as C-resonance. How is this done?

When we unravel the origin and evolution of life, we can find a clue to the solution. Life is formed under the structures shaped by the atmosphere, oceans, energy cycles, and gravity that characterize the Earth, a planet in our solar system, spinning on its own axis and orbiting the Sun. The direction of life's evolution is determined by the pressures exerted by these structures. Life is formed as an adaptive body with the functional and structural feature that work most efficiently in the environment. It is best captured by the four elements of Goals, Operators, Methods, and Selection rules (GOMS) [5]. In this study, we show that C-resonance, which integrates the memes activated in parallel as the effective actions in the real world, can be explained by the GOMS concept.

D. Organization of the Paper

This paper is organized as follows. Section II describes the PCM process and memes, referring to our previous work. Section III describes the GOMS theory presented by Card, Moran, and Newell in their book entitled "The Psychology of Human-Computer Interaction," and describe the mechanism of C-resonance. Section IV discusses the characteristics of the behavioral ecology that emerge from the interaction of the structured meme content and the C resonance by GOMS. Section V summarizes this study and discuss its implications for the digital generation.

II. PCM Process and Memes

In this section, we explain the details of the PCM process, memories, and memes outlined in Figure 1, based on our cognitive architecture "Model Human Processor with Realtime Constraints (MHP/RT)" [6][7].

A. PCM Process and Resonance for Linking with Memory

When interacting with the environment, humans respond to physical and chemical stimuli emitted from the external and internal environment by sensory nerves located at the interface with the environment and take in environmental information in the body. The brain acquires environmental information concerning the current activity of the self through the multiple sensory organs. Further, it generates bodily movements that are suitable for the current environment. The stable and sustainable relationship between the environment and the self is established through continuous coordination between the activity of the self and the resultant changes in the environment, which should affect the self's next action.

Figure 2, adapted from [4, Figure 1], shows the process, based on MHP/RT [6][7], by which environmental information is taken into the body via sensory nerves, processed in the brain, and then acted upon by the external world via motor nerves. This process involves memory, which is modeled as Multi-Dimensional Memory Frame, and perceptual, cognitive (Two Minds), and motor processes. The memory structure, Multi-Dimensional Memory Frame, consists of Perceptual-, Behavior-, Motor-, Relation-, and Word-Multi-Dimensional Memory Frame. Perceptual-Multi-Dimensional

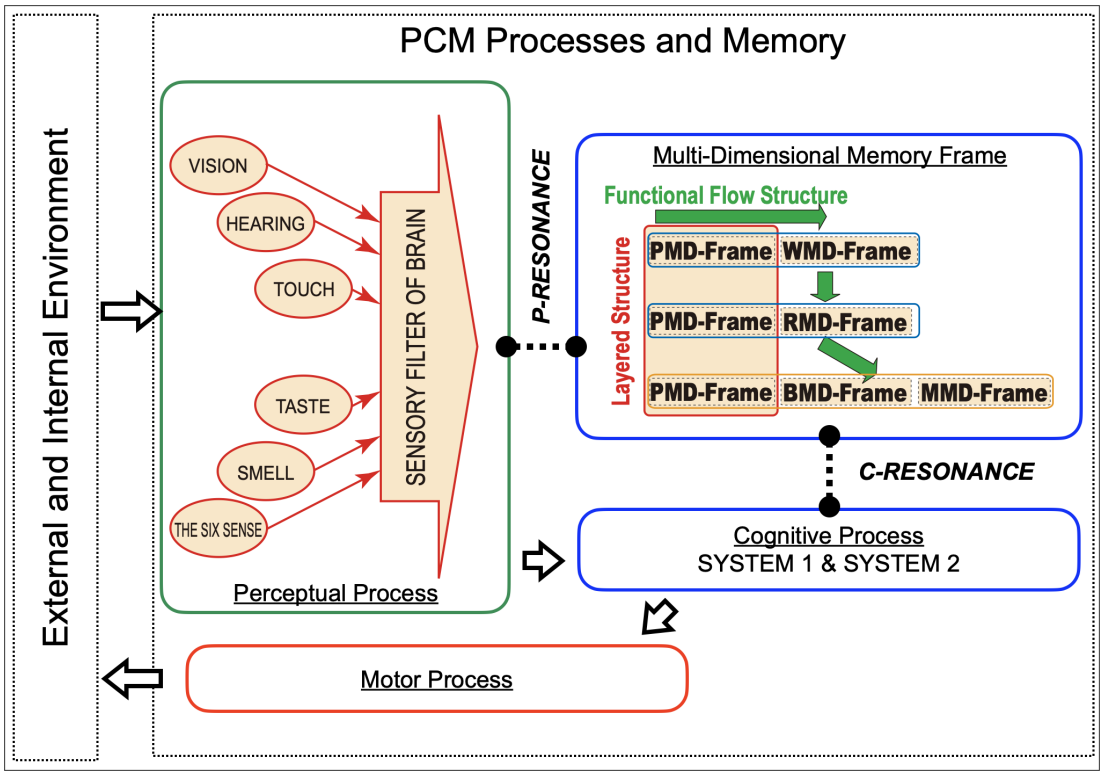

Figure 2. Information uptake by perceptual processes from the external and internal environment memory activation and execution of cognitive and motor processes through resonance [4, Figure 1].

Memory Frame overlaps with Behavior-, Relation-, and Word-Multi-Dimensional Memory Frame, for spreading activation from Perceptual- to Motor-Multi-Dimensional Memory Frame.

Perceptual information taken in from the environment through sensory organs resonates with information in the memory network structured as Multi-Dimensional Memory Frame, that is, P-Resonance. In Figure 2, this process is indicated by •—•. Resonance occurs first in the Perceptual-Multi-Dimensional Memory Frame and activates the memory network. After that, the activity propagates to the memory networks that overlap the Perceptual-Multi-Dimensional Memory Frame, which are Behavior-, Relation-, and Word-Multi-Dimensional Memory Frame, and finally to the Motor-Multi-Dimensional Memory Frame. In cognitive processing by Two Minds, conscious processing by System 2, which utilizes the Word- and Relation-Multi-Dimensional Memory Frame via C-Resonance, and unconscious processing by System 1, utilizing the Behavior- and Motor-Multi-Dimensional Memory Frame via C-Resonance, proceed in an interrelated manner. The motor sequences are expressed according to the Motor-Multi-Dimensional Memory Frame, which is the result of cognitive processing. The memories involved in the production of actions are updated to reflect the traces of its use process and influence the future action selection process.

B. P-Resonance Connecting Perceptual Processes and Multi-Dimensional Memory Frame

Information from the environment is taken into the brain via multiple sensory organs. The sensory organs are distributed throughout the body. In addition, the information received by sensory organs is time-series information. Therefore, the information received by sensory organs is spatially and temporally distributed. The brain integrates this disparate sensory information in some way, perceives it, and passes it on to cognitive processing. The question of how this integration is performed is known as the binding problem. We proposed that P-resonance provides a solution to the binding problem and showed the existence of basic senses that enable orderly processing of information from sensory organs. The basic senses include rhythmic sense related to time, spatial sense related to spatial perception, and number sense [4].

C. Memory as Structured Meme

When the PCM process is running, the contents of Perceptual-Multi-Dimensional Memory Frame are updated in response to the perceptual process, those of Word-, Relation-, and Behavior-Multi-Dimensional Memory Frame are updated in response to the cognitive process, and those of Motor-Multi-Dimensional Memory Frame are updated in response to the motor process. Figure 2 characterizes the memories of PCM process, i.e., the Multi-Dimensional Memory Frame, as the traces of its operation and classifies it into five sub-memories, i.e., Perceptual-, Word-, Relation-, Behavior-, and Motor-Multi-Dimensional Memory Frame. In short, it is an expression of the way in which the memories are structured, focusing on the continuous updating of memory associated

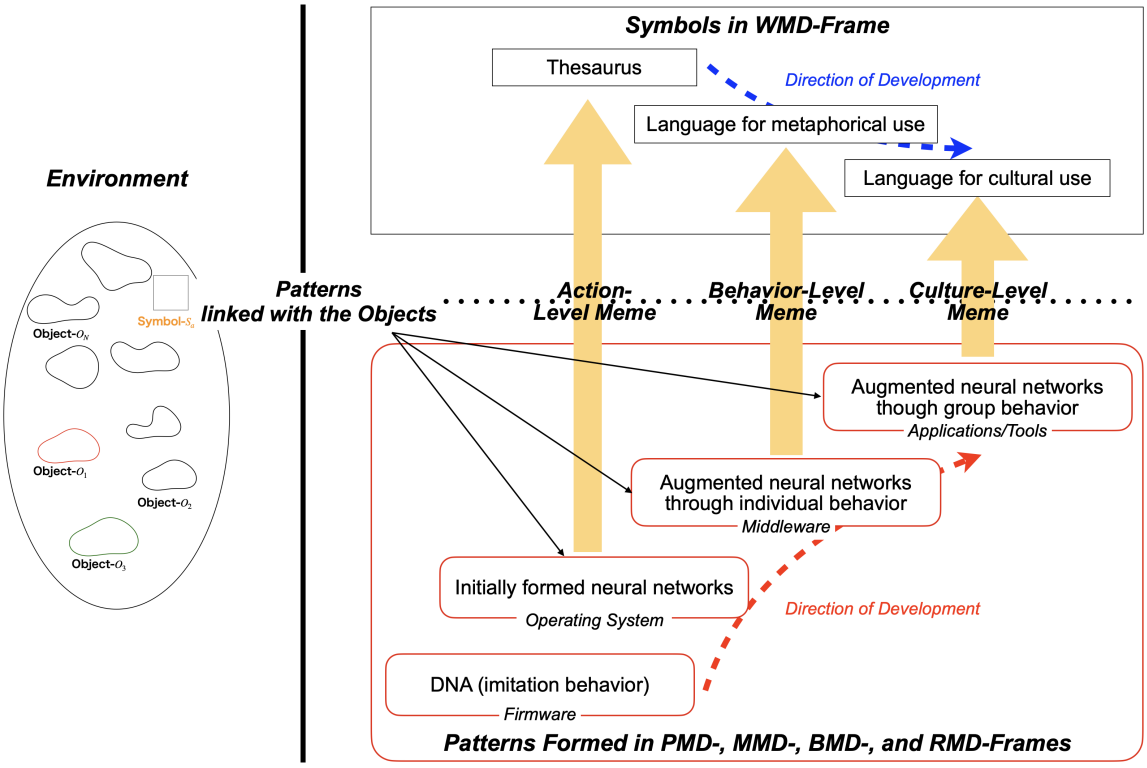

Figure 3. Structure of meme (adapted from [3])

with the execution of PCM process. It is important to note that, in the Multi-Dimensional Memory Frame, Perceptual-Multi-Dimensional Memory Frame overlaps with Behavior-, Relation-, and Word-Multi-Dimensional Memory Frame, for spreading activation from Perceptual-Multi-Dimensional Memory Frame to Motor-Multi-Dimensional Memory Frame.

Alternatively, the memory system can be viewed from the perspective of memory use. The integrated sensory information through the basic senses first activates the Perceptual-Multi-Dimensional Memory Frame (P-resonance); then the activation propagates to the Word-, Relation-, and Behavior-Multi-Dimensional Memory Frame, and finally to the Motor-Multi-Dimensional Memory Frame bound to the motor nerves. This process is repeated in an environment that changes from moment to moment, and satisfactory behavior is expressed in the environment. The basis of behavior is imitation, and what is imitable is limited according to growth stage. In addition, behaviors that can be imitated across generations are preserved as sustainable behaviors. In this way, we can organize the Multi-Dimensional Memory Frame, which is used by the PCM processes and updated by their execution, in terms of memes that can be inherited across generations [8].

Figure 3 shows a functional classification of the regions of the Multi-Dimensional Memory Frame that are activated by P-resonance after an object in the environment has been perceived. “Words” are considered the archetype of meme [9]. Words, i.e., symbols, in the Word-Multi-Dimensional Memory Frame are gradually incorporated into the environment in the form of *thesauruses*, i.e., lists of words in groups of synonyms and related concepts, languages used for person-to-person communication, *individual languages*, which might include not only direct but also metaphorical uses, and languages used in cultural contexts, *cultural languages*, in which appropriate understanding of common sense that has been established in the specific community, is essential for successful communication.

Thesauruses, individual languages, and cultural languages increase their complexity in this order in terms of the patterns they are linked with the objects in the environment. Thesauruses are associated with the objects in the environment that are encoded in the neural networks in the initial development stage from the birth to 3 years. Individual languages are associated with not only the objects in the environment but also the symbols that have already been incorporated in the environment. The same is true for cultural languages.

The process of “Mapping patterns on symbols in Word-Multi-Dimensional Memory Frame” can be subdivided into three processes based on the degree of complexity of mapping. The patterns that were mapped on the thesauruses, individual languages, and cultural languages are shown as Action-Level Meme, Behavior-Level Meme, and Culture-Level Meme, respectively, that were introduced in the Structured Meme Theory proposed by Toyota et al. [8]. Hereafter, the memes classified into Action-Level Meme, Behavior-Level Meme, and Culture-Level Meme are abbreviated by A-memes, B-memes, and C-memes, respectively.

The culture that exists in the environment is the integration of the C-memes that exist in the brain of an individual across all members of the group to which that individual belongs. This corresponds to the meme proposed by Dawkins. Blackmore, one of the theoretical followers of Dawkins' meme theory, argues that "memes are symbolized by the act of imitation" after examination of the theory of the meme [10]. This argument is consistent with the idea of memes as we have presented it, since we can think of it as saying that the A- and B-memes are physical and provide a stable basis for imitation, and that the C-memes above them is not mentioned because it is strongly dependent on the environment.

The mechanism by which the three levels of memes, and genes as well, inherit information is analogous to an information system. Genes serve as firmware that mimics behavior-level activities. A-memes serve as the operating system that defines general patterns of spatial-temporal behavioral functions. B-memes represent middle-ware that extends the general patterns to concrete patterns. C-memes act as application tools that extend the concrete patterns to the ones that work in a number of groups of people.

The relationships between the three levels of memes and the Multi-Dimensional Memory Frame are as follows:

- A-memes represent bodily actions stored in the Motor-Multi-Dimensional Memory Frame,
- B-memes represent behaviors in the environment stored in the Behavior-Multi-Dimensional Memory Frame, and
- C-memes represent culture stored in the Relation- and Word-Multi-Dimensional Memory Frame.

Meme-based behaviors, i.e., mimicry behaviors, are implemented in the real environment. Since what can be imitated depends on the individual growth stage, there are qualitatively different sets of mimicry behaviors to emerge depending on the growth stage. The bases of those mimicry behaviors are represented as A-memes, B-memes, and C-memes.

As Dawkins proposed, taking a meme-centric view of cultural inheritance is in itself essential. A person's genes express a memory resonance response mechanism. Through this mechanism, replications (resonance replications) are generated when there is a common experience. Memes are present in the environment as those that can cause these resonance replication. Such memes can be called cultures. Memes influence the phenotype called culture, but the resonance itself is formed as something unique in a person's experience. The fact that imitation is personal and influenced by environmental conditions does not guarantee that the phenotype will be perfectly imitated. This mechanism is common to the idea of ecological inheritance theory, named niche (ecological status) construction, advanced by Odling-Smee et al. in evolutionary ecology [11]. This mechanism makes it possible for humans to be highly adapted to their environment.

III. C-RESONANCE VIA GOMS

A. Binding Problem at the Cognitive Level

In Figure 3, the objects in the environment are shown to activate the A-, B-, and C-memes. In this activation process, various regions related to the objects are activated. In Figure 2, the propagation of activation within the Multi-Dimensional Memory Frame is shown as the functional flow structure. The expression is such that the activity propagates from the Perceptual-Multi-Dimensional Memory Frame to Word-, Relation-, Behavior-, and Motor-Multi-Dimensional Memory Frame in that order. However, the layers below the Word-Multi-Dimensional Memory Frame are not structurally overlapped. Therefore, the activity propagates layer by layer from the top to bottom via the Perceptual-Multi-Dimensional Memory Frame that overlaps with them; at the top, there is an activation flow from the Word- to Perceptual-Multi-Dimensional Memory Frame, at the middle from the Perceptual- to Relation-Multi-Dimensional Memory Frame, and at the bottom from the Perceptual- to Behavior-, finally to Motor-Multi-Dimensional Memory Frame. The portions of Word-, Relation-, and Behavior-Multi-Dimensional Memory Frame that are activated in this manner may contain multiple regions that may be related via the Perceptual-Multi-Dimensional Memory Frame but not directly related to each other.

Memories that hold memes are activated in parallel to be used by the PCM process, which is a serial process. Here, we can see another binding problem occurring at the cognitive level. In Figure 2, the bridge between cognitive and memory processes is shown as C-resonance for resolving the meme binding problem. The cognitive process might operate *carefully* by using the entire areas of the Multi-Dimensional Memory Frame that are activated in connection with the Perceptual-Multi-Dimensional Memory Frame. The advantage of this method is that reality can be guaranteed by referring to the contents active in the Perceptual-Multi-Dimensional Memory Frame. However, it is *inefficient* because it is an interpreter-like process. At the perceptual level, the binding problem of perceptual information is solved by P-resonance for effective use of the perceptual information. At the cognitive level, C-resonance resolves the problem of efficient use of memory by binding memes somehow that are activated in parallel [12]. What is the equivalent of the basic senses in P-resonance in C-resonance?

B. GOMS

1) GOMS as a Meta-Structure for Understanding Behavioral Ecology: Humans select actions that contribute to the realization of the state they desire to achieve. The principles at work in the execution of the cognitive activity of action selection are the bounded rationality and satisficing principles [13]. Such action selection processes are modeled by the serial firing of procedural knowledge expressed in the form of production rules, "IF conditions are satisfied, THEN perform actions [14][15][16]." Individual action choices are expressed in terms of firing sequences of production rules, which are procedural knowledge. However, if we take a bird's-eye view of the situations that each individual encounters, the firing sequences of procedural knowledge applied in more or less similar situations will show certain patterns. Card, Moran and

Activation of Memes via P-Resonance			Utilization of Memes via C-Resonance	
Perceptual Process	Multi-Dimensional Memory Frame	Memes	GOMS	Cognitive Process
Basic Senses	Word- & Relation-	Culture-Level	Goals and Selection Rules	System 2
	Behavior-	Behavior-Level	Methods	System 1
	Motor-	Action-Level	Operators	System 1

Figure 4. Relation between GOMS, memes, and Two Minds

Newell [5] identified GOMS as concepts that represent such patterns.

GOMS specifies concepts that define a meta-structure that is essential for understanding the ecology of human behavior. Aristotle's theory of the four causes was the first theory to systematize such a meta-structure. Allen Newell et al. reconstructed it from a cognitive scientific perspective and constructed the GOMS theory.

2) Definition of GOMS: GOMS is an analytic technique for making quantitative and qualitative predictions about skilled behavior with a computer system. GOMS is defined as follows (adapted from [5, Chapter 5, pp.144–146]):

> The user's cognitive structure consists of four components: (1) a set of Goals, (2) a set of Operators, (3) a set of Methods for achieving the goals, and (4) a set of Selection rules for choosing among competing methods for goals. We call a model specified by these components a GOMS model.
> ***Goals***. A goal is a symbolic structure that defines a state of affairs to be achieved and determines a set of possible methods by which it may be accomplished.
> ***Operators***. Operators are elementary perceptual, motor, or cognitive acts, whose execution is necessary to change any aspect of the user's mental state or to affect the task environment.
> ***Methods***. A method describes a procedure for accomplishing a goal. It is one of the ways in which a user stores his knowledge of a task. The description of a method is cast in a GOMS model as a conditional sequence of goals and operators, with conditional tests on the contents of the user's immediate memory and on the state of the task environment.
> ***Selection Rules***. When a goal is attempted, there may be more than one method available to the user to accomplish the goal. The selection of which method is to be used need not be an extended decision process, for it may be that task environment features dictate that only one method is appropriate. On the other hand, a genuine decision may be required. The essence of skilled behavior is that these selections are not problematical, that they proceed smoothly and quickly, without the eruption of puzzlement and search that characterizes problem-solving behavior. In a GOMS model, method selection is handled by a set of selection rules. Each selection rule is of the form "if such-and-such is true in the current task situation, then use method M."

Behavioral goals are represented by a robust hierarchical structure. There is a primary behavioral goal, G, and underneath it, there are subgoals, G′, that must be accomplished to complete the primary goal, and then there are sub-subgoals, G″, to complete the individual subgoals. The final node that unfolded the task is the operator. One node above it is the method, and one level above it is the node representing the selection rule. The goal structure from top to bottom looks like "G-G′-G″ $\cdots$ S-M-O."

3) Binding Memes via GOMS: In GOMS, behavioral goals form a robust hierarchical structure, and the goal structure mediates the organization of behavior. Achieving a goal, G, requires achieving the subgoals underneath it, G′s. This structure does not hold the time as its primary parameter. The order between G′s is important. The time elapsed for executing G′ is associated with the operators located at the bottom layer, which connect to the motor process of PCM that implements the contents of Motor-Multi-Dimensional Memory Frame, i.e., the operators, in the real world.

On the other hand, the mechanism of action execution based on MHP/RT is explained as follows. As shown in Figure 2, the environment is perceived and connected to the Multi-Dimensional Memory Frame by P-resonance. Then, as shown in Figure 1, the memes having been acquired by structuring the Multi-Dimensional Memory Frame through experience are activated, and the A-memes are connected to the real world to execute the action. As mentioned earlier, in the functional flow structure within the Multi-Dimensional Memory Frame shown in Figure 2, behavior generation following the flow of activity through the Perceptual-Multi-Dimensional Memory Frame is inefficient. It is reasonable to assume that GOMS is used to structure A-, B-, and C-memes that do not contain absolute temporal and spatial information as a method of realizing behavior generation without breaking down, while keeping in sync with the real world where the situation changes from moment to moment. GOMS should correspond to the phenomenon of A-, B-, and C-memes binding without the Perceptual-Multi-Dimensional Memory Frame when encountering certain situations, indicating the entity of the phenomenon of C-resonance. This may correspond to a shortcut that may be formed within the Multi-Dimensional Memory Frame.

Figure 4 shows the correspondence between memes and GOMS. Among the activated memes, the combinations of C-, B-, and A-memes that have formed GOMS bonds in the process of gaining experience are processed by System 2 and System 1, and the operator sequence is executed in the real

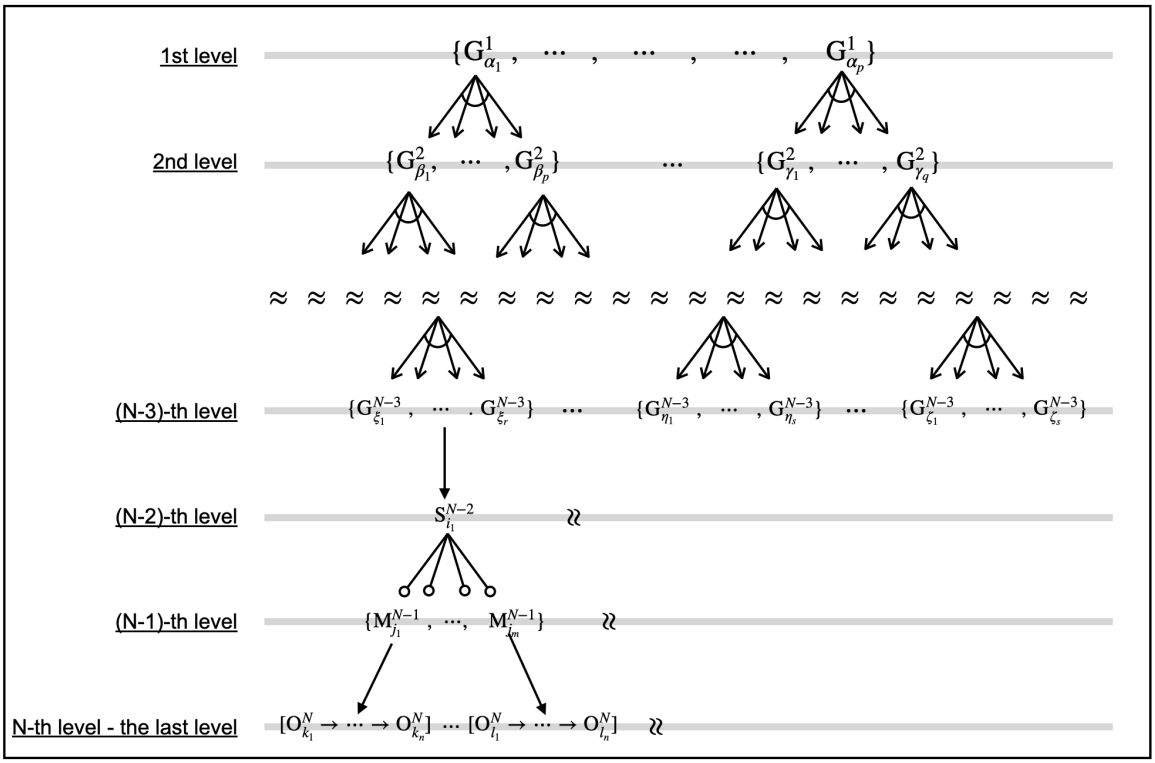

Figure 5. GOMS connection structure

world [17].

IV. Discussion: Deepening the Understanding of Behavioral Ecology

A. GOMS-construct Structure and Behavioral Ecology

1) GOMS-construct Structure: Figure 5 shows the overall picture of GOMS-construct, which has been constructed by experience, in a general form. The GOMS-construct is explained in the following by starting from the operator sequence, $\mathbf{O} = [\mathrm{O}^N_{k_1} \rightarrow \cdots \rightarrow \mathrm{O}^N_{k_n}]$, which is expanded at the lowest N-th layer, and working upward. At the immediately above the $(N-1)$-th layer, the method that connects to this operator sequence, $\mathbf{M} = \mathrm{M}^{N-1}_{j_1}$, exists. This can be regarded as a node that holds a pointer to this operator sequence, $\mathbf{O}$. This method serves to connect the goal, $\mathbf{G_i} = \mathrm{G}^{N-3}_{\xi_i}$, which resides two layers above it, at the $(N-3)$-th layer, with the operator sequence, $\mathbf{O}$, to achieve it. If there are multiple methods, $\{\mathrm{M}^{N-1}_{j_1}, \cdots, \mathrm{M}^{N-1}_{j_m}\}$, that can achieve $\mathbf{G_i}$, the selection rule, $\mathrm{S}^{N-2}_{i_1}$, is placed between these layers at the $(N-2)$-th layer.

Above the $(N-3)$-th layer, a hierarchical structure of goals is developed. The goals located at the top level, the first layer, $\mathbf{G^1_i} = \mathrm{G}^1_{\alpha_i}$, are expanded into a set of goals, $\mathbf{G^2} = \{\mathrm{G}^2_{\beta_1}, \cdots, \mathrm{G}^2_{\beta_p}\}$, at the second layer, and $\mathbf{G^1_i}$ is achieved by the achievement of all goals contained in $\mathbf{G^2}$. Hereafter, all goals at the first layer are expanded while maintaining this structure until the $(N-3)$-th layer. Note that in Figure 5, for convenience, the top-level goal is placed at the first layer and the N-th layer is represented as the lowest operator layer, but the depth of the hierarchy varies depending on the content of the top-level goal. Therefore, the concrete value of N varies depending on $\mathbf{G^1_i}$.

It would be appropriate to regard the individual G, O, M, S shown in Figure 5 as nodes that hold pointers connecting them to specific parts of the A-, B-, and C-memes. In the real behavioral situations, efficient use of memory is requited for smooth operation of the PCM process. Therefore, it is necessary to select and execute appropriate actions without continuously referring to the Perceptual-Multi-Dimensional Memory Frame, which is activated by P-resonance with the environmental information, while keeping in sync with the environment where the situation changes from moment to moment. Given this, the assumption that "there is an upper bound on the total number of G-, O-, M-, S-nodes available in C-resonance mediated by the GOMS structure" seems reasonable. The total number of goals is denoted as $\hat{G}$, the total number of methods as $\hat{M}$, the total number of selection rules as $\hat{S}$, the total number of operators as $\hat{O}$, the average depth of the hierarchy as $\bar{N}$, and the upper bound on the number of nodes as $\hat{C}$, which is a constant value. We then consider variations in the overall picture of GOMS-construct constructed through experience under the condition, $\hat{G} + \hat{O} + \hat{M} + \hat{S} \leq \hat{C}$, based on the relationship between each of the upper bounds.

An operator is an elemental perceptual, motor, or cognitive action; the execution of which produces a distinguishable change in the actor and/or the environment. Since the operator

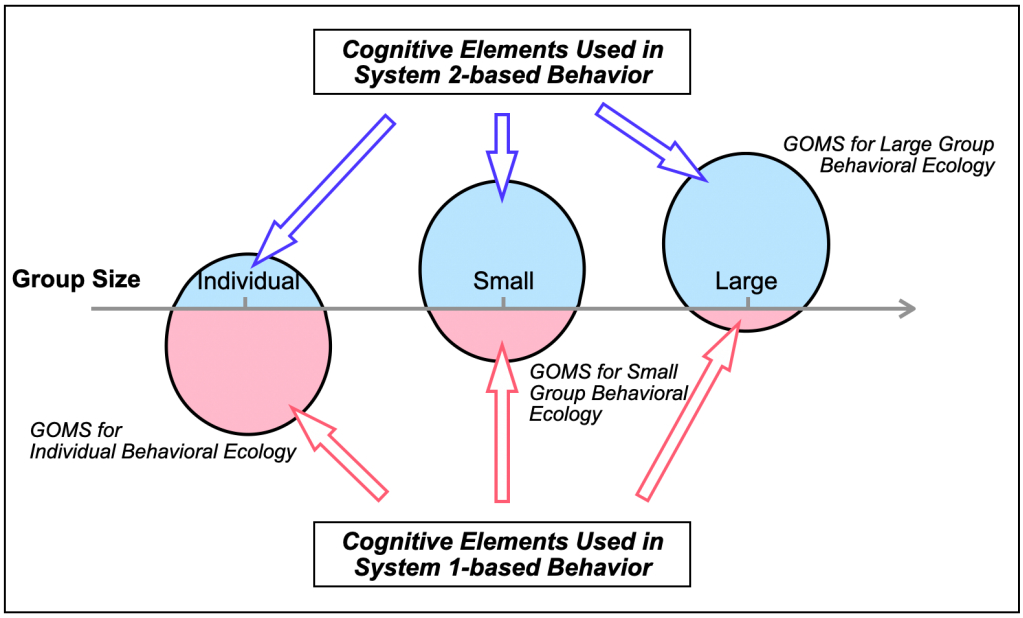

Figure 6. Changes in the Two Minds balance of GOMS components due to differences in behavioral ecology under brain processing capacity (time) constraints

is an elemental part of the construction of the method, $\hat{O}$ is presumed to be much smaller than $\hat{C}$. Then, how are the non-operator available nodes used? The top-level goals are expanded to sub-goals, eventually leading to the determination of a set of achievable methods to be defined under each goal. A method is a kind of goal that can be executed by the operators, pointing to a chunk of the operator sequence connected to it, so that the elements of the set of operators can be used as material to achieve the lowest goal that has been developed. If there are multiple methods that can achieve the goal, one method is selected based on the selection rule that defines the conditions for application of the method.

2) Characteristics of the GOMS-construct Structure: For an event $E(T)$ that occurs at time T, MHP/RT deals with it in its four processing modes [6]. They are as follows:

- System-2-Before-Event-Mode, which consciously considers $E(T)$ beforehand,
- System-1-Before-Event-Mode, which unconsciously adjusts its behavior to the environmental context immediately before $E(T)$,
- System-1-After-Event-Mode, which unconsciously adjusts the connections within the relevant Perceptual-, Behavior-, and Motor-Multi-Dimensional Memory Frame immediately after $E(T)$, and
- System-2-After-Event-Mode, which consciously reflects on $E(T)$ afterwards to adjust the connections within the Relation- and Word-Multi-Dimensional Memory Frame.

The GOMS-construct that each individual has developed should reflect the results of action selection in the System-1-After-Event-Mode and System-2-After-Event-Mode using the A-, B-, and C-memes in the System-2-Before-Event-Mode and System-1-Before-Event-Mode. By allocating more resources, i.e., brain processing power, to System-2-After-Event-Mode, he or she can construct a richer goal structure, which allows System-2-Before-Event-Mode to devote more resources to making accurate and reliable predictions in a variety of future situations he or she encounters. On the other hand, a sequence of methods involving successively occurring events, $E(T), \cdots, E(T+n)$, can be integrated into a single method by allocating more resources to System-1-After-Event-Mode. The integrated specialized method generates a specialized operator sequence for the corresponding sequence of events. In facing a variety of situations, the number of specialized methods will increase. Due to the limited processing capacity of the brain, either System-2-After-Event-Mode or System-1-After-Event-Mode will become dominant. Therefore, the following is predicted concerning the shape of GOMS-construct:

- If System-2-After-Event-Mode is dominant, then a goal-rich GOMS-construct, $\hat{G} \gg \hat{M}$, will be constructed.
- If System-1-After-Event-Mode is dominant, then a method-rich GOMS-construct, $\hat{G} \ll \hat{M}$, will be constructed.

3) Relationship between the Number of GOMS Components and the Balance of Conscious/Unconscious Processing: Figure 6 shows that the balance between System-1-After-Event-Mode-dominance and System-2-After-Event-Mode-dominance changes depending on the range of communities that the individual is directly and indirectly involved in during his/her life. In a behavioral ecology where individuals rarely interact with others, each individual can lead a sufficiently problem-free life by having a set of methods that are specific to the situations he or she encounters. Therefore, the relation, $\hat{M} \gg \hat{G}$, holds. As shown in the left portion

of Figure 6, most actions are generated through unconscious execution of methods by System 1.

In the case of community-based living, each individual is expected to act according to the way he or she functions within the group he or she belongs to. When communication among group members is established in surface language, individuals are unable to perform elaborate inferences. Therefore, the relationship, $\hat{G} > \hat{M}$, is established, which is shown in the middle portion of Figure 6.

When a group belongs directly to a community and that community constitutes a society, i.e., the group belongs indirectly to the society, and/or when communication is done in structural language, the behavioral ecology becomes System-2-After-Event-Mode-dominant and the relationship, $\hat{G} \gg \hat{M}$, is established as shown in the right portion of Figure 6. The individuals can respond to various situations flexibly by allocating resources to the execution of System-2-Before-Event-Mode with careful use of the well-developed goal structure.

Figure 6 also shows the change in the GOMS-construct as the size of the group changes from individual, to small group, to large group. The number of elements that make up GOMS, $\hat{C}$, is limited by the constraints imposed on the processing capacities of brain. As the social relationships increase, the number of methods, which are System 1 elements, decreases through the reorganization of the goal structure by abstracting multiple individualized methods together. The elements, which have been used for System 1, are used by the System 2 elements. Meanwhile, the number of System 2 elements increases as the complexity of the relationship increases. In other words, by shifting to a behavioral ecology in which System 2 elements are more important than System 1 elements, the composition of elements in the entire GOMS will change to a composition with a rich goal structure that allows for more logical thinking.

B. GOMS and Meme

1) Mutual Development of GOMS and Meme: The existence of memes is a prerequisite for the generation of GOMS. GOMS also plays an important role in efficient action generation. The generated actions update Multi-Dimensional Memory Frame and contribute to meme formation. Thus, GOMS and memes are in a mutually developing relationship. Actions are generated in two ways: driven by System 1 or driven by System 2. The bias, i.e., the dominance of System 1 or System 2, in the generation of action, should affect the aspect of mutual development. This point is discussed in the following.

Figure 3 shows three types of memes. These memes are maintained through generations with imitation as the basic mechanism. A- and B-memes involve physical behaviors that are executed by connecting the Perceptual-, Behavior-, and Motor-Multi-Dimensional Memory Frame. Since A-memes are elemental in generating behavior and B-memes are combinations of elements of A-memes, they are different in granularity and do not mix with each other. The content of the inherited memes is almost invariant, since the content of physical behavior does not change significantly over time. The C-memes, on the other hand, are disconnected from physical behavior. It includes language activities with linguistic symbols and inference through the application of rules. The Word- and Relation-Multi-Dimensional Memory Frame are used for these activities. Linguistic symbols and rules are gradually updated under the influence of the social and natural environment surrounding each generation. A-, B-, and C-memes exist in parallel, without mixing with each other, and each is inherited from generation to generation.

GOMS covers orthogonally to the parallel meme structure and allows A-, B-, and C-meme elements to be combined with each other to efficiently generate effective actions in response to the real-world situations. This is accomplished by combining the elements in Multi-Dimensional Memory Frame in the form of a GOMS-construct. Since words are typical of memes, we can regard memes as carriers of meaning, i.e., *semantics*. GOMS can be thought of as *syntax* because it specifies how words are combined together.

C-memes represent inherited cultures. Cultures are diverse. Based on the discussion in the previous section, Section IV-A3, we can broadly distinguish between cultures that are rich in the goal structure of GOMS, G-culture, and cultures that are rich in the variety of methods, M-culture. Individuals acting in each culture acquire and act upon the inherited memes of that culture. The memes in the G-culture might be updated through System-2-After-Event-Mode, whereas those in the M-culture might be updated through System-1-After-Event-Mode. In either case, if the meme is deemed valid within the population in the updated structure, it will trigger a meme update. The update of a meme requires time for validation. Thus, it does not mean that the meme will be updated immediately.

Since a GOMS-construct links goals and operators, it guarantees corporeality for the goals present in the Word- and Relation-Multi-Dimensional Memory Frame. This ensures that even in the G-culture, the development of GOMS for various goals does not dissociate them from the real world. In other words, the connection of the Word- and Relation-Multi-Dimensional Memory Frame, to which G belongs, with Behavior- and Motor-Multi-Dimensional Memory Frame, to which M and O belong, guarantees the corporeality of the goal, G. By applying the GOMS-construct to memes, it is possible to make the meme, which is not linked to the real world as it stands, not free from the real world.

2) Common Understanding of Words and GOMS: Words are a typical example of memes [9] and the elements of C-memes. Words are the primary communication medium and are passed on from generation to generation [3]. Individuals make sense of words and understand the situation by referring to the context in which the words have been uttered. However, individual members of a community that share a C-meme may not assign a common meaning to a particular word, even when placed in a common context [12].

It is said that the number of words known by native English-speaking adults is 20,000∼30,000, and the number of words used in daily conversation is 3,000∼4,000. Conceptually known words are inherited as the elements of C-

memes. However, the words used in daily activities unite the C-meme with the B- and A-memes, which are associated with corporeality, by means of GOMS. The goals in GOMS represented by symbols belonging to the C-memes are developed into the operators of GOMS belonging to the A-memes, and the meaning of goals can be shared as the B-memes as a sequence of operators, i.e., the methods of GOMS, that can be superficially observed as they carry out their daily activities.

3) Number of Top Located Goals and Behavioral Ecology: Culture and customs are examples of C-memes. Among them, what is desired to be achieved defines the goal structure of the community that inherits the C-memes. At the top level of the goal structure is the happiness goals [18] that members of a community commonly seek to achieve. Behavioral goals that lead to the achievement of the happiness goals exist beneath them [19].

In recent years, the characteristics of societies that rely on strong kinship relations and those in which individualism is prevalent have been discussed [20]. Based on our study, we can provide a perspective for understanding the behavioral ecology that forms in these societies. In the societies where the C-memes reflecting strong kinship are inherited, the number of goals that can exist is limited, and the System 1-driven behavioral ecology is formed as shown in the left portion of Figure 6. In contrast, in the societies with advanced individualism, each individual constructs his/her own goal structure, thus forming the System 2-driven behavioral ecology as shown in the middle and left portion of Figure 6.

In the latter case, many elements are used to construct the goal structure, and flexible action selection is achieved by flexibly replacing the higher-level goals depending on the situation. Since the replacement of the topmost happiness goal also occurs, the behavior is executed by switching between GOMS structures that are quasi-independent of each other. The fact that switching of the GOMS structure occurs can be described as a manifestation of the modalization of behavior. Modalization of behavior results in the appearance that an individual switches his or her behavioral norms depending on the situation.

This also does not necessarily guarantee that even if the same operator sequence is observed, the goal structure developing on top of that sequence is unique. And the possibility of misunderstandings, i.e., communication errors, arising from this cannot be excluded. The problems inherent in an individualistic society will appear here.

V. Conclusion

MHP/RT consists of the perceptual, cognitive (Two Minds), and motor processes that operate synchronously with changes in the environment, and the Multi-Dimensional Memory Frame that is used during action selection and execution of the PCM processes and is updated after action execution. The latter is an internal process of Multi-Dimensional Memory Frame, so it is executed separately from the PCM process. On the other hand, for the former, it is necessary to realize the connections between the perceptual process and Perceptual-Multi-Dimensional Memory Frame, and between the cognitive process and Word-, Relation-, and Behavior-Multi-Dimensional Memory Frame. MHP/RT introduces P-resonance for perception and C-resonance for cognition; the connections are realized by *resonance* shown in Figure 2. For P-resonance, we have introduced the basic senses as the mechanism in the preceding paper [4].

In this study, the mechanism of C-resonance was examined. In the Multi-Dimensional Memory Frame, there are memes, which are A-, B-, and C-memes, structured by three hierarchies as shown in Figure 3. These memes are mapped to each memory in the Multi-Dimensional Memory Frame and are linked to each other by sharing Perceptual-Multi-Dimensional Memory Frame as shown in Figure 2. For this reason, reality is ensured by perceptual information. On the other hand, C-resonance works under a time-constrained situation in which the PCM process must select and execute actions while synchronizing with changes in the environment, and connects the Multi-Dimensional Memory Frame and cognitive processes. In this study, we introduced GOMS proposed by Card, Moran, and Newell [5] as the mechanism to link Word-, Relation-, Behavior-, and Motor-Multi-Dimensional Memory Frame directly, without going through the Perceptual-Multi-Dimensional Memory Frame.

Each element of GOMS is represented as a node in the brain. The finite number of nodes that can be maintained allows different behavioral ecologies to emerge depending on how the number of nodes allocated to goals and selection rules operated by System 2 and the number of nodes allocated to methods and operators operated by System 1 are balanced. Regarding the C-memes, we examined the characteristics of behavioral ecology in the societies characterized by strong kinship, which inherit simple goal structures, and in the societies with a strong individualistic flavor, which inherit complex goal structures. Although the former is not expected to be flexible in action selection, it can achieve effective and efficient action selection and execution in stable social situations. In the latter, on the other hand, a modalized goal structure is maintained to cope with various situations, and the individual flexibly switches to the appropriate goal structure while selecting and executing actions. We also pointed out that although actions are observed as operator sequences, they are prone to communication errors caused by the non-uniqueness of the goal structure that develops on top of them.

The memes determine the content of the action. The PCM processes determine how to act. The GOMS structure intersects them. By viewing behavioral ecology from the perspective of GOMS, this study showed that static memes can be implemented and brought to life in behavioral ecology. Behavioral ecology is created by living organisms. On the basis of MHP/RT, the manifestation of memes in behavioral ecology has been clarified in the case studies [21][22]. This study is positioned as a proposal for a method to give life to static digital information while building on the results of these case studies.

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