Title	Future Trends in the Biology of Language: Constructive modeling of grammaticalization for the origin and evolution of language
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Citation	
Issue Date	2012-03-30
Type	Book
Text version	author
URL	http://hdl.handle.net/10119/11924
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Description	

4 Constructive Modeling of Grammaticalization for the Origin and Evolution of Language

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I. Introduction: evolution of language, grammaticalization, and the constructive approach

1. Origin and evolution of language

Human language is a communication system distinct from those of other animals. We have been interested in the question of how, when and why a transition between the state of not having language and the state of having it took place. This is a question about the origin of language. It is modernized as follows: how did biological characters unique to human language and various physical and cognitive abilities that make human language possible evolve? This is concerned with the biological evolution of human characters. On the other hand, we have also been interested in the process of evolution of language itself; that is, how, when, and why the initial language became more complex and structuralized into present languages[1]. This is thought of as a process of cultural evolution.

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[1] Here, it is posited that the initial language or proto-language was simpler and less structuralized than modern languages.

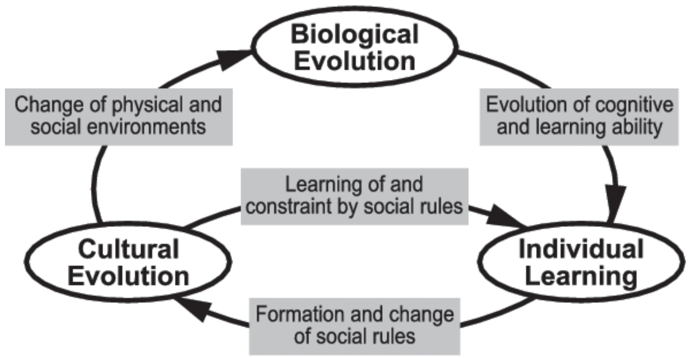

Figure 1. Double-loop interaction dynamics among biological evolution, individual learning, and cultural evolution in the origin and evolution of language

The process of the origin and the evolution of language forms a double-loop dynamic among biological evolution, individual learning, and cultural evolution as displayed in Fig. 1 (Hashimoto, 2006). The outer loop is mainly associated with the origin of language, since humans acquired the physical and cognitive abilities for language over the course of human evolution. Without modifications in such abilities through biological evolution, language may not have been able to change. This change through time is a universal feature of human language. Thus, the inner loop between individual learning and cultural evolution is devoted to the evolution of language.

2. Grammaticalization in the evolution of language

In this paper, we consider the process of grammaticalization through modeling and computer simulations. Grammaticalization is a type of change in meaning, in which content words acquire functional features, or functional words become more functional (Heine, 2005). There are two remarkable features of the process of grammaticalization. The first is unidirectionality, which refers to the fact that changes in the opposite direction of grammaticalization, called de-grammaticalization, are very rare. The other feature is its universality, or the fact that similar types of changes are observed independently in many languages in the world, without any contact between them (Heine and Kuteva, 2002a). Grammaticalization has attracted notice in evolutionary linguistics since it is thought of as a key process in how grammatical forms emerged and evolved, and how language was structuralized in the evolution of language through the inner loop from Fig. 1 (Heine and Kuteva, 2002b, 2007; Hurford, 2003; Hashimoto and Nakatsuka, 2006).

Unidirectionality suggests that proto-languages could probably be reconstructed (Hurford, 2003) and that they may consist of only verbs and nouns (Heine and Kuteva, 2002b). In fact, Heine and Kuteva (2007) show the hypothetical reconstruction of the evolutionary history of grammatical categories by reverse tracing the processes of grammaticalization. Newmeyer (2003, 2006), however, claims that such reconstruction hypotheses, which claim that proto-language had only content words, are not appropriate since the processes of grammaticalization are often cyclical, rather than being a straightforward process from content to functional items.

3. A constructive approach to grammaticalization

The feature of universality is suggestive of humans' universal cognitive abilities, biases, and the other motivations that help cause grammaticalization. We hypothesize that unidirectionality is an indication of some universality of cognitive characters, and we pursue them using a constructive approach.

In order to clarify the cognitive mechanisms related to certain phenomena, investigation using the constructive approach is often effective. With the help of this method, we construct abstract cognitive models based on existing knowledge, and then use computer simulations to hypothesize and analyze the processes, conditions, and mechanisms for the phenomena to be realized (Hashimoto, Sato, Nakatsuka, and Fujimoto, 2008). It is especially difficult to conduct real experiments to consider the possible cognitive mechanisms and critical conditions for grammaticalization to occur, since meaning changes in natural language have a historically dependent and one-time-only nature. To understand such complex phenomena, and not to merely reproduce real phenomena, the constructive simulations must have controllability, repeatability, and analyzability, each of which plays a complementary role in a methodology that uses observation, description, and the analysis of concrete phenomena.

In studies of language evolution using computer simulations and mathematical modeling, the processes that involve individual learning and cultural evolution, that is, the inner loop in Fig. 1, are incorporated into various models (Cangelosi and Parisi, 2002). The question of language origin is believed to be unanswerable by models that include only the inner loop in Fig. 1, since they premise the presence of language and language abilities. In this paper, we make a model of the inner loop within the double loop, in which we hypothesize cognitive abilities and biases, and analyze the model to reveal their conditions for realizing some characteristic phenomena unique to and universal in human languages, such as grammaticalization. If we can understand such phenomena, we can also understand how the hypothesized cognitive abilities and biases are important for humans to make human language possible. Of course, this method does not prove that human language was caused by such cognitive abilities and biases. It merely shows possible and logical conditions or scenarios for the origin of language. Since we cannot produce direct and concrete evidence for the origin of language, we think this possible and logical scenario may be an important clue to understanding the origin and evolution of language. Such possible and logical conditions and scenarios provide a path by which we can interpret and organize other indirect evidences.

4. Purpose and structure of this paper

The purpose of this paper is to clarify the cognitive mechanisms underlying grammaticalization by focusing on unidirectionality through a constructive approach and discussing the origins and the evolution of language. With this aim in mind, we will present a model of cognitive agents and analyze it using computer simulations. Furthermore, we will propose a hypothesis on the origin and the evolution of language through our discussion on the significance of the cognitive mechanisms that realized unidirectional meaning changes for human evolution.

The rest of this paper is organized as follows: In Section II, we examine a hypothesis proposed by Hopper and Traugott (2003) in which reanalysis and analogy are considered indispensable processes of grammaticalization. We reconsider these two processes to be cognitive abilities. A computational model is described in Section III. This model is a kind of iterated learning model that was proposed by Kirby (2002) with straightforward extensions to include functional meanings of grammaticalization phenomena. In Section IV, we examine the relationship between the cognitive abilities introduced in Section II and the learning operations in the model explained in Section III. The simulation results are described in Section V with focus on meaning changes. We will show the importance of linguistic analogy in cognitive abilities mentioned above. Linguistic analogies have the ability to expand the applicable domain of a learned grammatical rule. In this section, we also show that iterated generalized learning is not sufficient for unidirectional meaning change. In order to illustrate unidirectionality, we introduce cognitive biases into the model in Section VI, and show the results of various simulation conditions of each cognitive bias. In Section VII, we discuss the significance of the simulation results and propose a hypothesis about the origin and the evolution of language justified by our discussion of the results. Section VIII is devoted to summarizing and concluding this paper.

II. Reanalysis and analogy as cognitive abilities

Hopper and Traugott (2003) claim that reanalysis and analogy are indispensable processes to grammaticalization. Reanalysis is an internal structural change without an observable change in forms. An analogy is a generalization of a grammatical rule that is applied to forms in which the rule was not formerly applied.

We can explain these two processes by using a typical example of grammaticalization, “be going to” in English, excerpted from Hopper and Traugott (2003) (see Fig. 2 also). The collocation “be going to do” was originally the progressive tense of the verb “go.” A sentence such as “be going to visit Bill” was analyzed as “be going [to visit Bill],” in which the bracketed words form a specific phrase. This sentence was reanalyzed by a listener as “[be going to] visit Bill.” At this stage, the phrase “be going to” represents the future tense. The rule that “be going to” represents something that will be done in the future is established only in the listener’s mind; therefore, it is an internal structural change. Furthermore, the rule is applicable only to verbs of action, such as “visit.” At the next stage, a sentence such as “be going to like Bill” is uttered. In this sentence, the rule is extended to other verbs, and the structural change is revealed in its form. The extended application of a grammatical rule is called an “analogy” in Hopper and Traugott (2003).

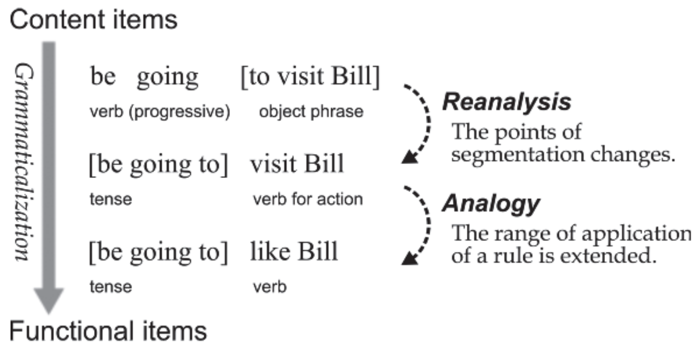

Figure 2. Reanalysis and analogy in the process of grammaticalization. Modified from Hopper and Traugott (2003).

We believe that language users have special cognitive abilities to cause these two processes. Reanalysis as a changing process may be caused when a hearer recognizes a sentence as having a different structure from speaker's intent. At that time, the hearer determines the segmentation points in a sentence by himself. Thus, in order for reanalysis to occur, the hearer needs the ability to determine the structure of a sentence by himself according to his own criteria. When analogy as a changing process occurs, a speaker extends a grammatical rule's range of application. We call this "linguistic analogy" in order to emphasize that this ability is exhibited in the expansion of the application domain of grammatical rules.

In short, we introduce the following two cognitive abilities that we consider to be necessary to bring about grammaticalization:

- *Reanalysis*: The cognitive ability to decide how to segment a sentence by oneself according to one's own knowledge and situations (contexts).
- *Linguistic analogy*: The cognitive ability to apply a grammatical rule extensively to forms that the rule has not formerly been applied.

III. Modeling

We will construct an agent-based model for the analysis of the grammaticalization mechanism using computer simulations. We also will adopt an agent

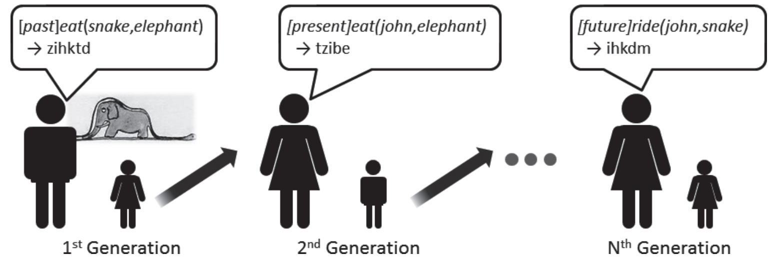

Figure 3. Schematic picture of an iterated learning model.

model introduced by Kirby (2002), hereafter called the Kirby model. In this section, we describe the model[2], concretely, the iterated learning framework, linguistic knowledge of the agent, and learning operations.

1. Iterated learning model

In the iterated learning model (ILM), there are two agents: an adult agent who has linguistic knowledge and a child agent who acquires linguistic knowledge from the adult agent. The model is schematically shown in Fig. 3. Situations to be described are displayed for both agents. The adult agent utters sentences corresponding to the situations using his or her own linguistic knowledge. The child agent receives pairs of a meaning, which is the described situation, and a form, which is the utterance by the adult agent. The child commits the pairs to his or her linguistic knowledge and tries to generalize this linguistic knowledge using learning operations.

After the acceptance of a certain number of utterances, the child agent becomes an adult agent in the next generation, and a new child agent who does not have linguistic knowledge is introduced. The former adult agent is removed. The new adult agent provides the new child agent with utterances using his or her acquired linguistic knowledge, which is often different from the adult's linguistic knowledge from the former generation. This is a sequence of language acquisition processes in which the linguistic knowledge changes across generations.

In the initial generation, neither the adult nor the child agent has linguistic

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2 In addition to the Kirby model, we introduce cognitive biases for meaning recognition. That is explained in Section IV.

knowledge. When an adult agent cannot produce an utterance corresponding to a situation using his or her linguistic knowledge, a new sentence is randomly invented and it is incorporated into the adult's store of linguistic repertoire. Therefore, the adult agent's linguistic knowledge in the first generation is a random mapping between forms (utterances) and meanings that are representative of whole situations. The child agent in the first generation memorizes these random mappings and generalizes them for its memorized linguistic knowledge. The randomness of the mappings usually reduces through generations, because typically only some of the possible situations are displayed for each subsequent generation. This structuralization across multiple generations is a remarkable feature of ILM.

Kirby (2002) shows that the random mappings, which begin as a kind of holistic language, eventually become systematic mappings between elemental meanings and words that compose whole utterances, when the situations are composed of elemental meanings. Since the resultant linguistic knowledge is a compositional language, Kirby insists that its compositional properties evolve through a series of language acquisitions, which is a kind of cultural evolutionary process. Note that the meanings (situations) given to the agents are compositional in advance. From a cognitive viewpoint, it is presupposed that agents have the cognitive ability to recognize the world as being composed of elementary entities and actions. Thus, we can interpret Kirby's theory to mean that the compositionality of the world or in the recognition of the world is reproduced in part in language, through cultural evolution.

The evolution of compositionality has been shown using various generalization algorithms, such as grammar induction (Kirby, 2002), minimal description length (Brighton, 2002), associative networks (Smith, 2002), and Bayesian learning (Griffiths and Kalish, 2005). Kirby, Cornish, and Smith (2008) confirmed that compositionality emerged even in a laboratory experiment using human participants. Furthermore, the knowledge that was structuralized via iterated generalized learning is not limited to language. Kalish, Griffiths, and Lewandowsky (2007) showed, using Bayesian inference and human experiment, that the functional relationship between two sets of natural numbers is also structuralized through iterated learning. We can say that the fact that structuralization occurs in the knowledge of mappings between two entities, such as between meanings and forms, between two sets of variables, through iterated generalized learning is a kind

of universal law of cultural evolution. This implies that general generalized learning is sufficient to make language compositional. This is because compositionality is too general as a universal feature of human languages. Such structure can be found in any information system that has a certain level of efficiency. Therefore, we should make more human language specific feature a target of our constructive research using an iterated generalized learning framework, and we take gramaticalization in this study. Grammaticalization is thought of as universal and unique to human language.

In this paper, we are interested in not the convergence point of the iterated learning but the process and mechanism of change of linguistic knowledge. The linguistic knowledge in the ILM also changes after an agent acquires linguistic knowledge capable of producing any utterance for any situation. Therefore, we observe the process of changing, especially changes in meaning, after attaining the expressive ability of an agents' linguistic knowledge.

2. Linguistic knowledge

The linguistic knowledge in this agent model is expressed by definite clause grammar, the same as Kirby (2002) used, which is a modified version of context-free grammar. A grammar is a rule set in which a rule creates a correspondence between a meaning (situation) and a form (utterance). Non-terminal symbols in the right-hand side are rewritten by other rules having the non-terminals in the left-hand side. The rewriting is conditioned. The condition is specified as N/c, where N is a non-terminal symbol and c is a condition; it is interpreted as a meaning in the present representation of linguistic knowledge.

There are three types of rules: a sentence rule (1), a sentence rule with variables (2), and a word rule (3), as follows.

$$S/c_s \rightarrow A^*, \quad (1)$$
$$S/c_x \rightarrow (A \cup N/x)^*, \quad (2)$$
$$N/c_w \rightarrow A^*. \quad (3)$$

In the sentence rule, $S/c_s \rightarrow A^*$, the left-hand side is a non-terminal symbol S corresponding to a sentence with a condition c_s; the right-hand side is a sequence of terminal symbols A^*. The condition c_s corresponds to the meaning of the whole situation to be described. It is represented by a first-order predicate

$$[T_i]P_j(X_k, X_l), \tag{4}$$

where T_i represents tense, P_j is a verb meaning representing an action, and X_k and X_l are noun meanings representing an actor and a patient (object of action), respectively[3]. For example, the situation “a snake ate an elephant” is represented by a predicate “[*past*]*eat* (*snake*, *elephant*)” and a rule,

$$S/[past]eat\ (snake, elephant) \rightarrow \text{zihktd}, \tag{5}$$

means linguistic knowledge that indicates that the form “zihktd” is used for describing the situation.

A sentence rule can hold variables. In a sentence rule with the variable $S/c_x \rightarrow (A \cup N/x)^*$, the condition c_x in the left-hand side has variables such as $[T_i]P_j(x, X_l)$. The right-hand side is a sequence of terminal symbols and non-terminal symbols, in which the number of non-terminal symbols coincides with the number of variables c_x. A sentence rule with variables is used to describe any situation that matches a condition in which all variables are substituted with concrete meanings. For example,

$$S/[past]eat(x, elephant) \rightarrow \text{zi}\ N/x\ \text{d}, \tag{6}$$

can be used to describe the situations “*any actor* ate an elephant.”

Word rule is used to rewrite non-terminal symbols in a sentence rule with variables. In a word rule, $N/c_w \rightarrow A^*$, the left-hand side is a non-terminal symbol N with a condition c_w, and the right-hand side is a sequence of terminal symbols A^*. The condition c_w in the word rule is any single element from $\{T_i, P_j, X_k, X_l\}$. For example, a rule set

[3] In Kirby’s original model, only content items, specifically verb meanings and noun meanings, are used. In this paper, we extend the model to incorporate tense as a functional meaning in order to treat meaning changes from content to functional items.

$$S/[past]eat(x, elephant) \rightarrow \text{zi}\ N/x\ \text{d}, \tag{7}$$
$$N/snake \rightarrow \text{hkt}, \tag{8}$$

can describe the situation “[*past*]*eat*(*snake*, *elephant*)” as follows. The variable as the actor in rule (7) is substituted by a concrete meaning, “snake,” and the rule becomes

$$S/[past]eat(snake, elephant) \rightarrow \text{zi}\ N/snake\ \text{d}. \tag{9}$$

The condition of the non-terminal symbol on the right-hand side is “snake,” and therefore rule (8) can be used to rewrite this non-terminal symbol. Eventually, this rule set produces the same form “zihktd” as rule (5).

This type of rule set, with a sentence rules with variables, is called a hierarchical rule set. Non-terminal symbols in word rules are considered to indicate categories in a lexicon. Thus, rule (8) is interpreted as “a meaning *snake* in a category *N* is represented by a word ‘hkt’.”

In the present paper’s model, we prepare five verb meanings, five noun meanings, and three kinds of tense (*past*, *present*, and *future*) as functional meanings. Meaning given to agents has the propositional form “[tense]verb(noun, noun),” and the two nouns being used must not be the same; thus, the number of possible meanings is 300.

3. Generalization learning algorithm

A child agent tries to generalize its linguistic knowledge by applying learning operations. A generalization learning algorithm for the linguistic knowledge that Kirby (2002) introduced consists of three types of operations: chunk, category integrate, and replace[4].

The operation called chunk introduces a variable into a sentence rule

[4] The term “replace” was coined by Hashimoto and Nakatsuka (2006), which is explained in Kirby (2002, appendix), where it is not named. This operation plays a critical role in generalization learning, as well as in the evolution of language, as we see later. Although Kirby (2002) described category integrate as merge, we renamed it to reflect the content of operation, since it might be confusing with Merge in the minimalist program, which is completely different from the operation in this model.

based on similarities between meanings and between forms. The operation called category integrate arranges word rules in different categories based on similarities between word rules. The operation called replace introduces a variable into a sentence rule based on similarities between a word rule and a sentence rule. In this subsection, we further define each learning operation.

3.1. Chunk

If two rules are the same other than one part in the meanings and in the forms, respectively, the chunk operation can be applied. The chunk operation integrates the two sentence rules into one sentence rule with a variable and adds two word rules corresponding to the different parts. A new non-terminal symbol is invented for the variable in the sentence rule and the new word rules.

For example, two rules

$$S/[past]eat(tiger, sausages) \rightarrow \text{uiktt}, \quad (10)$$
$$S/[past]eat(john, sausages) \rightarrow \text{uottt}, \quad (11)$$

have different actors, *tiger* and *john*, on the left-hand side, and a part of forms, “ik” and “ot,” on the right-hand side. Through the chunk operation, these two rules are substituted by the following three rules in the child’s linguistic knowledge:

$$S/[past]eat(N/x, sausages) \rightarrow \text{u } N/x \text{ tt}, \quad (12)$$
$$N/tiger \rightarrow \text{ik}, \quad (13)$$
$$N/john \rightarrow \text{ot}. \quad (14)$$

3.2. Category integrate

If the meaning and form of a rule in a category are the same, respectively, as those of a rule in a different category, the operation of category integrate can be applied, in which a category is a set of word rules sharing a non-terminal symbol. This operation integrates the two categories into one category; specifically, the non-terminal symbol of one set of word rules is substituted by the non-terminal symbol of the other set. At the same time, all the non-terminal symbols that are the same as the substituted one is substituted throughout the child’s linguistic knowledge.

For example, in the following rule set,

$$N/john \rightarrow \text{it}, \quad (15)$$
$$N/tiger \rightarrow \text{ot}, \quad (16)$$
$$N/mary \rightarrow \text{ksx}, \quad (17)$$
$$C/john \rightarrow \text{it}, \quad (18)$$
$$C/peter \rightarrow \text{aaig}, \quad (19)$$

rules (15) and (18) have the same meaning on the left-hand side, have the same form in the right-hand side, and have different non-terminal symbols. These rules eventually have the same non-terminal symbol. That is to say, two categories, *N* and *C*, are integrated when the category integrate operation is performed:

$$N/john \rightarrow \text{it}, \quad (20)$$
$$N/tiger \rightarrow \text{ot}, \quad (21)$$
$$N/mary \rightarrow \text{ksx}, \quad (22)$$
$$N/peter \rightarrow \text{aaig}. \quad (23)$$

3.3. Replace

The replace operation can be applied if both the meaning and the form of a word rule are included in a sentence rule. In the sentence rule, the meaning that corresponds to the word rule is replaced by a variable, and the corresponding part of the form is replaced by the non-terminal symbol of the word rule.

For example, in a rule set

$$N/john \rightarrow \text{it}, \quad (24)$$
$$S/[present]read(john, book) \rightarrow \text{swite}, \quad (25)$$

both the meaning *john* and the form “it” in the word rule (24) are included in the sentence rule (25). In this case, the sentence rule is replaced by

$$S/[present]read(x, book) \rightarrow \text{sw } N/x \text{ e}, \quad (26)$$

where the non-terminal symbol in the sentence rule with variable (26) is the same as the non-terminal symbol used in the word rule (24).

Although Kirby (2002) describes the replace operation only in appendix and does not name it, we define this operation individually, because the role of replace operation from the cognitive viewpoint is important as we discuss in Section IV and V.

IV. Relationship between cognitive abilities and learning operations

In this section, we analyze the cognitive abilities introduced in Section II, reanalysis and linguistic analogy, and the learning operations defined in Section III.3.

In the chunk operation, different parts are extracted from similar sentence rules and are then transformed into word rules. This is so that an agent can determine the segmentation of sentences based on their own recognition and comparison of situations (meanings), memory, and forms. This corresponds to the ability of reanalysis.

In the category integrate operation, two categories are integrated into one category, if two rules in each category have the same meanings and the same forms, respectively. This prepares the object of a linguistic analogy that is to expand the range of rule application, since a rule applied to one category before integration can be applied to all the rules in the integrated category.

Let us consider the effect of the replace operation. If the agent, having the linguistic knowledge indicated in the example from Section III.3.3, has other word rules in the category *N* (for example, *N*/*elephant*→ir), the rule set after replace operation is:

$$N/john \rightarrow \text{it}, \qquad (27)$$

$$N/elephant \rightarrow \text{ir}, \qquad (28)$$

$$S/[present]read(x,\ book) \rightarrow \text{sw } N/x \text{ e}. \qquad (29)$$

In this rule set, the sentence rule with variable (29), which is used to represent a meaning "[*present*]*read*(*john*, *book*)" in combination with the word rule (27), can by extension be applied to the other word rule (28). The agent is endowed with the ability of linguistic analogy by the replace operation.

We examine the differences between linguistic analogies by the operations category integrate and replace. In categorically integrated linguistic analogies realized, a rule used for one category applies to rules in the other category via the integration. A rule set must be hierarchical prior to integration in order for its application to be extended. The replace operation makes a rule set hierarchical by introducing a variable into a sentence rule, such as (25). This operation directly extends the application of the rule. This feature makes the replace operation more direct and powerful as a linguistic analogy than category integrate operation, which contributes only indirectly by preparing the application object of the linguistic analogy.

Although the chunk operation also introduces a variable, as shown in (12), this operation always introduces a new non-terminal, i.e., a new category. Therefore, the rule with a variable can only be applied to the rules in the new category, and no extension occurs.

The replace operation seems to have an effect of reanalysis. For example, this operation segments the form "swite" in (25) into the sequence "it", variable, and "e" in (26). However, the agent has the linguistic knowledge (24) that "it" represents *john* before the replace operation occurs. In this case, the replace operation sets up the premise for the existence of a word rule, and only chunk operations produce the word rule by extracting a part of the sentence. Thus, chunking mainly takes the ability of reanalysis.

From the examination above, we can summarize the relationship between cognitive abilities and learning operations as follows: the ability of reanalysis is taken principally by chunking, and the ability of linguistic analogy is taken principally by replace operation.

V. Analysis of meaning change

1. Directionality and process of meaning change

We analyzed the change in linguistic knowledge across generations using computer simulations of the model introduced in Section III. The focus of the analysis was the change of meaning over time. We observed which forms represented which meanings, and how such relationships changed over generations. Various meaning changes were observed. Among the changes, there were changes from content meanings to functional meanings. However, other types of changes, such as changes within one syntactic category and changes from functional to content meanings (such as de-grammaticalization) occurred with the same frequency. We concluded that the iterated generalized learning with the algorithm expressing the abilities introduced in Section II is not sufficient to bring about unidirectional meaning change, which is one of the characteristics of grammaticalization.

We scrutinized the process of meaning changes in which a form representing a meaning comes to represent another meaning. From this examination, the importance of synonymy and polysemy for meaning change was confirmed. Let us examine further the process of meaning change. Imagine the following rule set for an adult agent, which is a general case with synonymous and polysemous forms, as the starting point of the meaning change process:

$$N_1/meaning_1 \rightarrow form_1, \quad (30)$$
$$N_2/meaning_1 \rightarrow form_2, \quad (31)$$
$$N_3/meaning_2 \rightarrow ...form_1..., \quad (32)$$

where $meaning_1$ is a source and $meaning_2$ is a destination of meaning change of the $form_2$. The rule set has multiple word rules representing the same source meaning, such as (30) and (31). The rule set also has another rule, such as (32), in which the right-hand side includes one of the forms of the rule (30), and the left-hand side is different from the meaning of the rules. Specifically, $form_1$ and $form_2$ are synonyms, and $form_1$ is somehow polysemous. Suppose that a child agent with rule (30) faces a situation to be described, including both $meaning_1$ and $meaning_2$, and that the adult agent utters a sentence in which rules (31) and (32) are used to represent the situation. Since the child agent considers $form_1$ as representing $meaning_1$, it interprets $form_2$ as different meaning. The $meaning_2$ is a candidate of such meaning. Thus, the meaning of $form_2$ changes from $meaning_1$ to $meaning_2$.

2. Effect of learning operations

The effect of generalized learning operations on the cultural evolution of language are investigated in this section. By setting up various conditions in

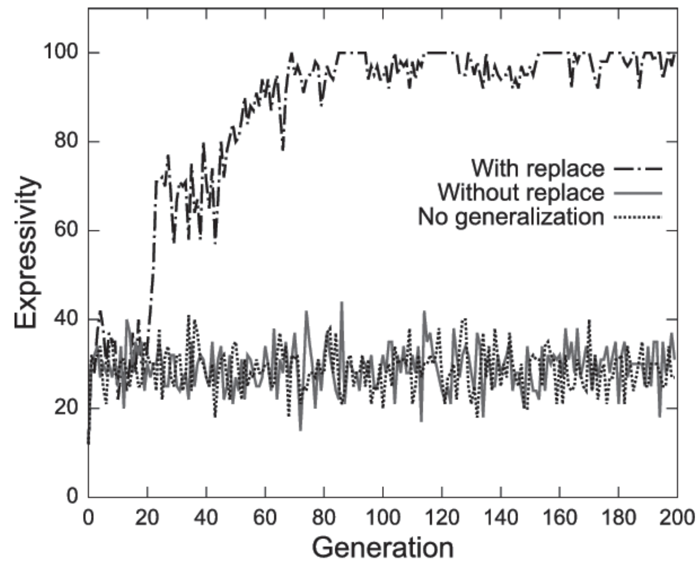

Figure 4. Transition of expressivity over generations for three different settings of learning operations (an example of a typical run).

the introductions of each learning operation, we analyzed how expressivity changes across generations. The expressivity is the ratio of meanings that are expressed by the linguistic knowledge of a child agent at the end of the learning period in each generation to all possible meanings, which is 300 in the present setting of the model. In this experiment, 70 randomly selected meanings from the 300 were given to the agents in each generation.

The typical results are shown in Fig. 4, where the time series of expressivity for three settings about learning operations are shown. The three settings are as follows: all three operations are introduced, labeled as “with replace”; the chunk and category integrate operations are introduced, labeled as “without replace”; and no learning operation is introduced, labeled as “no generalization.” The x-axis is for the generations and the y-axis is for expressivity. For “no generalization,” the expressivity did not develop and randomly fluctuated, because the child agents simply memorized given pairs of meaning and form. For “without replace,” the expressivity stayed at the same level as in the case of “no generalization.” Cultural evolution towards sufficiently expressible language did not occur effectively when the replace operation was not introduced. Only in the case of all three learning operations being introduced, shown by “with replace,” did expressivity rise and could a

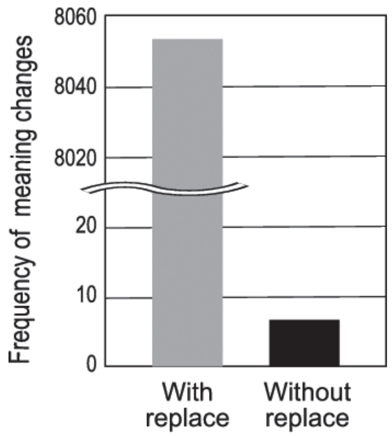

Figure 5. The differences in the frequencies of meaning changes between "with replace" and "without replace" operations (average of 100 runs).

language capable of expressing all possible meanings evolve. Language with full expressivity is not a grammar with all sentence rules corresponding to all possible meanings, but a rule set that is generalized and that can produce any meaning when required; more specifically, it is a grammar having appropriate productivity.

The replace operation is also important for meaning change. Figure 5 shows the differences in the frequencies of meaning changes between the conditions "with replace" and "without replace" operations. In simulations with all three learning operations ("with replace"), meaning change was often observed. In contrast, virtually no meaning change occurred when the replace operation was excluded ("without replace").

VI. Cognitive biases for unidirectionality

1. Introduction of cognitive biases

Some disposition in the recognition of situations and in learning and using a language may be necessary for the rise of directionality in meaning change. We introduced two designs of cognitive biases in the recognition of meanings and using language.

The design of cognitive bias named "pragmatic extension" is just that: an

agent recognizes an overlap of a meaning domain with another particular meaning, and thus the agent can use a form corresponding to the latter meaning to represent the former meaning. This is formally defined as follows: If $meaning_1$ and $meaning_2$ have overlapped meaning domains, and a speaker has a rule $N_2/meaning_2 \rightarrow form_2$ but does not have a rule for the other meaning, $meaning_1$, the speaker can use $form_2$ in order to express $meaning_1$. In the present model, we set the meaning of *go* as $meaning_1$, and *walk* and *run* as $meaning_2$. That is to say, agents recognize an overlap between meaning domains of *go* and *walk*, and that of *go* and *run*, but not with other two meanings.

The other design of cognitive bias is named "co-occurrence." This is when an agent recognizes the relevance between two meanings, and thus, when the agent accepts an utterance including one meaning in relevance, the agent is likely to recognize the other meaning in the utterance. This is simply introduced in the present model as follows: a combination of two meanings, *go* and *future*, is more frequent (twice in the following analysis) than the other combinations in the situations to be described.

2. Effect of cognitive biases

We analyzed the effect of two cognitive biases in the frequency of meaning changes. There are four possible settings in introducing the two biases. As shown in Fig. 6, both cognitive biases increased the frequency of meaning changes. However, only the difference between (-,-) and (-,+), without pragmatic extension and with co-occurrence, was not significant under the 5% significance level. Pragmatic extension always increases the frequency of meaning changes.

This analysis investigated the frequency of all meaning changes and did not reveal unidirectionality, one of the characteristics of grammaticalization. Following this, we analyzed how the forms corresponding to the meaning of *go* changed to represent three tense meanings. The reason that meaning changes from *go* to tense were analyzed is that both the cognitive biases were introduced for the meaning of *go*, and co-occurrence was introduced between *go* and *future* tense. Figure 7 shows the result. We found that co-occurrence promoted meaning changes from *go* to *future* more than double in the other meaning changes. The differences among three meaning changes for the

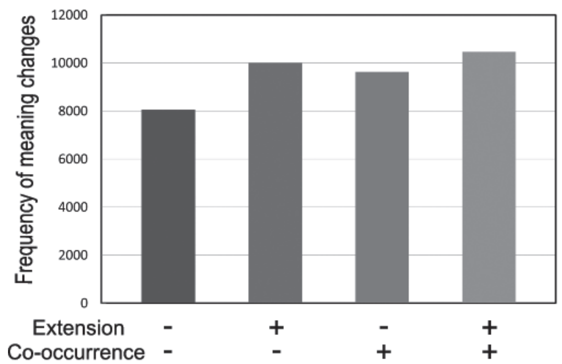

Figure 6. The effect of cognitive biases on the frequencies of meaning changes for four settings about the cognitive biases (average of 100 runs). The symbols + and - indicate whether each bias is introduced or not, respectively.

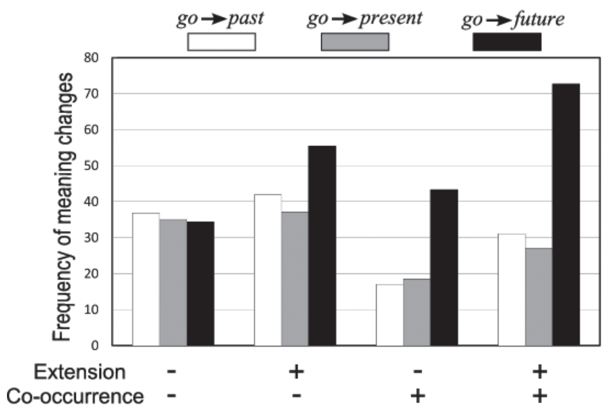

Figure 7. The effect of cognitive biases on the frequencies of meaning changes from the meaning of *go* to three tense meanings (average of 100 runs). The symbols + and - indicate whether each bias is introduced or not, respectively.

case (+,-), with pragmatic extension and without co-occurrence, was not significant under the 5% significance level, as well as no cognitive bias.

Using the analysis above, we summarized the effect of cognitive biases on unidirectional meaning change. The cognitive bias that recognizes an overlap between meaning domains and uses words extensively according to the overlaps causes a change in meaning, and the cognitive bias that recognizes relevancy between source content meaning (*go*) and destination functional meaning reinforces directionality in the meaning change.

VII. Discussion

1. The role of cognitive biases in directionality

Let us consider the mechanism of unidirectional meaning change in the present model. In the current setting of "pragmatic extension," an agent recognizes overlaps between *go* and *walk* and between *go* and *run*, and uses forms representing *walk* and *run* to represent *go*. That a form representing *run* can be used to represent *go* implies that the form is polysemous. At the same time, that two or more forms represent the meaning of *go*[5] implies that synonyms for *go* exist. Thus, pragmatic extension brings polysemy and synonymy to a meaning. This results in the increase of meaning change, as suggested by the observation in Section V.1.

Since the situation to be described is denoted as $[T_i]P_j(X_k, X_l)$, which means [*tense*]*verb*(*agent, patient*), in the model, *go*, *run* and *walk* are in predefined paradigmatic relationships. Thanks to the pragmatic extension setting, meanings have prototype structures and *go* is the core and the most general among those meanings. In a production process, a speaker applies a rule *N/run→ form* to *go* extensively based on the recognition of the relevance of *run* to *go*. This process is considered to be metaphoric inferencing, in which expressions in a meaning domain are applied to another domain based on the relevance between them. In a situation with polysemy and synonymy due to prototype category, meaning change from the general meaning occurs by metaphoric inferencing. This phenomenon corresponds to the hypothesis that a source word of grammaticalization is the most general one among words in the source domain (Bybee, 2003).

A form representing *go* changes to represent another meaning. When an agent infers a form's meaning, which the agent does not already know, the agent looks for a meaning in a situation where the form is uttered. In the current setting of "co-occurrence," the meanings of *go* and *future* are likely to appear in the same situation. Therefore, the probability that the form is assigned to *future* is greater than for the other meanings.

"Co-occurrence" means that a hearer recognizes the contingency between

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[5] One is a proper form for *go,* and others are forms pragmatically extended to *go*.

specific meanings in a predefined syntagmatic relationship, and the meanings *verb* and *tense* are in a syntagmatic relation in the given situations in the model $[T_i]P_j(X_k, X_l)$. It can be said that the meaning change from *go* to *future* that is based on the recognition of the syntagmatic relevance is induced via metonymic inferencing by the hearer.

Altogether, we have shown that the fact that the core of some meanings having paradigmatic relevance, such as *go* with *run* and *walk*, is the source of unidirectional meaning change, and a meaning having syntagmatic relevance with the source is the target. It is suggested that the cognitive biases of language users, the recognition of similarity and contingency, make unidirectionality possible: concretely, a speaker makes a metaphoric inferencing in which he or she recognizes a paradigmatic relevance or similarity, and applies a rule extensively, and the hearer does the metonymic inferencing, shifting meanings based on the recognition of syntagmatic relevance or contingency. The importance of metaphoric and metonymic inferencing in the process of grammaticalization coincides with the claim by Hopper and Traugott (2003).

2. Creativity through linguistic analogy

In this section, we discuss linguistic analogy from the viewpoint of creativity. First, we will explain the replace operation, which corresponds to linguistic analogy: if both a meaning and a form of a word rule are included in a sentence rule, the corresponding parts in the sentence rule are replaced by a variable with the same category label as the word rule. For example, suppose that a learner acquires the linguistic knowledge

$$N/\text{girl} \rightarrow \text{GIRL}, \quad (33)$$
$$S/[\textit{present}]\textit{read}(\textit{girl}, \textit{book}) \rightarrow \text{GIRL READ BOOK}, \quad (34)$$

where *S* is a category label for sentences. In these rules, both the meaning *girl* and the form GIRL in the word rule (33) are included in the sentence rule (34). In this case, the sentence rule (34) is replaced by

$$S/[\textit{present}]\textit{read}(x, \textit{book}) \rightarrow N/x \text{ READ BOOK}. \quad (35)$$

The replace operation provides the basis for the extended application of rules. If this agent has other word rules in the category *N*, the new rule can be applied to such word rules. For example, if the learner agent has a word rule, *N*/*stone* →STONE, then the agent can produce the utterance “STONE READ BOOK.” However, the agent has never seen or heard a situation such as “[*present*]*read*(*stone*, *book*)” since the utterance is not learned through experience but created through extended inference. The ability of linguistic analogies provides the important feature that language users can employ to refer to entities away from “here, now, and I.” This is called *displacement,* which is considered unique to human language (Hocket, 1960).

Linguistic analogy enables language users to create novel expressions. Such expressions, however, are not always valid and meaningful. Some novel expressions may be ignored and some may be taken seriously. The latter expressions have to make sense in order to be used for communication with others or for thought about reality. Two methods, at least, can be assumed for sense-making: one is to change the interpretation of the expression and at the same time to change the conceptualization of the reality, and the other is to change the reality *per se*.

The former method means to reinterpret the expression to be true or to be meaningful by changing the entity that is referred to by the words in the expression. At the same time, the entity referred to must be reconceptualized. For example, the word STONE is reinterpreted to indicate an obstinate person who is reading a book, rather than a kind of material. Here, the interpretation of the word is changed and the interpretation of the reality, an obstinate person, is also reconceptualized as an entity that is similar to stone. This leads to new metaphors as well as artistic and poetic representations.

The latter method is to change the world itself for the novel expression to become reasonable and meaningful. For the example above, if the speaker creates a stone statue of a reading person, or, more interestingly, a reading machine made from stone, the novel expression can be reasonable. Thus, this leads us to contrivances and technical innovations.

Both ways are manifestations of creativity through producing novel expressions by virtue of linguistic analogy and making sense of novel expressions. We suppose that linguistic analogy can exert creative power after the acquisition of a basic ontology about the world, which is plausible both ontogenetically and phylogenetically.

We can consider extensions of the number system as an instance of creativity using such a process. Suppose that a learner experiences situations such as “there are two cows” and “there are three baskets with two apples each,” and abstracts such experiences to mathematical expressions of multiplication with natural numbers like “$1 \times 2 = 2$” and “$2 \times 3 = 6$,” respectively. If the learner acquires the rule of multiplication, he or she will become able to answer expressions with unknowns such as “$5 \times 2 = x$,” “$x \times 3 = 9$,” and “$x \times x = 9$.” In the last expression, the right-hand side must be a number that is limited to the square of an integer. That is to say, it is considered that the application range J of the construction rule “$x \times x = J$” is the set of squared numbers. If the learner exhibits the ability to perform linguistic analogies, they can produce an expression like “$x \times x = 7$” by expanding the application range of the rule to any natural number. This is a meaningless expression, since there is no answer in the system of natural numbers, which was acquired through experience. If the learner creates a new number, $x = \sqrt{7}$, then the expression can be meaningful. This is an introduction of square root, that is, the extension of the number system to the system of irrational numbers[6].

The way to extend a concept is summarized as follows. First, acquire a rule from experiences through abstraction and induction. Then, produce a novel expression by extended application of the rule. Finally, make sense of the novel expression. This method can afford further extensions of the concept. Extensions to systems of complex numbers is realized by the extended application of $\sqrt{\mathrm{P}}$ with a positive number “P” to a negative number, and the introduction of an imaginary unit to justify a novel expression, $\sqrt{-1}$ to make sense. Note that the rule acquired at the first stage must have a slot or a variable part in order to be used in an extended way, such as “be going to V,” in which V is a slot for a verb of action. Fixed idioms like “rain cats and dogs” cannot be extended. Thus, rule acquisition at the first stage is not just finding a pattern in experiences, but extraction of a pattern with slots, which includes abstraction and inductive generalization.

We should point out the difference between linguistic analogy and usual analogy. While analogies are usually grounded in a certain similarity between source and target domains, the ability to come up with linguistic analogies does not require similarity as a basis of its manifestation. We suppose that language uses can extend the application of a rule without finding similarities between a domain in which the rule has been used and a domain to which the rule is extended when they produce novel expressions at the second step in the process summarized above. In reality, similarity and contingency restrict the sense-making of novel expressions. Bringing linguistic creativity unbounded by cognitive similarity and contingency is an essential part of the ability of linguistic analogy.

[6] We can extend mathematical theory in such a way, but in reality, it is believed that the square root was considered to be the length of a diagonal line through an equilateral rectangle (square).

3. A hypothesis about origin and evolution of language

We will now further discuss the creativity of linguistic analogy in the context of human evolution. Stone tools have been produced since the *Homo* genus appeared around two million years ago, but the diversity of such tools was limited. *Homo sapiens* began producing stone tools with greater diversity in space and function around 50,000 years ago. Arts also started to be developed around 50,000 years ago. Archaeological evidence such as wall paintings, statues with human-like bodies and animal heads, and stones with symbolic scratches have been found. This major development in arts and culture is called the cultural explosion (Mithen, 1996).

The developments of arts and tools can be considered manifestations of creativity through linguistic analogy. They correspond to novel metaphors and technical innovations, and also the two methods of the sense-making of novel expressions mentioned above: changing both the interpretation of the expression and the conceptualization of the reality, and changing the reality. After around 50,000 years ago, humans also migrated out of Africa and expanded their habitat over most of the world, including the polar regions and islands in the oceans. For this achievement, linguistic creativity could be used to solve severe environmental problems by allowing the production of tools, clothes, houses, and ships.

We believe that the adaptive function of language lies in its creative power rather than its communicative function. The creative power of language causes the autonomous development of its diversity and complexity through linguistic analogy beyond the direct experiences of language users. The diversity and complexity of language can affect the diversification and

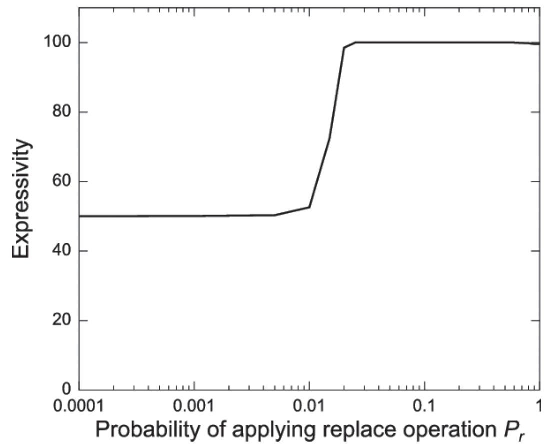

Figure 8. The change of expressivity in terms of the probability of applying the replace operation: The expressivity reaches 100% for *Pr* >0.01, and drastically decreases at *Pr* = 0.01.

the complexification of concepts and the world through sense-making. There may be coevolutionary processes of diversification and complexification among language, concepts, thoughts, and the world.

Was the transition of human language capacity due to acquiring the ability of linguistic analogy a gradual or sudden change? We investigated how the change of expressivity is controlled by the degree of applying the replace operation. In this simulation, learners use the replace operation according to the probability *Pr* when they have a chance to use the operation in the process of generalization learning. As shown in Fig. 8, the expressivity drastically drops at a very low level of *Pr*. This suggests that the transition is a sudden change. When language learners obtain the ability of linguistic analogy—specifically, the extended application of acquired rules—no matter how little of this ability they have, they can develop a full language.

As a summary of this discussion, we propose a hypothetical scenario about the origin and the evolution of language based on the findings and considerations above. Humans, not only modern but also ancestral, were capable of communication using memory-based symbol systems, called proto-languages[7]. Around 50,000 years ago, *Homo sapiens,* modern humans, acquired the ability of linguistic analogy and suddenly became able to autonomically develop linguistic knowledge. Only modern humans attained displacement and linguistic creativity. Thanks to this ability, their creativity realized the cultural explosion and the migration outside Africa. Thus, the origin of modern language among *Homo sapiens* should be dated before or around 50,000 years ago. Following this, grammaticalization occurred through cognitive biases for metaphoric and metonymic inferencing. Grammaticalization with linguistic analogy brought the evolution of language through coevolutionary processes of diversification and complexification among language, concepts, thoughts, and the world. Those processes enabled languages to develop into the present (full-fledged) languages in terms of complexity and structure.

[7] Brain size has developed extensively since the *Homo* genus appeared. The evolved brains might have been devoted to memorizing fruitful lexical items, constructions, and short sentences through experience. The fact that *Homo sapiens* has a smaller brain than *Homo neanderthalensis* can be a supporting evidence for the difference between proto-(memory-based) language and modern (rule-based and productive) language.

VIII. Conclusion

We think of grammaticalization as a universal and particular feature observed in human language. In order to discuss the origin and the evolution of this distinct linguistic feature, we investigated the cognitive mechanisms and biases that cause unidirectional meaning change knowing that these are remarkable characteristics of grammaticalization through constructing a cognitive model that shows unidirectional meaning changes in the process of iterated generalized learning.

From the simulation analysis of the model, we concluded that linguistic analogies as cognitive ability of the language user are important for the cultural evolution of language with sufficient expressivity and meaning change. The linguistic analogy ability applies a grammatical rule extensively onto forms to which the rule has not been applied.

Furthermore, we found that general generalization mechanisms are insufficient for realizing unidirectional meaning change, and that instead two cognitive biases are critical for this change to occur. One is the recognition of similarity concerning the source meaning of unidirectional change. This bias forms the basis of metaphoric inferencing. The other, as the basis of metonymic inferencing, is the recognition of contingency between the source and destination of unidirectional change.

The ability of linguistic analogy is also critical for displacement and creativity through language. Based on the discussion from these findings, a hypothetical scenario was proposed about the origin and the evolution of language. The origin of language took place before or around 50,000 years ago, when the ability of linguistic analogy was acquired and then the evolution of language occurred through grammaticalization where metaphoric and metonymic inferencing played significant roles.

Acknowledgement

The authors are grateful to Hiroyuki Miyashita, James R. Hurford and Hajime Yamauchi for their fruitful discussion. This research was supported by KAKENHI, Grant-in-Aid for Young Scientists (A) (17680021) and Grant-in-Aid for Scientific Research (B) (20300082), of Japan Society for the Promotion of Science (JSPS).

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