Transforming Conscious Goals into Unconscious Actions in Real-world Interactions: Real-world Use of Behavioral Ecological Memes via GOMS

Muneo Kitajima
Nagaoka University of Technology
Nagaoka, Niigata, Japan
Email: mkitajima@kjs.nagaokaut.ac.jp

Makoto Toyota
T-Method
Chiba, Japan
Email: pubmtoyota@mac.com

Jérôme Dinet
Université de Lorraine
Nancy, France
Email: jerome.dinet@univ-lorraine.fr

Katsuko T. Nakahira
Nagaoka University of Technology
Nagaoka, Niigata, Japan
Email: katsuko@vos.nagaokaut.ac.jp

***Abstract*— Our daily actions are executed to achieve desired states. Perceiving our own situation, we select actions that are expected to realize the desired states and successively execute them. The memory used in this process is a representation in the brain in the form of memes that are passed on from generation to generation. Memes are structured into three levels—action, behavioral, and cultural—and are acquired through mimetic behavior. Higher-level memes are acquired as one gets older. This study draws 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 the three layers, termed C-resonance in MHP/RT. Meanwhile, knowledge built as a result of iterative actions toward a goal state is represented by a GOMS hierarchical structure comprising goals (G), operators (O), methods (M), and selection rules (S). We show that GOMS bundles memes belonging to different levels, combining 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 behaviors in the behavioral ecology. By examining the behavioral ecology from the perspective of GOMS, we can see how static memes are implemented in a dynamic behavioral ecology and how behaviors with guaranteed corporality are expressed.**

Keywords*- *GOMS; Behavioral ecology; Meme; Resonance; Corporeality.

I. INTRODUCTION

This work is based on a study previously presented at COGNITIVE2025 [1]. The basics of the concept of the process of developing perceptual, cognitive, and motor processes, and forming memories while interacting with the real world were added to Section I-A to reinforce the introduction of Figures 3 and 4, which provide the basis of this work. In addition, we added Figure 6 to Section III-B3, referring to the role of GOMS in the process of embodying "words", a typical example of memes. Furthermore, a discussion of the relationship between the nature of the happiness goals at the top of the goal structure and the GOMS that develops the behavioral goals underneath it was added to Section IV-B3 as Section IV-B3a.

A. Development and Memory Formation through Real-World Interaction

What we observe as each individual's physical behavior is the result of multiple processing with a Parallel Distributed Processing (PDP) system [2], [3] and 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.

According to Damasio [4], a vertebrate animal develops its neural network system in the following way. It starts with the development of the paired structure comprising the sense of touch and its associated reflex movements. Then, the senses of smell and taste, and finally, sight and hearing develop their associations with reflex 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 to establish "selective sensing," which is a paired structure with feedback between perception and movement. For example, the sense of hearing and motor movements for vocalization establish a feedback loop between them immediately after one acquires the function of voicing.

In summary, the neural network system first forms the autonomic nervous system of the respective autonomous organs shown in the center of Figure 1 as a genetic fundamental structure. Then, it is crossed with the somatic nervous system that controls reflexive movements associated with the perceptual stimuli from the five senses. Finally, it develops feedback loops with a system of interneurons that connect these systems. Figure 1 schematically depicts this loop.

Each individual lives in the environment by operating the perceptual, cognitive, and motor (PCM) processes along this loop. They then systematically develop a cross-network of sensory, motor, and intervening nervous systems [7]. The genealogy of the DNA of vertebrates suggests that Perception, Interneuron, and Motion—i.e., PIM—form the basis for de-

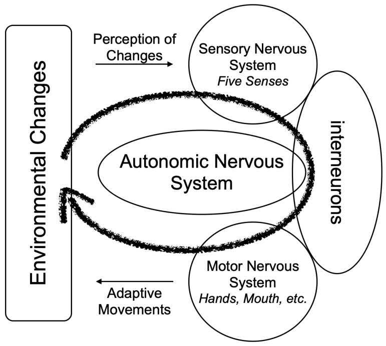


Figure 1. Continuous cyclic loop of perception and movement (adapted from [5, Figure 1])

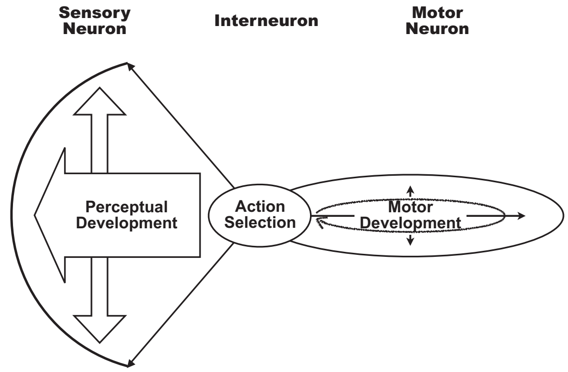


Figure 2. Development of the sensory nervous system and the somatic nervous system, and interneurons connecting them with action selection process (adapted from [6, Figure 1])

velopment. Figure 2 shows that PIM is the basis of the formation of the body based on neural circuits and the whole body is formed as PIM develops. Perception (P) captures various kinds of environmental changes via the sensors with different properties (M-dimension). Motor movement (M) is performed continuously and cyclically from birth, and develops gradually through increasing precision and optimizing intensity (N-dimension). The interneurons (I) memorize the effective interlocking relationships between P and M ($M \otimes N$ mapping), and construct neural circuits that function in a feedforward fashion and which allow for more complex feedback control to enhance the effectiveness of reactions. PIM develops by expanding the behavioral-ecological bandwidth. The behavioral ecological categories of vertebrates, such as acquiring food and raising children, are almost identical and within a limited range. Everyday human life is performed cyclically in a behavioral ecological band which is expanded by performing new actions to realize a goal within the limited behavioral ecological categories and adding these to the existing band.

While interacting with the environment for living, humans develop by selecting and executing actions, and accumulating execution results while operating The PCM processes along the loop are shown in Figure 2. *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.

B. Meme Proposed by Dawkins [8]

The mechanism by which the 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. 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 [8]. This idea itself received substantial support, but time passed without the mechanism being clarified [9].

When Dawkins proposed the meme, the function of genes was not yet understood. Therefore, Dawkins' explanation and that of 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. 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 genes that enabled humans to be highly adaptable.

C. 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 each individual's memory. 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 [10]. 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 3 shows a schematic representation of the action selection and execution process in the real environment as a PCM process. In the perceptual process, humans perceive the state of the real environment through parallel processing of the five senses and integrate what they individually perceive by binding them. In the cognitive process, memes related to the perceived information are activated in parallel and 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

	P: Perceptual Process		C: Cognitive Process (Memory)		M: Motor Process	
Environment	⇒ Hearing ⇒ Vision ⇒ Smell ⇒ Touch ⇒ Taste	⇒ Integration ***P-Resonance***	⇒ Meme_1 ⇒ Meme_2 ⇒ Meme_3 · · · ⇒ Meme_{N-1} ⇒ Meme_N	⇒ Integration ***C-Resonance***	⇒ Behavior ⇒	**Environment**

Figure 3. PCM process and memes

pace and synchronizing with changes in the environment in an unconscious manner.

D. Problem Statement

The PCM process synchronously runs with the environment. Meanwhile, the "memory system" used by the PCM process updates asynchronously itself with the environment to reflect the results of the PCM process. Supported by the PCM process and memory system, each individual repeats action selections in an ever-changing environment without any breakdown. Here, we must clarify the interface between the PCM process, which operates synchronously with the environment, and 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 [11]. 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 3, 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 features that work most efficiently in the environment. This is best captured by the four elements of Goals (G), Operators (O), Methods (M), and Selection (S) rules (GOMS) [12]. Here, 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.

E. Organization of the Article

This remainder of this article 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, "The Psychology of Human-Computer Interaction," and describe the mechanism of C-resonance. Section IV discusses the characteristics of the behavioral ecology that emerges from the interaction of the structured meme content and C-resonance by GOMS. Section V summarizes this study and discusses its implications for the digital generation.

II. PCM Process and Memes

Here, we explain the details of the PCM process, memories, and memes outlined in Figure 3, based on our cognitive architecture "Model Human Processor with Real-time Constraints (MHP/RT)" [13], [14].

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 via the sensory nerves located at the interface with the environment, and take in environmental information in the body. The brain acquires environmental information concerning the self's current activity through the multiple sensory organs. Further, it generates bodily movements suitable for the current environment. The stable and sustainable relationship between the environment and self is established through continuous coordination between the activity of the self and resultant changes in the environment, which should affect the self's subsequent action.

Figure 4, adapted from [11, Figure 1], shows the process, based on MHP/RT [13], [14] via 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, comprises Perceptual-, Behavior-, Motor-, Relation-, and Word-Multi-Dimensional Memory Frame. Perceptual-Multi-Dimensional Memory Frame overlaps with Behavior-, Relation-, and Word-Multi-Dimensional Memory Frame for spreading activation from Perceptual- to Motor-Multi-Dimensional Memory Frame.

The 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 4, this process is

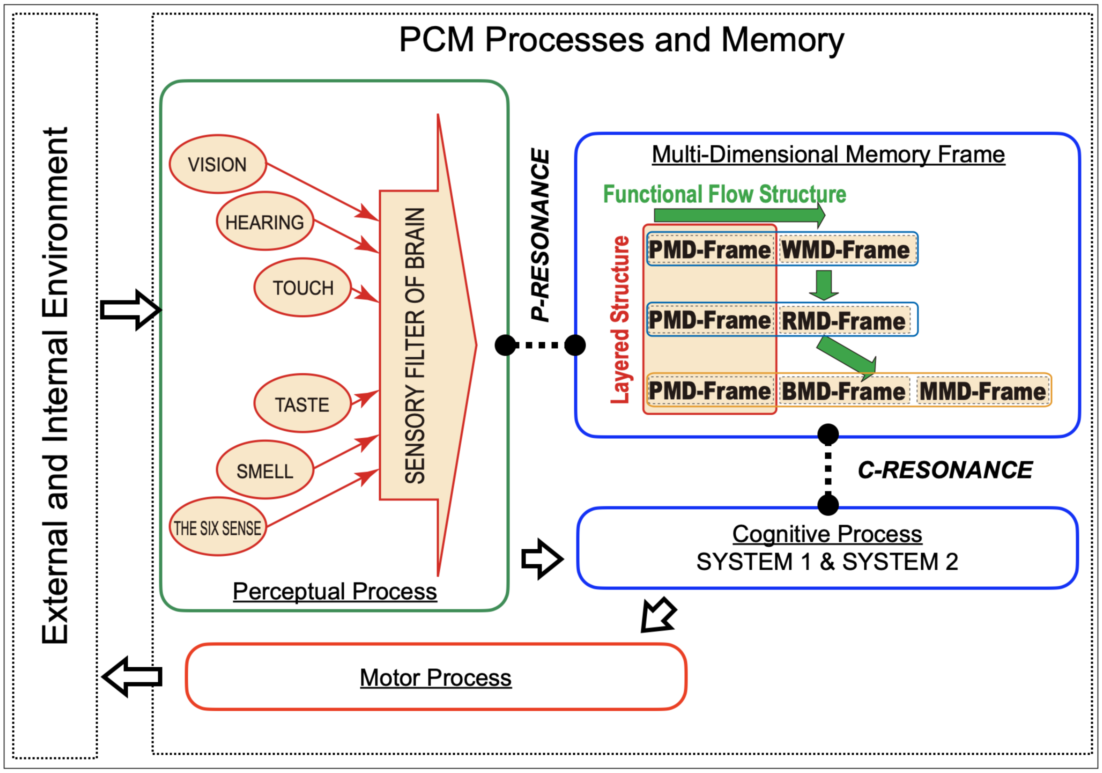


Figure 4. Information uptake by perceptual processes from the external and internal environments' memory activation, and execution of cognitive and motor processes through resonance (adapted from [11, Figure 1])

indicated by •—•. Resonance occurs first in the Perceptual-Multi-Dimensional Memory Frame and activates the memory network. Then, 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 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.

This feature of MHP/RT should be contrasted with the goal-oriented cognitive architectures such as ACT-R [15], [16] in which the conscious processes are considered as the processes to control people's behavior and the unconscious processes are considered subordinate to the conscious or intentional processes. What ACT-R tries to do is to show how System 2 can be implemented on top of System 1. The procedural memory system is very similar to System 1 (fast, learning based on rewards/experience, intuitive), and then ACT-R models tend to consist of a set of production rules that—when run on this System 1 module and in combination with symbolic working memory buffers and a long-term memory system—give rise to the slower, deliberative planning behaviors seen in System 2. This is a very different approach to that given in this paper. However, ACT-R models are totally adequate for simulating stable human activities with weak time constraint in which deliberate decision making would work effectively, but might be hard for the situations with strong time constraint where the environmental condition changes chaotically and deliberate decision making implemented on System 2 might not work as effective [13].

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, they receive time-series information. That is, this 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 the orderly processing of information from sensory organs. The basic senses include the rhythmic sense related to time, spatial sense related to spatial perception, and number sense [11].

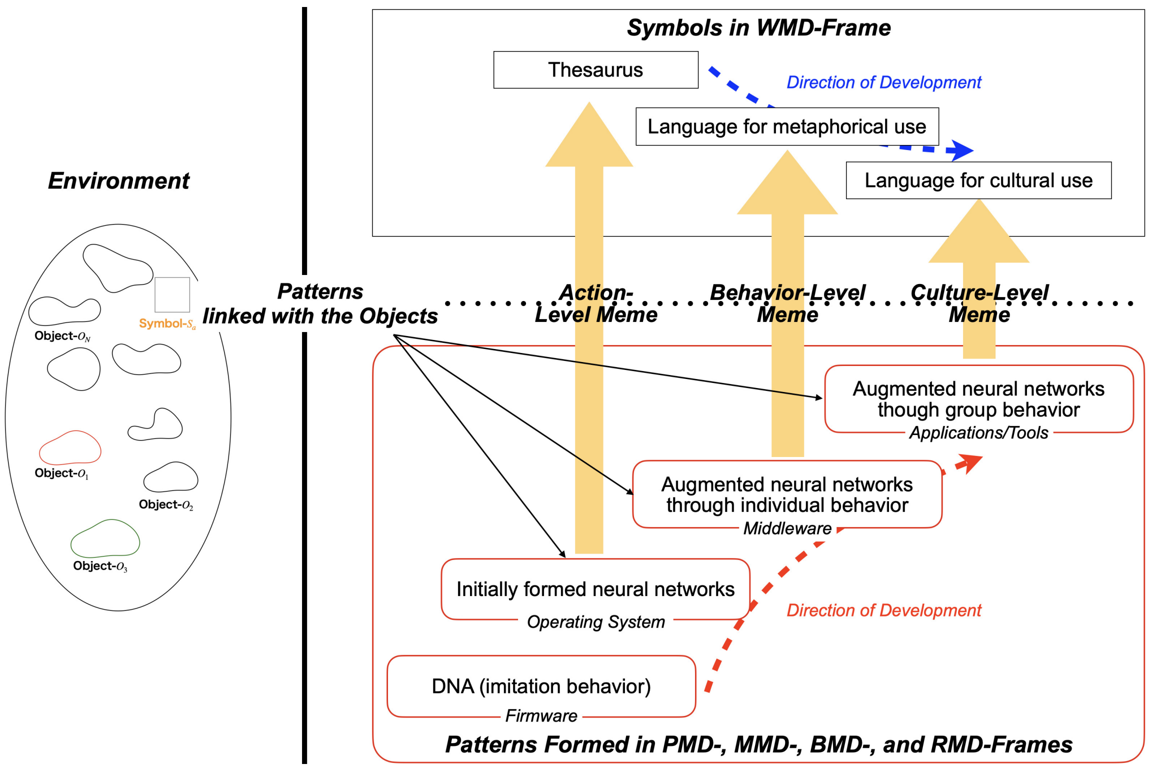


Figure 5. Structure of the meme (adapted from [10, Figure 5])

C. Memory as a 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 4 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: Perceptual-, Word-, Relation-, Behavior-, and Motor-Multi-Dimensional Memory Frame. In short, it expresses how the memories are structured, focusing on the continuous updating of memory associated with the execution of PCM process. Notably, 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. Satisfactory behavior is expressed in the environment. The basis of behavior is imitation; however, 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 [17].

Figure 5 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 [18]. 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. Words are essential for successful communication.

Thesauruses, individual languages, and cultural languages increase their complexity in this order in terms of the patterns linked with the objects in the environment. Thesauruses are associated with the objects in the environment which are encoded in the neural networks in the initial development stage from the birth to three years. Individual languages are associated with not only the objects in the environment but also the symbols already 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-, Behavior-, and Culture-Level Memes, respectively, which were introduced in the Structured Meme Theory proposed by Toyota et al. [17]. Hereafter, the memes classified into these memes are abbreviated by A-, B-, and C-memes, respectively.

The culture that exists in the environment is the integration of the C-memes which 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 [19]. This argument is consistent with the idea of memes presented here, 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 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 which work in a number of groups of people.

The relationships between the three levels of memes and 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-, B-, 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 which replications (resonance replications) are generated when there is a common experience. Memes are present in the environment as those which can cause these resonance replication. Such memes can be called cultures. Memes influence the phenotype called culture. However, 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. [20]. This mechanism allows humans to be highly adapted to their environment.

III. C-Resonance via GOMS

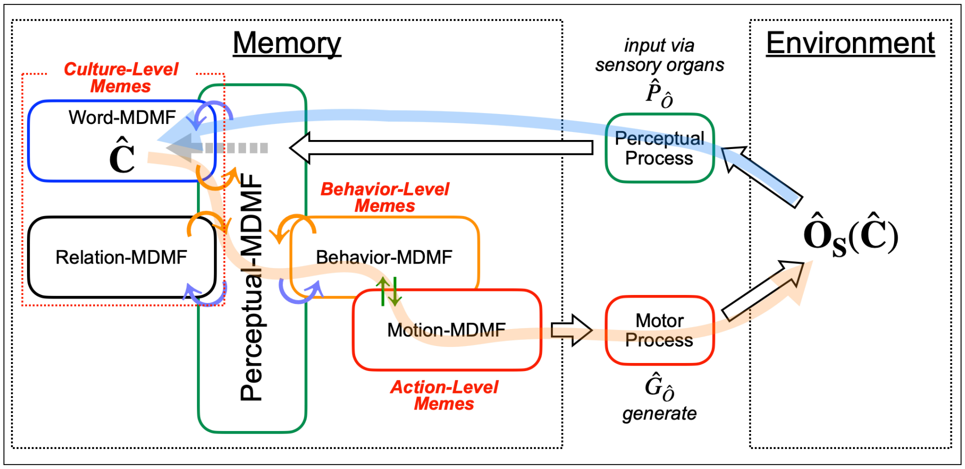
A. Binding Problem at the Cognitive Level

In Figure 5, the objects in the environment activate the A-, B-, and C-memes. In this activation process, various regions related to the objects are activated. In Figure 4, 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-, and finally, to Motor-Multi-Dimensional Memory Frame. The portions of Word-, Relation-, and Behavior-Multi-Dimensional Memory Frame which 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.

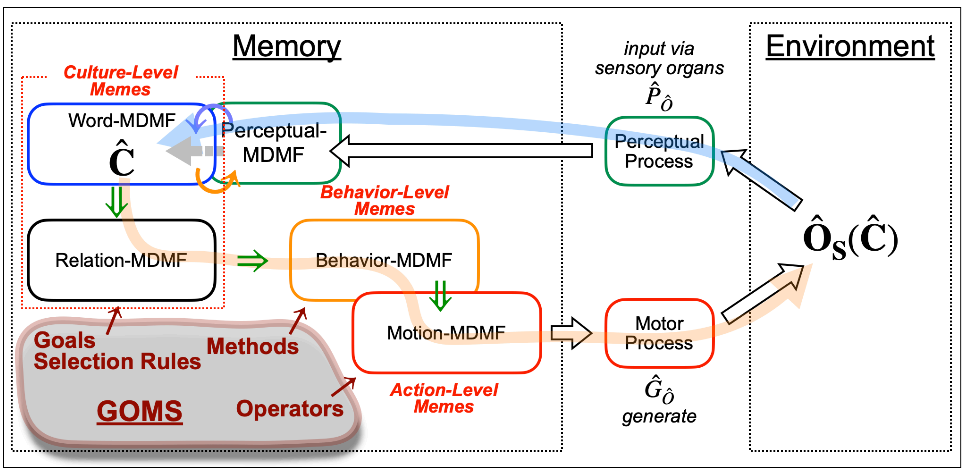
Memories that hold memes are activated in parallel to be used by the PCM process, which is a serial process. Here, we can see another binding problem occurring at the cognitive level. In Figure 4, the bridge between cognitive and memory processes is shown as C-resonance for resolving the meme binding problem. The cognitive process may 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 the 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 [21]. 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 help realize the state they desire to achieve. The principles at work while executing



(a)



(b)

Figure 6. (a) Symbol grounding when the self generates an object $\hat{\mathrm{O}}_{\mathrm{S}}(\hat{\mathrm{C}})$ that embodies the concept $\hat{\mathrm{C}}$ (adapted from [22, Figure 3]). Goal is a kind of $\hat{\mathrm{C}}$, and $\hat{\mathrm{O}}_{\mathrm{S}}(\hat{\mathrm{C}})$ represents the state in the environment showing that "the goal is accomplished."; (b) Symbol grounding for object generation—i.e., goal accomplishment—using GOMS which *does not* involve Perceptual-Multi-Dimensional Memory Frame

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

Figure 7. Relation between GOMS, memes, and Two Minds

the cognitive activity of action selection are bounded rationality and satisficing principle [23]. 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." As a cognitive architecture for modeling such situations, ACT-R exists [15], [16], [24]. 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 Newell [12] identified GOMS as a concept that represent such patterns. GOMS specifies concepts that define a meta-structure which 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 [12, 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 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 this 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, the user may have more than one available method to accomplish the goal. The selection of which method to be used need not be an extended decision process. It may be that the task environment features dictate that only one method is appropriate. Meanwhile, a genuine decision may be required. The essence of skilled behavior is that these selections are not problematical, and 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. Underneath it, there are subgoals, G', that must be accomplished to complete the primary goal. Finally, there are sub-subgoals, G'', to complete the individual subgoals. The final node that undertakes the task is the operator. One node above it is the method, while 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. 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.

Meanwhile, the mechanism of action execution based on MHP/RT is explained as follows. As shown in Figure 4, the environment is perceived and connected to the Multi-Dimensional Memory Frame by P-resonance. Then, as shown in Figure 3, the memes acquired by structuring the Multi-Dimensional Memory Frame through experience are activated, while 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 4, behavior generation following the flow of activity through the Perceptual-Multi-Dimensional Memory Frame is inefficient. This process is shown in Figure 6(a). For the concept $\hat{\mathbf{C}} \in$C-meme that the self wants to realize in the real world, the activation propagates from the Word-Multi-Dimensional Memory Frame to Relation- and Behavior-Multi-Dimensional Memory Frame via Perceptual-Multi-Dimensional Memory Frame, and finally reaches the Motor-Multi-Dimensional Memory Frame. The goal expressed in language here is a kind of concept. Then, the object $\hat{\mathbf{O}}_{\mathbf{S}}(\hat{\mathbf{C}})$ is realized in the real world through the motor process. Here, the state in which the goal has been achieved is realized; it exists as a perceptual object in the environment. This object is perceived by the self and Perceptual-Multi-Dimensional Memory Frame is activated. The activation propagates to the Word-Multi-Dimensional Memory Frame and the object is recognized as $\hat{\mathbf{C}}$, $\hat{\mathbf{C}} \equiv \hat{\mathbf{O}}_{\mathbf{S}}(\hat{\mathbf{C}})$ is established and the envisioned concept is realized in the real world. In other words, the envisioned goal has been realized in the environment. The establishment of this relationship also means that the symbol grounding problem [25], which has been a challenge in the field of artificial intelligence, has been solved [22].

One may reasonably assume that GOMS is used to structure A-, B-, and C-memes which 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 7 shows the correspondence between memes and GOMS. Among the activated memes, the combinations of C-, B-, and A-memes which have formed GOMS bonds in the process of gaining experience are processed by System 2 and System 1, while the operator sequence is executed in the real world [26]. Figure 6(b) shows how GOMS provides a shortcut by substituting the mapping from the Word- to Motor-Multi-Dimensional Memory Frame, where the symbol grounding shown in Figure 6(a) is guaranteed.

IV. Discussion: Deepening the Understanding of Behavioral Ecology

A. GOMS-construct Structure and Behavioral Ecology

1) GOMS-construct Structure: Figure 8 shows the overall GOMS-construct, which has been constructed by experience,

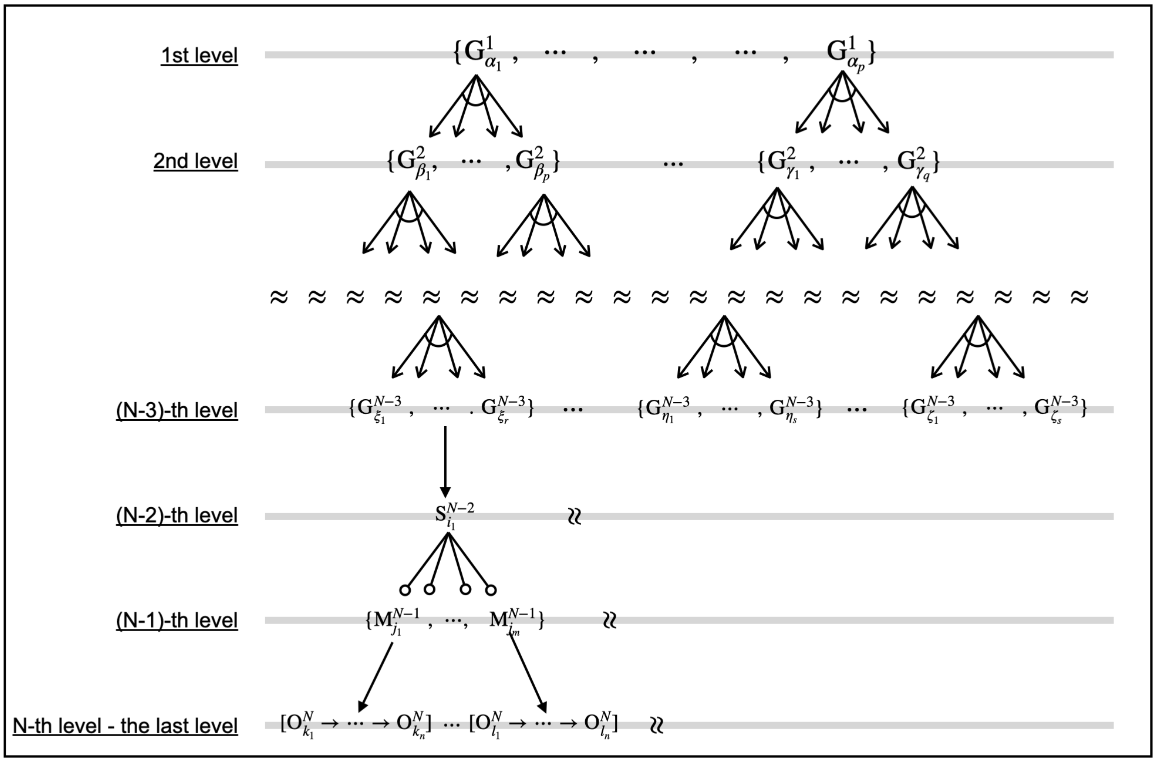


Figure 8. GOMS connection structure

in a general form. The GOMS-construct is explained in the following order starting from the operator sequence, $\mathbf{O} = [\mathrm{O}^N_{k_1} \to \cdots \to \mathrm{O}^N_{k_n}]$, which is expanded at the lowest N-th layer and worked upward. 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 helps 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, encompassing 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. $\mathbf{G^1_i}$ is achieved by meeting 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 8, for convenience, the top-level goal is placed at the first layer; the N-th layer is represented as the lowest operator layer. However, the depth of the hierarchy varies depending on the content of the top-level goal. Therefore, the concrete value of N varies depending on $\mathbf{G^1_i}$.

The individual G, O, M, S shown in Figure 8 can be considered as nodes that hold pointers connecting them to specific parts of the A-, B-, and C-memes. In real behavioral situations, efficient memory use is required for the smooth operation of the PCM process. Therefore, selecting and executing appropriate actions is important 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 $\hat{G}$, total number of methods as $\hat{M}$, total number of selection rules as $\hat{S}$, total number of operators as $\hat{O}$, average depth of the hierarchy as $\bar{N}$, and 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 created through experience under the condition, $\hat{G} + \hat{O} + \hat{M} + \hat{S} \leq \hat{C}$, based on the relationship between each upper bound.

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

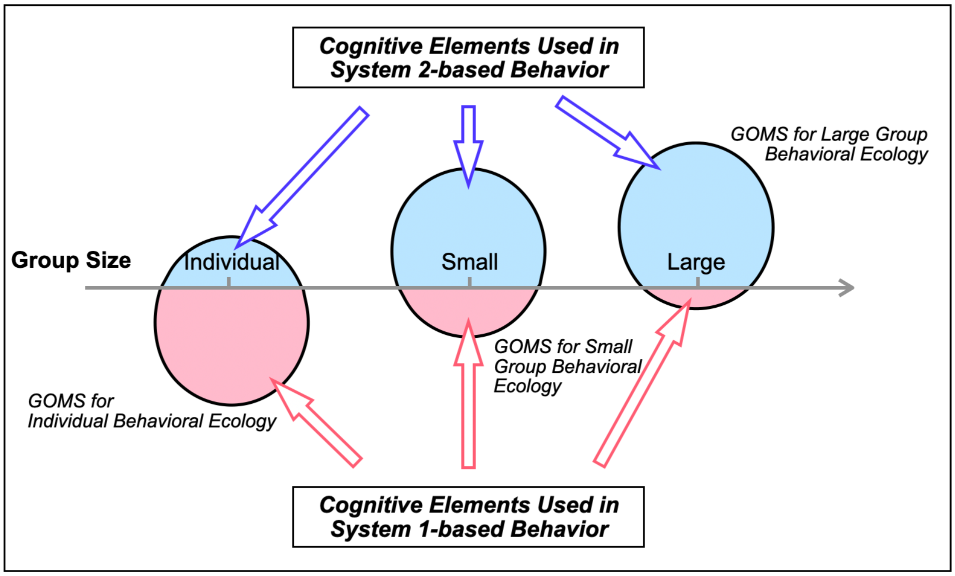


Figure 9. Changes in the Two Minds balance of GOMS components due to differences in behavioral ecology under brain processing capacity (time) constraints

achieve the lowest goal that has been developed. If multiple methods can achieve the goal, one method is selected based on the selection rule that defines the conditions for applying 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 [13] outlined below

- In System-2-Before-Event-Mode, MHP/RT consciously considers $E(T)$ beforehand;
- In System-1-Before-Event-Mode, MHP/RT unconsciously adjusts its behavior to the environmental context immediately before $E(T)$. Here, a series of action selections is executed through feedforward processing led by System 1 as a shortcut. During this time, System 2 evaluates the results of the action selections in a timely manner. If it determines that the system is likely to deviate from the expected trajectory or has already deviated, it issues instructions to System 1 for trajectory correction;
- In System-1-After-Event-Mode, MHP/RT unconsciously adjusts the connections within the relevant Perceptual-, Behavior-, and Motor-Multi-Dimensional Memory Frame immediately after $E(T)$; and
- In System-2-After-Event-Mode, MHP/RT 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 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, they can construct a richer goal structure. This allows System-2-Before-Event-Mode to devote more resources to making accurate and reliable predictions in various future situations they may encounter. Meanwhile, 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. While facing various 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 the 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 Balance of Conscious/Unconscious Processing: Figure 9 shows that the balance between System-1-After-Event-Mode- and System-2-After-Event-Mode-dominance changes depending on the range of communities that the individual is directly and indirectly involved in during their 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 they encounter. Therefore, the relation, $\hat{M} \gg \hat{G}$, holds. As shown in the left portion of Figure 9, most actions are generated through the unconscious execution of methods by System 1.

In the case of community-based living, each individual is expected to act according to the way they function within the group they belong 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 and is shown in the middle portion of Figure 9.

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 occurs in a structural language, the behavioral ecology becomes System-2-After-Event-Mode-dominant. Further, the relationship, $\hat{G} \gg \hat{M}$, is established, as shown in the right portion of Figure 9. The individuals can flexibly respond to various situations by allocating resources to the execution of System-2-Before-Event-Mode with the careful use of the well-developed goal structure.

Figure 9 also shows the change in the GOMS-construct as the size of the group changes from an individual to a small and then a large group. The number of elements that comprise GOMS, $\hat{C}$, is limited by the constraints imposed on the brain's processing capacities. 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. That is, 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 generating 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 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 5 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 significantly change over time. Meanwhile, the C-memes are disconnected from physical behavior. It includes language activities with linguistic symbols and inference by applying 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 environments 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 those 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 G-culture might be updated through System-2-After-Event-Mode, whereas those in 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 immediately updated.

Since a GOMS-construct links goals and operators, it guarantees corporeality for the goals present in the Word- and Relation-Multi-Dimensional Memory Frame. How to achieve a corporeality guarantee is the symbol grounding problem in AI. Figure 6(a) [22] shows that it can be guaranteed in an interpretive process via the Perceptual-Multi-Dimensional Memory Frame. Figure 6(b) shows that the process can be compiled by GOMS to make it more efficient while still guaranteeing corporeality. This ensures that even in G-culture, the development of GOMS for various goals does not dissociate them from the real world. That is, 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, one can 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 [18] and the elements of C-memes. Words are the primary communication medium and are passed on from generation to generation [10]. 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 [21].

Supposedly, the number of words known by native English-speaking adults is 20,000∼30,000, while 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, via

Table I
HAPPINESS GOALS [27] AND THEIR RELATION TO SOCIAL LAYERS. (ADAPTED FROM [21])

Category	No.	Name of Happiness	Types	Social Layers		
				Individual	Family, Relatives and Community	Society
I	8	Painful Happiness	The Masochist	+++		
	11	Tranquil Happiness	The Mediator	+++		
	14	Chemical Happiness	The Drug-taker	+++		
	15	Fantasy Happiness	The Day-dreamer	+++		
II	7	Rhythmic Happiness	The Dancer	+++	+++	
	16	Comic Happiness	The Laugher	+++	+++	
	4	Genetic Happiness	The Relative	+++	+++	
	5	Sensual Happiness	The Hedonist	+++	+++	
III	10	Selective Happiness	The Hysteric	+++	++	
	13	Negative Happiness	The Sufferer	+++	++	
IV	9	Dangerous Happiness	The Risk-taker	+++	++	+
	6	Cerebral Happiness	The Intellectual	+++	+++	++
V	1	Target Happiness	The Achiever	+++	+++	+++
	17	Accidental Happiness	The Fortunate	+++	+++	+++
VI	12	Devout Happiness	The Believer		+++	++
	2	Competitive Happiness	The Winner		+++	+++
	3	Cooperative Happiness	The Helper		+++	+++

+'s denote the degree of relevance of each goal to each layer, i.e., Individual, Community, and Social system, respectively.
+++: most relevant, ++: moderately relevant, and +: weakly relevant.

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. Further, 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 perform 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 are the happiness goals [27] that members of a community commonly seek to achieve. Behavioral goals that help achieve the happiness goals exist beneath them [28].

a) Happiness and Behavioral Goals: Happiness and satisfaction felt by humans occur in various forms in behavioral ecology. Many studies have aimed to classify situations when happiness and satisfaction are expressed. Among them, Morris's classification of happiness [27] is consistent with the feeling we attain in our daily life and can be accepted. He conducted comparisons with apes and other primates, and classified the cases wherein many humans shared a sense of happiness in the behavioral ecology that humans represent, which is the closest to the purest state. Based on Morris's classification, a matrix of happiness in contemporary life, organized in relation to the characteristics of the place in which the individual is placed, is shown in Table I. The third, fourth, and second columns indicate the type of happiness indicated by Morris, type of person seeking that happiness, and order in which they are presented in his book, respectively. On the right-hand side, the social fields in which individuals are located are classified into three layers: fields in which only they are involved (individuals), where the presence of others with whom they directly and intimately interact is essential (family, relatives, and community), and where social norms, culture, and language are related to their behavior (social systems). Each happiness goal's relevance to each layer is tentatively assigned and indicated by +'s as follows; +++: most relevant, ++: moderately relevant, and +: weakly relevant. Human beings encounter various situations in the course of their daily lives. Clearly, the 17 happiness goals, are designed to judge whether the behaviors expressed in various situations are good or bad. In addition, certain items are valid for all levels (1. setting and achieving goals and 17. benefits brought about by chance), a certain level (8. pain tolerance, 11. meditation, 14. chemical stimuli, and 15. day dreaming), and multiple levels. Thus, this classification scheme can be used in various human daily activities.

Furthermore, the happiness goals are classified and organized into six categories according to the pattern of the degree of association between individual happiness goals and the social layers. These categories roughly define the context in which the associated behavioral goals are intended to be achieved. The happiness goals in Category I can be achieved by individuals, independent of the community or social system. The happiness goals in Category II are achieved in a non-social context.

Kitajima et al. [29] proposed the maximum satisfaction architecture (MSA). MSA assumes that the human brain pursues one of the 17 happiness goals defined by Morris [27] at every moment and switches to another happiness goal when appropriate by evaluating the current circumstances. Each happiness goal is associated with one or multiple layers of society. Any activity for achieving specific behavioral goals would be conducted by individual persons in the pursuit of any of the 17 happiness goals in the social layers presented in the right portion of Table I. Happiness goals define the person's value structure when they make decisions by running the PCM and memory processes under specific circumstances while selecting their next actions. The achievement of behavioral goals that lead to the attainment of happiness goals utilizes GOMS characterized by the balance shown in Figure 9, depending on the level of the social layer in which the happiness goal is involved. The more uniform the happiness goal, the narrower the range of behavioral goals.

b) Society that Relies on Strong Kinship versus Prevailing Individualism: Recent studies have discussed the characteristics of societies that rely on strong kinship relations and those in which individualism [30]. In Table I, we consider the difference between the two to be the extent to which the happiness goal is realized (the number of cells in the matrix in which the happiness goal is achieved). The latter is considered to be more diverse than the former. Based on our study, we can provide a perspective for understanding the behavioral ecology that forms in these societies. In societies where the C-memes reflecting strong kinship are inherited, the number of goals that can exist is limited. Further, the System 1-driven behavioral ecology is formed as shown in the left portion of Figure 9. This is because the scope of happiness goals is limited and, consequently, that of behavioral goals is also limited. Conversely, in societies with advanced individualism, each individual constructs their own goal structure, thus forming the System 2-driven behavioral ecology as shown in the middle and right portion of Figure 9.

In the latter case, many elements are used to construct the goal structure. Further, 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. This switching of the GOMS structure can be described as a manifestation of the modalization of behavior, which results in the appearance that an individual switches their 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. Further, 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 comprises the perceptual, cognitive (Two Minds), and motor processes that synchronously operate with environmental changes, and the Multi-Dimensional Memory Frame that is used during action selection and execution of PCM processes and is updated after action execution. The latter is an internal process of the Multi-Dimensional Memory Frame. Hence, it is executed separately from the PCM process. Meanwhile, 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 4. For P-resonance, we introduced the basic senses as the mechanism in the preceding paper [11].

We examined the mechanism of C-resonance. In the Multi-Dimensional Memory Frame, there are A-, B-, and C-memes, structured by three hierarchies as shown in Figure 5. These memes are mapped to each memory in the Multi-Dimensional Memory Frame and are linked to each other by sharing the Perceptual-Multi-Dimensional Memory Frame as shown in Figure 4. Thus, reality is ensured by perceptual information. Meanwhile, 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. Here, we introduced GOMS proposed by Card, Moran, and Newell [12] as the mechanism to directly link Word-, Relation-, Behavior-, and Motor-Multi-Dimensional Memory Frame, 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 those allocated to methods and operators operated by System 1 are balanced. Regarding the C-memes, we examined the characteristics of behavioral ecology in societies characterized by strong kinship, which inherit simple goal structures, and those with a strong individualistic flavor, which inherit complex goal structures, from the perspective of behavioral goals; these are located under the 17 happiness goals and are developed as a GOMS structure. 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, a modalized goal structure is maintained to cope with various situations. The individual flexibly switches to the appropriate goal structure while selecting and executing actions. We also showed 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. Finally, the GOMS structure intersects them. By viewing behavioral ecology from the perspective of GOMS, this study shows that static memes can be implemented and brought to life in behavioral ecology. Behavioral ecology is created by living organisms. Drawing on MHP/RT, the manifestation of memes in behavioral ecology has been clarified in prior case studies [31], [32]. This study proposes a method to give life to static digital information while building on the results of these case studies.

To enable effective and efficient analysis of behavioral ecology across various contexts using the concepts proposed in this paper, guidelines are required for extracting and describing A-, B-, and C-memes, as well as for converting them into GOMS. This mirrors the development of Natural GOMS Language (NGOMSL) [33], which arose from the need to resolve the issue of analysts generating diverse GOMS models. This is one of the issues that must be resolved in the future.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI (Grant Numbers 19K12246 / 19K12232 / 20H04290 / 22K12284 / 23K11334) and the National University Management Reform Promotion Project. The authors thank Editage (www.editage.com) for English language editing.

REFERENCES

[1] M. Kitajima, M. Toyota, J. Dinet, and K. T. Nakahira, "Implementation of Structured Memes into Behavioral Ecology via GOMS", in *COGNITIVE 2025 : The Seventeenth International Conference on Advanced Cognitive Technologies and Applications*, 2025, pp. 6–16.

[2] J. L. McClelland and D. E. Rumelhart, *Parallel Distributed Processing: Explorations in the Microstructure of Cognition: Psychological and Biological Models*. The MIT Press, Jun. 1986.

[3] D. E. Rumelhart, J. L. McClelland, and P. R. Group, *Parallel Distributed Processing: Explorations in the Microstructure of Cognition: Foundations*. A Bradford Book, Jul. 1987.

[4] A. Damasio, *Feeling of What Happens: Body and Emotion in the Making of Consciousness*. Orlando, FL: Houghton Mifflin Harcourt, 1999.

[5] M. Kitajima and M. Toyota, "Hierarchical Structure of Human Action Selections – An Update of Newell's Time Scale of Human Action", in *Procedia Computer Science, BICA 2014. 5th Annual International Conference on Biologically Inspired Cognitive Architectures*, vol. 41, 2014, pp. 321–325. DOI: http://dx.doi.org/10.1016/j.procs.2014.11.082.

[6] M. Kitajima and M. Toyota, "Guidelines for designing artifacts for the dual-process", *Procedia Computer Science*, vol. 71, pp. 62–67, 2015, 6th Annual International Conference on Biologically Inspired Cognitive Architectures, BICA 2015, 6-8 November Lyon, France, ISSN: 1877-0509. DOI: https://doi.org/10.1016/j.procs.2015.12.201.

[7] L. W. Swanson, *Brain Architecture*. Oxford University Press, 2011.

[8] R. Dawkins, *The Selfish Gene*. New York City: Oxford University Press, 1976.

[9] R. Aunger, Ed., *Darwinizing Culture: The Status of Memetics As a Science*. Oxford Univ Pr on Demand, Jan. 11, 2001, p. 242.

[10] M. Kitajima, M. Toyota, and J. Dinet, "How Resonance Works for Development and Propagation of Memes", *International Journal On Advances in Systems and Measurements*, vol. 14, pp. 148–161, 2021.

[11] M. Kitajima *et al.*, "Basic Senses and Their Implications for Immersive Virtual Reality Design", in *AIVR 2024 : The First International Conference on Artificial Intelligence and Immersive Virtual Reality*, 2024, pp. 31–38.

[12] S. K. Card, T. P. Moran, and A. Newell, *The Psychology of Human-Computer Interaction*. Hillsdale, NJ: Lawrence Erlbaum Associates, 1983.

[13] M. Kitajima and M. Toyota, "Decision-making and action selection in Two Minds: An analysis based on Model Human Processor with Realtime Constraints (MHP/RT)", *Biologically Inspired Cognitive Architectures*, vol. 5, pp. 82–93, 2013, ISSN: 2212-683X. DOI: http://dx.doi.org/10.1016/j.bica.2013.05.003.

[14] M. Kitajima, *Memory and Action Selection in Human-Machine Interaction*. Wiley-ISTE, 2016, ISBN: 9781848219274.

[15] J. R. Anderson and C. Lebiere, *The Atomic Components of Thought*. Mahwah, NJ: Lawrence Erlbaum Associates, 1998.

[16] J. R. Anderson, *How can the Human Mind Occur in the Physical Universe?* New York, NY: Oxford University Press, 2007.

[17] M. Toyota, M. Kitajima, and H. Shimada, "Structured Meme Theory: How is informational inheritance maintained?", in *Proceedings of the 30th Annual Conference of the Cognitive Science Society*, B. C. Love, K. McRae, and V. M. Sloutsky, Eds., Austin, TX: Cognitive Science Society, 2008, p. 2288.

[18] D. C. Dennett, *From Bacteria to Bach and Back: The Evolution of Minds*. W W Norton & Co Inc, Feb. 2018.

[19] S. Blackmore, *The Meme Machine*. OUP Oxford, 2000.

[20] F. J. Odling-Smee, K. N. Lala, and M. Feldman, *Niche Construction: The Neglected Process in Evolution: The Neglected Process in Evolution*. Princeton University Press, Feb. 15, 2013.

[21] M. Kitajima *et al.*, "Language and Image in Behavioral Ecology", in *COGNITIVE 2022 : The Fourteenth International Conference on Advanced Cognitive Technologies and Applications*, 2022, pp. 1–10.

[22] M. Kitajima, M. Toyota, and K. T. Nakahira, "Why the Symbol Grounding Problem Matters in Virtual Reality: A Meme-Focused Solution Based on the Model Human Processor with Real-Time Constraints", *International Journal On Advances in Intelligent Systems*, vol. 18, no. 3 & 4, in press, 2025.

[23] H. A. Simon, *The Sciences of the Artificial*, Third. Cambridge, MA: The MIT Press, 1996.

[24] J. R. Anderson, *Rules of the Mind*. Hillsdale, NJ: Lawrence Erlbaum Associates, 1993.

[25] S. Harnad, "The symbol grounding problem", *Physica D: Nonlinear Phenomena*, vol. 42, no. 1, pp. 335–346, 1990, [retrieved: 2, 2025], ISSN: 0167-2789. DOI: https://doi.org/10.1016/0167-2789(90)90087-6.

[26] M. Kitajima, J. Dinet, and M. Toyota, "Multimodal Interactions Viewed as Dual Process on Multi-Dimensional Memory Frames under Weak Synchronization", in *COGNITIVE 2019 : The Eleventh International Conference on Advanced Cognitive Technologies and Applications*, 2019, pp. 44–51.

[27] D. Morris, *The Nature of Happiness*. London: Little Books Ltd., 2006.

[28] M. Kitajima, M. Toyota, and J. Dinet, "Guidelines for Designing Interactions Between Autonomous Artificial Systems and Human Beings to Achieve Sustainable Development Goals", *International Journal On Advances in Intelligent Systems*, vol. 15, pp. 188–200, 2022.

[29] M. Kitajima, H. Shimada, and M. Toyota, "MSA:Maximum Satisfaction Architecture – a basis for designing intelligent autonomous agents on web 2.0", in *Proceedings of the 29th Annual Conference of the Cognitive Science Society*, D. S. McNamara and J. G. Trafton, Eds., Austin, TX: Cognitive Science Society, 2007, p. 1790.

[30] J. P. Henrich, *The weirdest people in the world: How the west became psychologically peculiar and particularly prosperous*. Picador: Farrar, Straus and Giroux, 2021.

[31] M. Kitajima, M. Toyota, and J. Dinet, "Art and Brain with Kazuo Takiguchi - Revealing the Meme Structure from the Process of Creating Traditional Crafts -", in *COGNITIVE 2023 : The Fifteenth International Conference on Advanced Cognitive Technologies and Applications*, 2023, pp. 1–10.

[32] K. T. Nakahira, M. Kitajima, and M. Toyota, "Understanding Practice Stages for a Proficient Piano Player to Complete a Piece: Focusing on the Interplay Between Conscious and Unconscious Processes", *International Journal on Advances in Life Sciences*, vol. 16, pp. 164–177, 2024.

[33] D. Kieras, "GOMS modeling of user interfaces using NGOMSL", in *Conference Companion on Human Factors in Computing Systems*, ser. CHI '94, Boston, Massachusetts, USA: Association for Computing Machinery, 1994, pp. 371–372, ISBN: 0897916514. DOI: 10.1145/259963.260467.