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The Emergent Constructive Approach to Evolinguistics: Considering Hierarchy and Intention Sharing in Linguistic Communication

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Abstract. Evolinguistics is an attempt to clarify the origins and evolution of language and communication, thereby deepening our understanding of humans from an evolutionary perspective. The origins of language is characterized by the biological evolution of abilities related to language and communication, and the evolution of language by the structuralization and complexification of language knowledge as well as communication systems through cultural evolution. In Evolinguistics, two idiosyncrasies of human linguistic communication are the primary focus, namely, using hierarchically organized symbol sequences in language and sharing intentions in communication. We believe that the integration of these two characteristics made humans co-creative and smart, and in particular gave us knowledge co-creation capacity. The emergent constructive approach plays an important role in this research, which is a methodology to analyze complex systems by constructing and operating the evolutionary and emergent process of complex phenomena. Two studies taking this approach are introduced in this paper. One is a language evolution experiment in a laboratory to consider the process, mechanisms, and neural basis of symbolic communication systems. The other is an evolutionary simulation of recursive combination, which is thought of as the essential ability to form hierarchical structures. A hypothesis integrating intention sharing and recursive combination is discussed as an abductive reasoning mechanism for understanding others intentions.

Keywords: Evolinguistics, origins and evolution of language, hierarchy, intention sharing, symbolic communication, recursive combination, abduction

1. Introduction

Humans use languages both for thought and communication. Language is a basis for creating knowledge; communication is a tool for knowledge sharing. The combination of these two functions is a basis for knowledge co-creation. Knowledge co-creation and organizational knowledge creation (Nonaka and Takeuchi 1995) are the core issue in knowledge science. Knowledge science is an endeavor in science and technology to understand the creation, sharing, utilization, and management of knowledge in individuals, organizations, society, and nature and to apply this understanding to solve practical problems in modern society (Nakamori 2011). Our understanding of human language and communication forms one of the foundations of knowledge science.

From the knowledge co-creative perspective, human language and communication have two crucial features, hierarchy and intention sharing. The former is mainly important in knowledge creation and the latter in knowledge sharing. Although they are among the most important features of human cognition and intelligence and many efforts have been made to understand them, we believe that the present artificial intelligence has not been equipped with these features. In this paper, we introduce studies of these features from an evolutionary perspective. By the evolutionary perspective we mean here an attempt to comprehend an object, particularly a human biological and cultural characteristic, through detailed examinations of its phylogenetic, ontogenetic, and cultural origins and evolution and its adaptability and diversity, as well as relationships with and uniqueness from the relevant properties of own and other species. Taking this perspective gives us a deep understanding of humans. Specifically, we introduce the Evolinguistics project (http://evolinguistics.net/en/), which is one of the attempts to understand language evolution. We emphasize the importance of an emergent constructive approach, explained in Section 2.4, as a systems scientific methodology to treat dynamic and complex systems (Kaneko and Tsuda 1994, Hashimoto 2002, Hashimoto et al. 2008).

Language evolution is considered in two meanings: the origins of language and long-term language change. Humans have language ability as a biological species trait. How did the cognitive and physical abilities required for using language evolve biologically? This question concerns the origins of language. Although the study of language evolution is called evolutionary linguistics, it is not purely linguistics but biology, especially the study of the biological evolution of language-related abilities. Of course, linguistics, which pursues well understanding of human language and communication, must play an important role in identifying what language-related abilities and their cores are in order to answer the question of the origins of language. Here, we consciously use the plural form, origins, since human language is a complex phenomenon and a complex system, and what makes us possible to use language is not singular but a complex of many components. In other words, language is an emergent property of language-related abilities as components that we did not acquire all at once in our evolutionary history.

Languages change through vertical transmission across generations and horizontal transmission within a generation. Humans have systematic knowledge about their mother tongue, which is acquired through development and changes through uses in society. It is believed that the first language might have been simpler than at present. Simple means that the lexicon was small and that there were not many sophisticated grammatical features. How did a first language come to the present state through complexification and structuralization? This question concerns language evolution and the problem of cultural evolution. This question in evolutionary linguistics is different from historical linguistics, which investigates historical changes of language over around five thousand years, where we have written language evidence, while the evolution of language is considered as having occurred over 100,000 to 200,000 years. Grasping historical change and on-going cultural evolution of language, especially their principles and general properties, are useful for pursuing the evolution of language since the same principles and properties may valid for long-term complexification and structuralization.

Understanding language evolution is to understand humans from the evolutionary perspective by considering language as part of human nature. The evolution and remarkable developments of material and spiritual cultures in modern humans, *Homo sapiens*, must be evidence that linguistic communication made us co-creative, not just as individuals, but as organizations and society.

The rest of this paper is structured as follows. First, in Section 2, as an introduction to Evolinguistics, we explain the importance of intention sharing, hierarchy, and their integration in human language and communication. We also introduce an emergent constructive approach as an indispensable methodology to understand the origins and evolution of language as complex phenomena. Two examples of research follow. One is a language evolution experiment about the emergence of symbolic communication systems for intention sharing (Section 3). The other is an evolutionary simulation of recursive combination as the underlying mechanism of hierarchy formation (Section 4). Further, in Section 5, we present a hypothesis integrating recursive combination with intention sharing. Finally, we summarize the contents in Section 6.

2. Evolinguistics

A project called Evolinguistics tries to elucidate the mechanism of language evolution or co-creative language evolution, relying on two main conceptual grounds - hierarchy and intention sharing. This project also tries to advocate a future form of communication for the survival of human beings.

2.1 Intention Sharing in Communication

Human communication is neither just information transmission nor knowledge sharing. We share intentions. Here we define an intention as "an attitude about a situation to be realized", and a situation is any physical, social, or epistemological state. For example, imagine a situation where a mother had a meal with her son. She said, "Can you pass me the salt?" Then, he just answered, "Yes", and did not pass the salt to his mother. This interaction is not a successful communication in the usual sense. She wanted to realize a situation where her son gives the salt container to her by making him understand her request. This was her intention in communication, which the boy was expected to realize. Autistic children often struggle to do so (Frith 1989).

While present machine translation may be able to translate the sentence, "Can you pass me the salt?" into any language, we must understand there are two meanings in this sentence. One is the denotation, which is its literal or referential meaning. The boy understood that the word salt indicates an object, a saltcellar, and a literal meaning asking his ability to pass the object. Machine translation can do as well concerning the literal meaning. However, the intention of the speaker is not literally expressed in the sentence. Such a meaning is connotation or intentional meaning. Any expression in communication, including a non-linguistic one, has this duality between denotation and connotation. In daily human communication, we understand both meanings and respond to connotation rather than denotation.

2.2 Hierarchy and Recursive Combination in Language

The meaning of human language expression is not entirely determined by the meaning of its parts and their orders. The meaning also depends on the hierarchical structure composed of parts in an expression (Everaert et al. 2015). Namely, parts are syntactically combined into an expression. For example, the phrase "old men and women" is interpreted as [[old men] and [women]], meaning "a collection of women (young or old) and old men", and as [old [men and women]], meaning "a collection of men and women, all of them old" (Bolhuis et al. 2018). This is also the case for some single words composed of parts. For example, the word "unlockable" consists of three parts, un, lock, and able, and has two meanings, "able to unlock" and "unable to lock". These different meanings correspond to two different hierarchical structures, [[un, lock], able] and [un, [lock, able]], respectively (Nobrega and Miyagawa 2015). This feature is ubiquitous in human language and has not been found so far in animal communication.

This kind of hierarchical structure in language can be constructed through recursive combinations of linguistic items, such as words and morphemes. The recursive combination, called Merge in generative linguistics, is a process to combine two items into one unit, after which another item is combined with that unit. Different orders of combination from the same set of items to the same position produce different hierarchical structures with the same items in the same linear order.

We insist that this recursive combination of linguistic items, where each item represents some concept, serves to construct complex concepts, not just to utter a sentence or a compound word. Figures 1 (a) and (b) exemplify different hierarchical structures produced through different orders of recursive combination, respectively:

(a) un + think → unthink + able → un + unthinkable

(b) think + able → un + thinkable → un + unthinkable

The meaning of word formed at each step, namely, the concept constructed, is described in Table 1. Note that the word and concepts marked by ∗ are not listed in general English dictionaries but created here. Even though some resulting words and concepts formed through recursive combinations are novel, it is not difficult to recognize their concepts.

We believe that the ability of complex concept formation is the essential function of language ability and one of the most remarkable characteristics of human language use. Animals might have concepts, but we can combine concepts to make new ones. We do not always externalize newly constructed concepts in communication but can utilize them for thought, especially creative thinking.

Everett (2005) claimed the absence of embedding in the Pirahã language, although this claim has been questioned (Nevins et al. 2009). Here embedding means putting one phrase inside another phrase, e.g., "I know that she wanted to have a salt container", and is a typical hierarchical structure in language. What we are arguing for, however, does not depend on whether there is embedding in a given language, since the recursive combination to produce hierarchical structure above mentioned is not limited to embedding, as referenced by Everett (2005), but may be identified in a simple sentence and even in a compound word in any human language.

2.3 Integrating Intention Sharing and Hierarchy

Intention sharing and hierarchy are two idiosyncratic characteristics of human language and communication. What is realized with and without them is summarized in Table 2. Without both, simple information transmission and emotion sharing are possible. It is typical in animal communication where signaling is used for the control of recipient. This type of communication in animals is often studied in ethology and behavioral ecology.

Both intention sharing and hierarchy in language are studied in linguistics and cognitive science. Among other approaches, cognitive linguistics puts importance on intention sharing in communication. In particular, Tomasello develops the concept of shared intentionality to understand cognitive development (Tomasello 1999), language acquisition (Tomasello 2003), and the origins of communication (Tomasello 2008). With intention sharing, we can achieve reciprocity and unity of society through symbiotic communication. At the same time, division emerges among people who cannot share intentions and establish symbiotic communication.

Hierarchy and recursion to produce it are the important concepts in generative linguistics, which Chomsky (1957 1993) initiated and developed. Recursion is essential to realize the discrete infinity of human language (Chomsky 2005) and is hypothesized as unique to human language faculty and, therefore, its acquisition marked one of the origins of language (Hauser et al. 2002). As discussed above, the hierarchy of language functions to construct concepts and an individuals complex thought.

We recognize the importance of these two strands of study but, at the same time, argue that intention sharing and hierarchy have been studied somewhat separately. No study has integrated them. In fact, human cognition in-

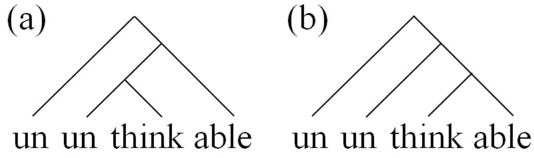

Figure 1 Complex Concept Formation

Table 1 Example of Complex Concept Formation with Different Orders of Combinations of the Same Items

Order	Resulting word	Meaning (Hierarchical structure of Figure 1(a))	Meaning (Hierarchical structure of Figure 1(b))
0	think	To have an idea about something	
1(a)	unthink	Not to use head about something	-
1(b)	thinkable	-	Possible to imagine as a possibility
2	unthinkable	Possible to stop thinking about something, to keep an idea out of head*	Impossible to imagine or accept
3	ununthinkable*	Impossible to stop thinking about something*	Possible to imagine as a possibility

tegrates them, and this integration is crucial to the development of human culture. Hierarchically structured complex concepts constructed through recursive combination are difficult for others to understand since, as exemplified in Section 2.2, linearized expressions ambiguously represent internally constructed hierarchical structures and, therefore, the concepts represented in hierarchical structures are not fully designated by externally uttered linearized sentences. We need to infer speakers minds to share their complex ideas (Scott-Phillips 2015). Thus, with both hierarchy and intention sharing, we can share complex concepts among people and construct further concepts based on shared ones, which allows the cumulative creation of knowledge. Misunderstanding, however, may occur at any time since inferences of others minds are not always accurate due to the invisibility and complexity of others minds. In the context of the sharing of hierarchically structured concepts, misunderstanding is an unexpected combination of concepts by others, which could be a source of creation.

In sum, the integration of intention sharing and hierarchy is the basis of co-creative communication and the cumulative creation of culture in human society. This is why intention sharing and hierarchy are two main conceptual grounds of the Evolinguistics project, and their integration is the key challenge. In Evolinguistics, we focus on clarifying the mechanisms and evolutionary scenarios of intention sharing, hierarchy formation, and the integration of these two.

2.4 Emergent Constructive Approach

For this endeavor, linguistics and evolutionary biology are two fundamental fields of Evolinguistics, for, as we pointed out, the origins of language are at root the problem of the biological evolution of human language ability. To clarify the evolutionary history of humans, human anthropology is required. As the evolution of language is a cultural evolutionary process, archaeology is also necessary. Developmental cognitive science on language acquisition is of value for understanding temporally developing phenomena of language ability and initial settings for properly acquiring language, which must be prepared through biological conditions.

Table 2 For Integrating Hierarchy and Intention Sharing

		Hierarchy No	Yes
Intention sharing	No	Simple information transmission, Emotion sharing, Control of recipient (ethology and behavioral ecology)	Construction of complex concepts, Individual complex thought (generative linguistics)
	Yes	Reciprocity, Unity and division, Symbiotic communication (cognitive linguistics)	Sharing complex concepts, Further construction of concepts based on shared concepts, Creation via unexpected combinations of concepts, Cumulative creation of culture (Evolinguistics)

In addition to these traditional approaches, we claim from the viewpoint of systems engineering and systems science that the constructive approach is significant for the progress of Evolinguistics, since the origins and evolution of language are apparently dynamic and complex phenomena, and we can make good use of the research approach for complex systems (Hashimoto 2002). The constructive approach is a methodology to understand complex phenomena through not just observing and analyzing objective phenomena but constructing objective systems and operating them by implementing them in workable systems (Kaneko and Tsuda 1994). For example, understanding life is tough because of its complexity and dynamic nature, and we try to simulate behavioral, functional, physical, and/or morphological characteristics of life using computer simulation (software), mechanics (hardware), and biological material (wetware). We believe that understanding the complexity of life can be advanced not only by making similar systems but also by operating and analyzing them.

In the emergent, or evolutionary, constructive approach, we do not try to construct systems of language and communication directly since both of them are very complex objects. Instead, as illustrated in Figure 2, systems thought of as their origins are designed, and processes of change, such as learning and biological evolution, are incorporated (Hashimoto et al. 2008). We observe the processes of emergence and evolution of complex systems of language and communication through the complexification and structuralization of the systems constructed. In addition to multi-agent simulations (software) (Cangelosi and Parisi 2002) and robotic experiments (hardware) (Steels 2003), cognitive experiments for language evolution in the laboratory (Scott-Phillips and Kirby 2010) are adopted as construction media, where agents including artificial agents, robots, and human participants initially do not have shared language and communication systems and develop them through interaction, learning, and evolution. In order to scrutinize internal mechanisms of emergence, cognitive experiments and simulations using computational models are compared and brain measurements during cognitive experiments are conducted. Big data analysis of experimental data and social data have recently been employed to analyze emergent phenomena in the brain and society. We integrate these various constructive methods to elucidate the process and mechanism of the origins and evolution of language and communication.

The constructive approach is, on the one

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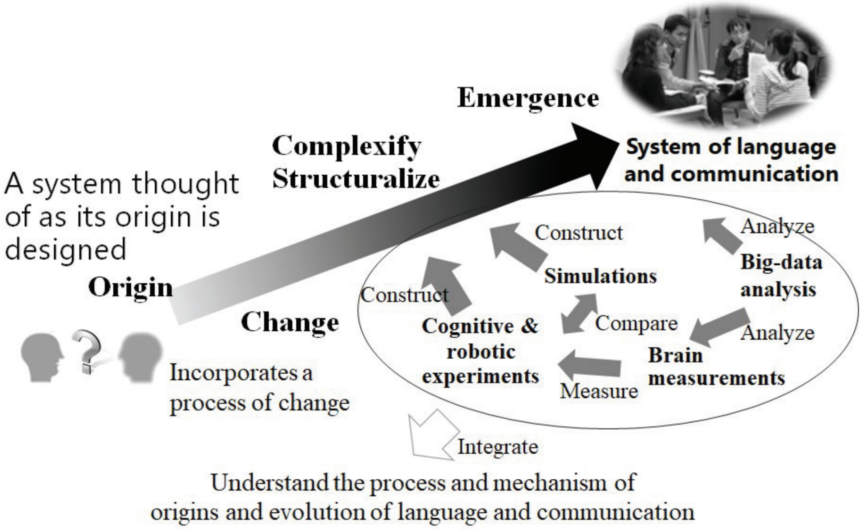

Figure 2 Emergent Constructive Approach

hand, necessary for understanding the complex world and, therefore, is a kind of methodology for science. On the other hand, constructing systems is a kind of engineering. Science proceeds from reality to concepts, whereas engineering does from concepts to reality. These two are combined in a reciprocal movement between concept and reality in the constructive approach. This approach plays a role in modeling the empirical data given by evolutionary biology, anthropology, and language acquisition. It is essential to gain insights as well to propose novel hypotheses that are to be tested by empirical approaches and are used to develop linguistic theory. Therefore, the emergent constructive approach should be an abduction engine. In the following two sections, we introduce two example studies of intention sharing and hierarchy, respectively, both taking the emergent constructive approach. The first one in Section 3 adopted a language evolution experiment in the laboratory. The second in Section 4 used evolutionary simulation.

3. A Language Evolution Experiment on the Formation of Symbolic Communication Systems

In daily human communication, we intensively use symbol sequences, such as letters, sounds, and gestures, to compose messages, where a symbol is a combination of form and meaning. For establishing communication, we share the symbolic communication systems including language, whereas it had not been shared from the beginning. The duality in a message between denotation and connotation is apparent in symbolic communication. The denotation corresponds to a literal meaning of a symbolic expression. The connotation is the intention of the speaker implied by the message. We should understand both meanings in symbolic and intentional communication. How do we establish symbolic systems and share the system among users to mutually understand intentions in communication?

We investigate this question using language evolution in the laboratory (Scott-Phillips and Kirby 2010) or experimental semiotics (Galantucci 2009). In our experiment (Konno et al. 2011), we replicated the feature of the symbolic communication system in a minimal system;

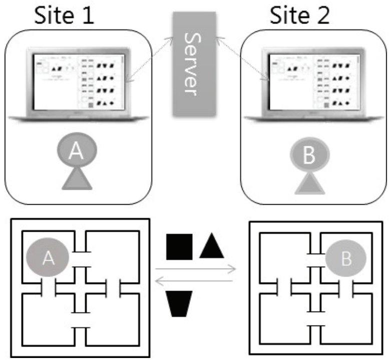

Figure 3 Communicative Coordination Game

namely, symbols are used to compose messages that have a duality between denotation and connotation. To realize rigorous quantitative analysis, the experimental task, which hereafter we call the "communicative coordination game", was made based on one introduced by Galantucci (2005) . A pair of participants played a kind of coordination game from separated sites using computer terminals so that they could not use the usual communication systems such as language, gestures, and facial expressions (Figure 3). Four rooms and each participants avatar were shown on each screen. Their goal was to bring their avatars into the same room by moving their avatars one step horizontally or vertically, or else staying in place; diagonal movement was not allowed. They were unaware of their partners room, which was initially allocated randomly while avoiding the same room. They were asked to compose a message using two figures from six options, including a blank. No predefined meaning and usage of figures was specified and shared. Messages they constructed were sent to their partner asynchronously and displayed immediately on the partners screen. After both participants sent messages, they moved their avatars. When both participants moved, the results were displayed, including their initial and destination rooms and messages. The initial rooms were then allocated randomly again and communicative coordination game repeated. The round when a pair brought their avatars into the same room was the successful round.

The characteristics of this experiment are as follows. 1) Meaning space is undefined, i.e., what is conveyed by messages (meanings of symbols) is not decided a priori. and not limited to something displayed on the screen. In fact, some participants tried to convey "I dont understand" or "It is not the same as my meaning". 2) Participants voluntarily sense-make for figures; therefore, we can analyze the formation process of symbolic communication systems. 3) Sharing a symbol system (semantics and syntax, i.e., the meaning of each figure and the rules of combination of figures, respectively) is not enough for full communication, which means that participants can meet in the same room at any time in any situation. The inhibition of diagonal movement causes this property. 4) Message sending is asynchronous. Thanks to this property, behavior other than composing symbolic messages, such as timing and turn-taking to send messages, may have information.

The third of these is critical to implement the duality of denotation and connotation. For example, suppose participant A is in the left top room, B the right top room, and they both send the same message. The denotation of the message was "the left top room", but the connotation by A was "Im in the left top room", and that by B was "Lets meet in the left top room". The former connotation is to intend to declare

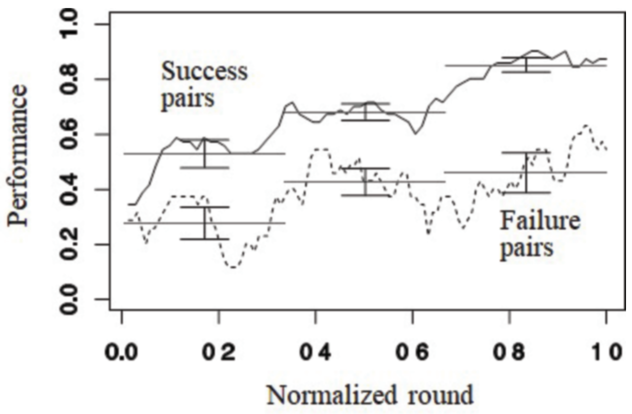

Figure 4 Dynamics of Performance in the Formation Process of Symbolic Communication Systems

the present position and the latter to intend to direct the destination. Participants needed to resolve this duality, namely, need to agree on the connotation (the intended meaning) in addition to the denotation (symbols reference). A useful strategy to solve it is to utilize the fourth property. In fact, successful participants established role division using turn-taking: the first sender sent its present position and the second their destination, with different intentions.

Success pairs could form symbolic communication systems with sharing intentions using symbolic messages. Konno et al. (2012c) showed that the formation process had three stages as shown in Figure 4, where the x-axis is the repeated round of communicative coordination game, which is normalized since the number of repeated rounds differed by pair, and the y-axis is performance, which is the moving average of the ratio of success rounds; the solid line is the average of success pairs (n = 14), and the broken line is that of failure pairs (n = 7). The average performances during the first and the second stages, and those of the second and third stages, were significantly different, respectively, in the success pairs, while there was no significant difference among the average performances at the three stages in the failure pairs. According to the analysis of behavioral data of avatars movements, symbol uses, and the timing of messaging, we confirmed that the first stage reflected the regularity in destinations, while the second stage reflected the regularity in symbol uses in addition to the regular destinations. However, these regularities did not contribute to the performance of the third stage (Konno et al. 2012a). Based on further analysis of the results of test sessions conducted immediately after the game, which controlled the messaging and its timing, we interpreted the first stage as corresponding to the formation of common ground based on conventional behavior and the second stage as corresponding to the formation of symbol systems (Konno et al. 2012b).

In order to clarify what contributed to and caused the third stage, we further analyzed the similarities of symbol systems and the information flow, calculated by transfer entropy (Hashimoto et al. 2015), and modeled the experiment computationally using a cognitive architecture (Morita et al. 2012 2018). In computational modeling, we adopted Adaptive Control of Thought-Rational (ACT-R) proposed by Anderson (2007) since it integrates symbolic and subsymbolic learning mechanisms, which is suited for modeling the behavior and learning in symbolic communication. We found that the similarity of symbol systems at the middle stage contributed to the establishment of role division. The information flow decreased more in the successful pairs than the failure pairs through the rounds of a communicative coordination game; that is, they began to behave in mutually certain and predictable manners. These results indicate that the success pairs could incorporate their partners behavior adequately thanks to their mutual awareness. Simulation analysis using ACT-R revealed that a model incorporating role-reversal imitation replicated the performance of success pairs. Role-reversal imitation is the imitation of the others behavior by reversing the roles of speaker and hearer, which Tomasello (1999) claimed to be essential for producing communicative symbols in childrens language acquisition. We argue that role-reversal is the mechanism for promoting similarity of symbol systems and predictability of behavior through mutual awareness.

Brain measurements were also conducted to find a neural substrate of the formation of symbolic communication systems. Two participants electroencephalograms (EEG) were recorded simultaneously during the communicative coordination game with a simplification of the experimental setting to four options in figures and one figure in a message. Our focus was on the mirror neuron system (MNS), which consists of remarkable neurons that were activated both by a subject doing a behavior and by observing the behavior of others (Rizzolatti and Craighero 2004). The MNS is thought to contribute to language understanding (Rizzolatti and Arbib 1998, Pulvermuller and Fadiga 2010) and also to language evolution (Corballis 2010), especially for establishing symbolic relationships between forms (sound and gesture) and meanings. When someone hears a sentence, "I bite it," he/she simulates the action of biting with his/her body, and he/she understands the speakers behavior and intention as well. This simulation is called the embodied simulation and performed with the MNS. Indeed, reading sentences directly related to body action showed congruent brain activities to watching the corresponding body actions (Aziz-Zadeh et al. 2006).

How about the MNS for symbolic expressions not directly related to body action? Symbols used in our experiment were simple, abstract figures such as circles and diamonds not related to any body action in advance. We analyzed the suppression of band power in the mu bands (8-13Hz) of the EEG recorded over sensorimotor areas, which is used as a marker of the activity of MNS in EEG (Pineda 2005), at the timing of receiving messages. A significant suppression of mu-band power was observed in communication using such an abstract symbol (Li et al. 2016). Further detailed analysis of EEG signals revealed that participants whose MNS tended to be activated, in other words, those who were likely to perform embodied simulation naturally, in non-communicative situations were more likely to understand connotations in communicative situations (Li et al. 2019). These findings imply that the MNS is the neural substrate for the formation of symbolic communication systems, not only in establishing symbols, that is, denotation, but also in understanding the connotation of symbolic messages through embodied simulation.

We summarize the findings of the language evolution experiment in the laboratory using the communicative coordination game in Figure 5. The formation of symbolic communication goes through three stages: forming a common ground, sharing a symbol system, and establishing role division. Each stage corresponds to conventional behavior, denotation, and connotation, respectively. For the last stage, which is the most important part of intention sharing, role-reversal imitation is a candidate of the underlying mechanism, and embodied simulation by the MNS may be the neural substrate.

By simplifying and elaborating on Galantucci (2005)'s study to allow for quantitative

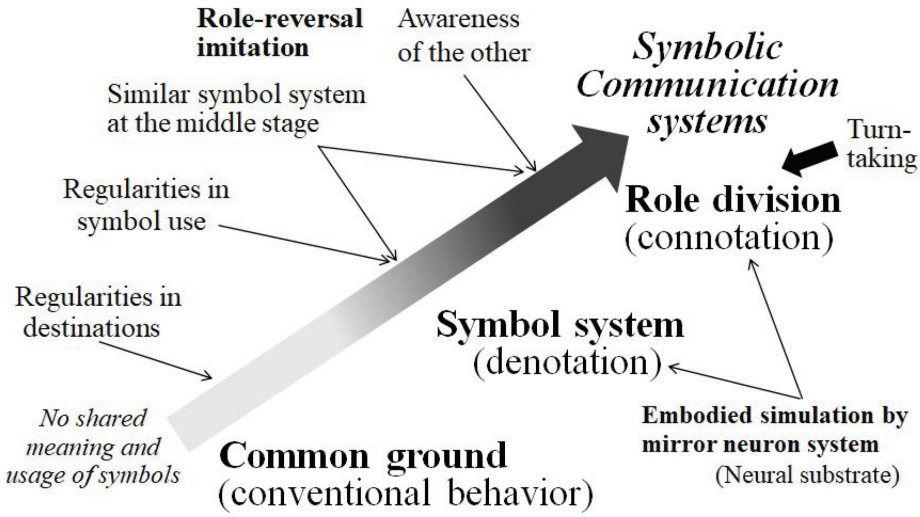

Figure 5 Process and Causes for the Formation of Symbolic Communication Systems

analysis, we have been able to shed light on the detailed process by which symbolic communication systems emerge from the absence of common predefined symbols, as described so far. To examine the significance of our findings of that process, we compare and discuss our results with similar experimental semiotic studies. It is, however, not very meaningful to directly compare the quantities because each study abstracted the problem and designed the experimental task independently. Therefore, the relationships between the qualitative results derived from quantitative analyses in each study are examined.

An experiment by Selten and Warglien (2007), which examined a coordination task between predetermined figures and meanings the figures are associated with, is closer to our experimental design than Galantucci (2005)'s experiment, in which the form is free to be created by experimental participants. Their study quantitatively analyzed how environmental constraints, such as the cost of communication and the number of usable figures, affect the emergence of communication systems. They argued that a common symbol system could not be formed unless the variety of symbols is somewhat large. However, they argue this based on results in a limited setting where the number of symbols is two and the number of interactions is 10. In our experiment, symbolic communication systems were formed using four figures for four objects (rooms). Their results may have been due to an insufficient number of interactions until coordination. They analyzed the correlations between indices reflecting the properties of the symbol systems. The asymmetry in the frequency with which players changed their symbols positively correlated with the agreement on symbol systems. The existence of this asymmetry means that the role differentiation of leader-follower has been established. In interactions between speaker and listener without fixed roles, the role differentiation of leader-follower, in which one party decides on symbols and the other accepts them, is often effective for coordination. It is important to note that the role differentiation of leader-follower in Selten and Warglien (2007) is quite different from a role division in our study. They examined role differentiation in determining symbolic relations, whereas we found it in the transmission of intentions and showed that participants in our experiment assigned roles to the order of message sending to convey connotations that cannot be conveyed by symbolic messages alone. Not many experimental studies of language evolution have focused on how symbols convey intentions.

Yoshida et al. (2010) conducted an experiment using the stag hunt game to investigate brain regions associated with the inference of others intentions. The stag hunt game is a model of cooperative hunting in which players decide whether to hunt a stag or a hare; if both players decide to take the stag, they gain the most, whereas if only one player decides to take the stag, the player gains nothing. Therefore, it is a type of coordination game. In their experimental task, participants moved their avatars in a two-dimensional space to hunt a stag or hare. Yoshida et al. (2010) showed that the brain regions that encode the depth of nested belief and its uncertainty in inferring others intentions (i.e., which prey the partner intended to hunt) from the movement in the space are the dorsolateral prefrontal cortex and rostral medial prefrontal cortex, respectively. This study is relevant to our study, where both used movement in a space and a kind of coordination game, and focused on intention. Although one could interpret partners movements as symbolic in the sense that the movements are used as evidence for inferring mental content, this task is not communication because one player in this study was a computer agent, and the participants in the experiment did not try to communicate anything to their partners by their movements. Yoshida et al. (2010) analyzed the entropy of inaccuracy of predictions within individuals, whereas we examined the dynamics of transfer entropy, quantifying information flow between two signal sources, because we are interested in the interaction between two parties. This analysis revealed the importance of awareness of the other to establish the role division at the last stage of the formation of symbolic communication systems in Figure 5.

Scott-Phillips et al. (2009) experimentally investigated an interesting process of the emergence and sharing of symbolic spatial movements that are meaningfully communicated between participants. The task in this experiment was to move participants avatars to a room of the same color as their partners avatar in the space of four 2 × 2 colored rooms, where the color of the partners room was not visible but movement was visible. Although this study also showed the formation stages of communication systems (a default color was shared, specific movements were created to represent the second and third optional colors, etc.), the stages were not quantitatively and objectively identified and tested, but the presentation was rather anecdotal. It was quantitatively shown that the formation of a convention (agreement on a default color in this experiment) effectively allowed the communication system to bootstrap. This finding is consistent with our results that the regularities in destinations and symbol use contributed to the first two stages in the formation of communication systems (Figure 5). The result that natural cognitive biases work effectively in forming the communication system is another consistent finding between the two studies. In their experiment, red color tended to be the default color, which may reflect human perceptual tendencies. Such natural biases generally contribute to behavioral coordination, and thus to the formation of the communication system as well. An "upward triangle" figure used in our experiment tended to be used as a symbol for the upper room. Scott-Phillips et al. (2009) showed that the ratio of "dialogue," which is an interaction in which one participant suggested and agreed on a different destination when the other could not go to the first destination, was correlated with the performance of successful communication, and argued that dialogue was necessary for a perfect communication system to be formed. In our experiments, we often

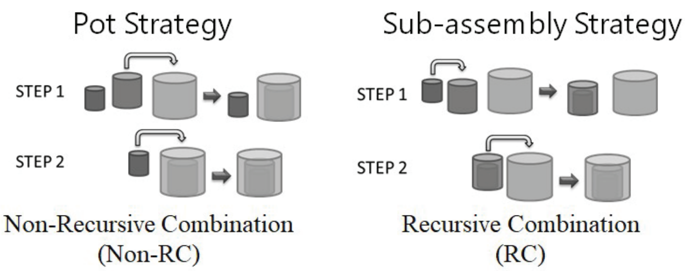

Figure 6 Two Strategies in Object Manipulation (From (Greenfield et al. 1972) with Modifications)

observed a process in which performance declined after the formation of a symbolic system, and then rose to form a complete communication system. We believe that this is a process for adjusting how to convey connotation. It is worth investigating whether this is a dialogue in our experiment.

The experimental task of sharing the meanings of movements in a space was also adopted by Stolk et al. (2014). They quantitatively showed that success rates developed in a logarithmic manner when sharing new symbols (new movement-meaning pairs) and found that activation of the right superior temporal gyrus (rSTG) was correlated with this development. What is unique to this study is that they showed that synchronization between the two parties occurs at a fairly low frequency (0.05 Hz = 20 seconds) in rSTGs in successful pairs. It seems, however, that this synchronization, over the period from the beginning to the end of a single interaction, would just reflect a situation in which participants performed the task successfully together. We have also conducted two-person simultaneous brain measurement, and we believe that there would be some correlation between pairs who successfully form communication systems. While we do not suppose a direct synchronization of brain activities between experimental participants interacting with symbols alone (no physical interactions), we hypothesize an increased similarity in the networks of functional connectivity in the brains. We actually found that at the final stage of interaction a functional connectivity was formed between the frontal and parietal brain areas in the success pairs (Fujiwara et al. in prep.). Because this coupling was neither formed early in the success group nor in the failure groups, our hypothesis is likely to be positively supported.

4. An Evolutionary Simulation of Recursive Combination

As explained in Section 2.2, recursive combination plays an essential role in the construction of hierarchy in language. Recursive combination is rare in animal behavior but ubiquitous in human behavior, nor is it limited to language but occurs in music, mathematics, object manipulation, and planning, and so on (Greenfield 1991, Conway and Christiansen 2001, Jackendoff 2011, Hauser and Watumull 2017). Clarifying the evolution of recursive combination ability, which we posit as a generalized version of Merge in generative linguistics, is one of the keys to understanding the origins of human language (Hauser et al. 2002). Greenfield et al. (1972) analyzed object manipulation by introducing the concept of action grammar and compared two strategies, pot strategy and sub-assembly strategy, in an experiment of cup manipulation (Figure 6). They argued that human infants under three years old and chimpanzees rarely performed the sub-assembly strategy. We identify sub-assembly as the recursive combination of objects since the object manipulated is a combined object, while the pot strategy is non-recursive combination but a repetitive op-

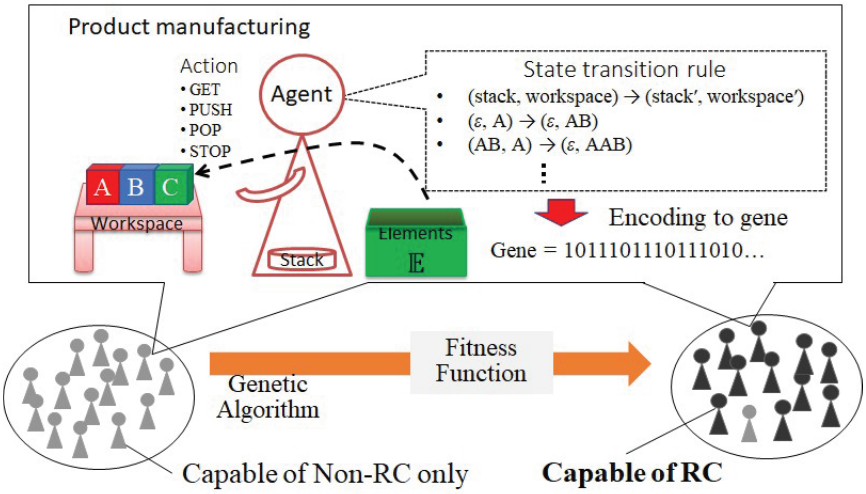

Figure 7 The Outline of the Model for Evolutionary Simulation of the Recursive Combination of Object

eration since the object manipulated is always a single object.

Fujita (2009) proposed a hypothesis that recursive combination in object manipulation was the precursor of syntactic recursive combination, i.e., Merge. Adopting this hypothesis, we proposed an evolutionary scenario of recursive combination, hereafter RC, from object manipulation to syntactic operation (Toya et al. 2020). At first, RC evolved in object combination from non-RC (object manipulation); next, RC transferred into the combination of action representation in the mental simulation of action sequence (image manipulation); then, RC in mental simulation was applied to symbols (symbolic operation); and finally was applied to lexical items (syntactic operation). In this section, we introduce an evolutionary simulation of the first step, which purposed to clarify the survival adaptability of RC (Toya and Hashimoto 2017 2018).

We premised that the evolution from non-RC to RC in object manipulation occurred with the evolution of stone tools in the genus *Homo*, from *Homo habilis* to *Homo erectus* and to *Homo sapiens*, i.e., between 200 million and 50,000 years ago, based on cognitive archeological researches (Moore 2010, Arbib 2011, Stout 2011). Supposing tool making, we modeled the cup manipulation experiment by Greenfield et al. (1972), Figure 6, using an automaton with a stack. An outline of our model is shown in Figure 7. An agent equipped with a state transition rule manipulated objects to make products using a workspace and a stack according to the state transition rule. Note that we set that all products could be made both with non-RC and RC, but RC took longer manufacturing steps than non-RC since RC used the stack. The state transition rule of the automaton was coded to a gene string that evolved with a genetic algorithm (GA). Agents were evaluated in terms of their products. Our usage of GA was different from usual biologically inspired optimization since we know the solution that is RC. We used GA to find suitable fitness functions that could evolve RC from non-RC. For this purpose, we tested a couple of fitness functions that could evolve RC in object manipulation.

Three candidates of fitness functions were analyzed: 1) making any product can earn fitness, based on the expectation that recursive combination is used in making many products; 2) making a specific complex product only can earn fitness, based on the fact that human-made products have become increasingly complex in structure (Stout et al. 2008, Arthur 2009); and 3) making products as di-

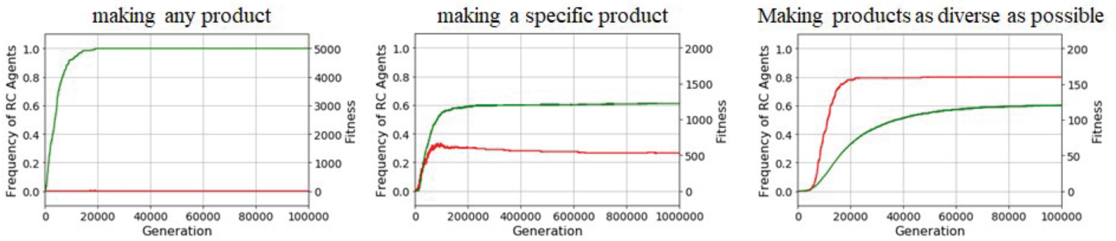

Figure 8 The Dynamics of Population Share of RC Agents (Red Lines) and the Average Fitness (Green Lines) under Three Fitness Functions Indicated above Each Graph. Average over 200 Runs. (From Toya and Hashimoto (2018) with Modifications)

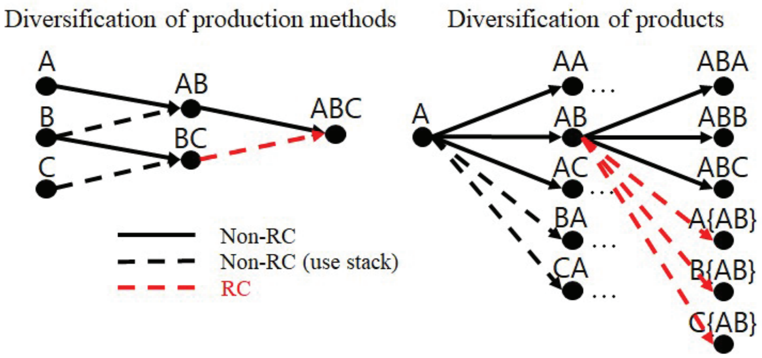

Figure 9 Two Functions of Recursive Combination. A, B, and C Signify Components, and Their Concatenations Indicate Products. The Red Dashed Arrows Represent the Production using RC

verse as possible can earn more fitness, based on the fact that humans make increasingly diverse products (Arthur 2009). Figure 8 shows the dynamics of the frequency of agents capable of RC (RC agents) and the average fitness under the three fitness functions, where the x-axis indicates the generation of GA, the y-axis on the left side shows the frequency of RC agents, and that on the right side shows the average fitness. RC evolved in the cases of the second and the third fitness functions.

We analyzed the functionality of RC in each fitness function that evolved RC. In the second fitness function, agents must find production methods of a specific product. RC works to diversify the production methods, while there is only one path to the specific product with non-RC, as schematically diagrammed by the solid arrows in the left of Figure 9. In other words, RC makes a search in the space of production methods effective. In the course of evolution, RC agents were replaced by non-RC agents once a production method was found due to larger manufacturing steps in RC production. Under the third fitness function, agents must produce more different products. RC functions to diversify the products by combining products into components, as illustrated at the right of Figure 9. We concluded that the adaptive functions of RC are the diversification of production methods and of products. We believe that these functions contribute to the development of material culture in human society (Toya and Hashimoto 2018).

By incorporating competition among agents, we analyzed the condition for RC to evolve. We supposed that products are tools to acquire and utilize resources and that the more a product is made of the same kind, the more the resource acquired by the product is consumed. A fitness function considering these suppositions was designed based on the third one above. We found that strong competition promoted the evolution of RC and that under strong competition generalist-type agents evolved, which produced many kinds of products (Toya and Hashimoto 2017). We argue that this condition corresponds to the evolutionary history of humans and the diversification of stone tools in *Homo erectus* (deMenocal 2011).

Because our model assumes object manipulation for tool making, we discuss how to situate our findings within the history of tool making. According to Klein and Edgar (2002), there have been three major types of stone tools in human evolutionary history. The oldest stone tool is the Oldowan, which appeared 2.5-1.7 Million Year Ago (Mya) (the Earlier Stone Age and Lower Paleolithic). The second type of stone tool is (early) Acheulean, which appeared 1.7Mya-0.25Mya (the Earlier Stone Age and Lower Paleolithic). The third type is the late Acheulean type, using the Levallois technique, 0.25Mya-0.05Mya (the Middle Stone Age and Mousterian).

Experiments on the actual making of these stone tools have been used to infer the methods of making stone tools and to speculate on whether recursive methods were used. Moore (2010) analyzed the production process in terms of tree structures, following Greenfield (1991). He found that the Oldowan tools were relatively simple tree structures without subtrees, while the early and late Acheulean manufacturing processes contained subtrees. Stout (2011), on the other hand, wrote down the repetitive structure of actions in lithic production in a hierarchical form and argued that the Oldowan also had a complicated tree structure, and that recursive actions were carried out in production. However, these analyses are arbitrary in their segmentation of acts, and any action can be represented by a tree structure. Therefore, we re-analyzed the production processes with structures of "combination of an object and a tool that acts on the object" as a basic unit, which corresponds to Merge in language. In this analysis, the Oldowan can be written as a simple repetition (non-RC) and need not be regarded as RC. Contrariwise, the early Acheulean can be seen as a process to prepare different types of objects, which are sub-goals of the final product and should be regarded as RC, or a sub-assembly type Merge, taking place in the production process (Sano et al. in prep.).

Thus, the evolution in our simulations corresponds to the evolution from the Oldowan to the Acheulean stone tools. It has been suggested that a climatic change occurred at 1.9-1.6 Mya caused a grass-land expansion which is supposed to cause the difficulty in obtaining foods from forests and the increase of competition for food and, then, to influence human evolution to *Homo erectus* (deMenocal 2011). The emergence of the Acheulean lithic artifacts corresponds to this period.

While the analyses of stone tool production introduced above examine recursion in action sequences, combining multiple objects to create a new tool, typically a bow-and-arrow, appeared in *Homo sapiens*. Lombard and Haidle (2012) provide a detailed analysis of this type of combinatorial tool-making and assumed cognitive processes in the Middle Stone Age, suggesting that early *Homo sapiens* were capable of recursive thinking, which would have amplified the flexibility in decision-making and taking action. A recent analysis of lithic pieces shows that the earliest known date for this kind of complex tool-making technology is 45-40 thousand years ago (0.045-0.040 Mya) (Sano et al. 2019). Such empirical evidence suggests that the ability of RCs in the action of object manipulation evolved in *Homo erectus* and that the ability to combine objects to make tools evolved more later in *Homo heidelbergensis* or *Homo neanderthalensis*.

Note that the RC mentioned so far concerns objects only. The cognitive load in manipulating objects is much lower than that in manipulating language because objects are easier to manipulate with the hands, and as the results of the manipulations remain in the world, they do not require working memory. It can be thought, however, that holding objects in the hands and manipulating them might enhance the ability to manipulate images as objects. The traces of the ability to put something together in the mind rather than handling objects by hand appeared in *Homo sapiens* with the development of modern behavior, leaving beautiful and realistic cave wall paintings and imaginary objects such as lion-headed human statues, suggesting a rich spiritual world (Mithen 1996). How the evolution from the manipulation of images to the manipulation of symbols needed for language has occurred and can occur is a significant challenge in the evolution of human cognition and the evolution of language.

5. An Attempt to Integrate Intention Sharing and Hierarchy Formation

Finally, we introduce a hypothesis to integrate intention sharing and hierarchy formation by recursive combination. These two features are integral in human cognition, making us co-creative. Intention sharing is necessary for sharing hierarchically structured complex concepts formed by recursive combination, as mentioned in Section 2.3. We also consider that recursive combination can be a basis of intention sharing.

Humans can understand others intentions even if the relationship between their behavior and intention is not as definitive as a shared code. It is often possible to share intentions with others, even when there are few definitive code cues and the behavior expressing intentions changes depending on situations (indefinitive communication). The inferential model of pragmatics (Grice 1975, Sperber and Wilson 1986/1995), which deals with indefinitive communication, argues that listeners make inferences about speakers intentions from utterances they receive using various information such as common sense, world knowledge, and knowledge about the speakers.

It is reasonable to consider this inference as abduction. Abduction is a type of reasoning to come up with a plausible hypothesis to explain an interesting phenomenon, which was proposed by the pragmatist philosopher Peirce (1940). It can be considered that abductive reasoning occurs in estimating a cause (a superficially invisible mechanism) behind a phenomenon, e.g., the phenomenon of an apple falling gives rise to the idea of universal gravitation (Yonemori 2007). Abduction is the inference that "when we observe an interesting phenomenon X, we can successfully explain X if we assume a certain cause C". Others intention must be in others mind, which is usually invisible. Inferring intentions in others minds from observable actions, such as speech, facial expressions, and body actions, can be explained by assuming that the same reasoning occurs as inferring a mechanism behind a phenomenon from its observable evidence. In other words, one infers that “when we observe a persons action A, we can be persuaded ourselves of the action A if we assume the persons intention H.”

There can be an infinite number of hypotheses in principle to explain a finite number of observations. In practice, one must assume a variety of hypotheses (hypothesis generation) and select an appropriate one (hypothesis selection). As shown in Section 4, one way to achieve a variety of generations is the recursive combination.

The "simulation theory" of intention understanding asserts that others intention is automatically and intuitively known through embodied simulation by MNS (Gallese and Goldman 1998), which is consistent with our finding introduced in Section 3. This assertion suggests that hypothesis selection in the abduction of others intentions is performed by

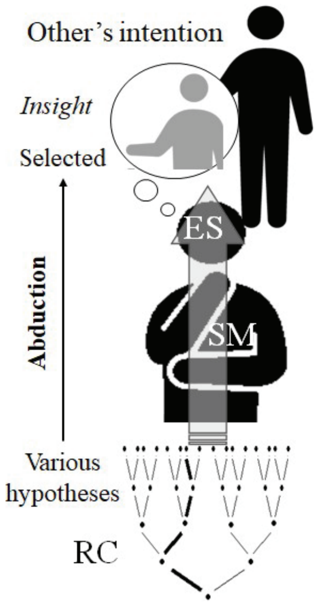

Figure 10 The Hypothesis to Integrate Recursive Combination with Intention Sharing in Hypothesis Generation and Hypothesis Selection

embodied simulation. Abduction is not only inference but also insight. According to the somatic marker hypothesis (Damasio et al. 1991), body-emotion responses that are expected to lead ones own body to good homeostasis are learned, which in turn directs decision-making and cognition. The somatic marker hypothesis suggests that hypotheses that are judged to have a certain "bodily value" are chosen and brought to consciousness.

What we said so far in these three sections may be summarized thus: Intention understanding is abductive reasoning that requires diverse hypothesis generation and hypothesis selection from them (this section); the recursive combination functions to diversify products (Section 4); people who are more likely to perform embodied simulation are more likely to guess the speakers intention in communication (Section 3); behaviors leading body to good homeostasis are leaned and orient cognition via somatic marker (this section). We connect them to our hypothetical claims, illustrated in Figure 10. The function of generating diversified representations by recursive combination (RC) is utilized in the formation of various hypotheses necessary for abductive reasoning about others intentions. Among the hypotheses generated in this way, ones that are simulably embodied and lead ones body to a good state are selected with embodied simulation (SM) and somatic marker (SM), respectively. In other words, we generate various hypotheses, including those that may or may not explain others actions and those that may or may not be realistic, through the formal computation of recursive combination operations, and select from them those that can be realized by ones own body as intentions that others may really have. Generating a variety of hypotheses implies the possibility that indefinite cases can be understood by inference (hypothetico-deduction), starting with unselected hypotheses by ES and SM. This idea is to propose a basic framework of the human cognitive system with creativity that "generation by combination × selection and sense-making by embodiment."

6. Summary

In this paper, we introduced the project Evolinguistics (http:/evolinguistics.net/en/), which is an attempt to elucidate the origins and evolution of human language and communication. The two conceptual bases of this project are intention sharing and hierarchy. Both are remarkable features of human linguistic communication. The vital point in clarifying the origins and evolution of language is that the two features are integrated in human cognition and that the integration may form the foundation of knowledge co-creation in human society as complex concepts are constructed through hierarchy formation in language, and the concepts are shared through intention sharing. In order to elucidate the evolution and integration of the two features, various fields related to language and biological evolution must cooperate, such as linguistics, evolutionary biology, anthropology, cognitive science, computer science, and complex systems study. Therefore, the project official name is "Evolinguistics: Integrative Studies of Language Evolution for Co-Creative Communication."

We claimed the significance of an emergent constructive approach, which is a methodology for complex systems study, to pursue such dynamic and complex phenomena as the emergence and evolution of language. Two examples of emergent constructive studies were introduced.

The first study is a language evolution experiment of the formation of symbolic communication. A cognitive experiment, computational modelings, and a brain measurement were integrated in this study. We showed that symbolic communication systems for intention sharing formed through three stages: establishing common ground through regular behavior, sharing symbol systems, and dividing roles for intention sharing; the last part is a unique and particularly noteworthy finding of our research. Role-reversal imitation and embodied simulation through the mirror neuron system play roles in the formation process.

The second one is an evolutionary simulation of recursive combination, which is the ability to construct hierarchical structures. Adopting a hypothesis that recursive syntactic combination evolved from recursive combination in object manipulation, we studied the evolution of recursive combination using a genetic algorithm of automata for object manipulation. We found that the adaptive functions of recursive combination are the diversification of production methods and of products. It is suggested that recursive combination may evolve under strong competition for resources and that this evolution might have occurred during the period of *Homo erectus*.

As we stressed the pivotal role of the emergent constructive approach as an abduction engine in Evolinguistics, we proposed the importance of the diversification function of recursive combination in the evolution of human cognition and culture. Indeed, we are making progress in the analysis of object manipulation behavior in chimpanzees and human children and the analysis of the evolution of stone tools in human prehistory from the viewpoint of recursive combination as collaborative research among comparative cognitive science, archeology, theoretical linguistics, and complex systems studies.

Although we introduced one hypothesis for the integration of intention sharing and hierarchy in this paper, other emergent constructive attempts are on-going, for example, determining how strings whose meanings depend on their hierarchical structures, called structure dependency, are used to transmit intentions using a language evolution experiment and brain measurement (Kataoka et al. 2020); another example is studying how strings used in intentional communication develop to be structure dependent in a competitive and cooperative game (Saito and Konno 2019). Thanks to the high degree of freedom of the emergent constructive approach, we will explore possible hypotheses about the integration of intention sharing and hierarchy to comprehend knowledge co-creation as the essential nature of humans.

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