A Simulative Study of the Roles of Cultural Transmission in Language Evolution

Tao Gong, *Member, IEEE*, James W. Minett, *Member, IEEE*, and William S-Y. Wang

***Abstract*—A multi-agent computational model is proposed to simulate language evolution in an acquisition framework. This framework involves many major forms of cultural transmission, and the simulation results of the model systematically examine the role of cultural transmission in language emergence and maintenance. In addition, this study discusses the effects of conventionalization during horizontal transmission on diffusing linguistic innovations, maintaining high levels of linguistic understandability, and triggering inevitable changes in the communal languages across generations. All these reflect that conventionalization could be a self-organizing property of the human communication system that drives language evolution.**

I. Introduction

HUMAN language is a cultural phenomenon, evolving among individuals of a community in a cultural environment. During *the ontogeny of language* (the process whereby a child acquires language from his/her environment), *cultural transmission* (language adaptation in a community via various kinds of communication [4]) is important in transmitting linguistic information among individuals of the same or different generations. Generally speaking, there are three main forms of cultural transmission [1]: *horizontal transmission*, communications among agents within the same generation; *vertical transmission*, a member in the previous generation talks to a biologically-related member in the future generation; and *oblique transmission*, any member in the previous generation talks to any non-biologically-related member in the next generation. Horizontal transmission is *intra-generational*, while vertical and oblique transmissions are *inter-generational*. In addition to the empirical study, computational simulation [3] has recently joined the endeavor to tackle ontogenetic problems by directly simulating these forms of cultural transmission. Its authenticity has been gradually accepted by many linguists [11].

There have been many computational models studying the roles of cultural transmission in language origin. For instance, Kirby's *Iterated Learning Model* (ILM) [10][12] simulated vertical transmission, and showed that the *bottleneck effect* (the restricted exposure of the previous generation's language to the next generation's learner [4]) could cause the emergence of a compositional language consisting of a set of common lexical items. Vogt's model [14] simulated both oblique and horizontal transmissions, and discussed the relation between children's creativity and the emergence of compositionality in the communal language. Acerbi and Parisi's model [1] also simulated the learning via inter- and/or intra-generational transmissions, and discussed the roles of such learning in triggering more adaptive behaviors in a changing or unchanging environment.

A more comprehensive study of both the ontogeny of language and the roles of cultural transmission requires several modifications of these contemporary models.

First, in ILM [10][12], each generation contained only one agent, who talked only to the agent in the next generation. Such purely vertical transmission is impossible even in small-scale societies [1], and the externally-imposed learning bottleneck is also much too arbitrary [14].

Second, in [14], two probabilistic parameters, *pS* and *pH*, were defined to indicate the probability of choosing a speaker or a hearer from the adult generation, and 1–*pS* and 1–*pH* correspond to the probabilities for a child to be chosen as a speaker or a listener. However, these parameters could not explicitly distinguish the transmission among children from other transmissions that involve children and adults. For instance, comparing the situation where *pS*=1 and *pH*=0 with the situation where *pS*=*pH*=0.5, the percentage of intra-generational transmission among children in the latter situation (0.25) was higher that that in the former situation. The percentages of intra-generational transmission among adults and of inter-generational transmission in which children talked to adults were also higher (0.25) in the latter situation. Therefore, instead of only intra-generational transmissions among children, all these forms of transmissions may contribute to the high level of compositionality in the latter situation.

Finally, in [1], inter- and intra-generational transmissions were simplified as an imitation process from some particular agent having high fitness. However, in the cultural environment, considering factors such as group size and social structure, it is usually impossible for all agents in a generation to be aware of who is the 'best' in their own or other generations—even if they notice the 'best' one, it is generally difficult for all of them to get chances to learn from this 'best' one. In a sense, neither intra- nor inter-generational

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Tao Gong is with The Chinese University of Hong Kong, Shatin, N.T., Hong Kong (e-mail: tgong@ee.cuhk.edu.hk).

William S-Y. Wang is with The Chinese University of Hong Kong, Shatin, N.T., Hong Kong and the Linguistic Institute, Academic Sinica, Taipei, Taiwan (e-mail: wsywang@ee.cuhk.edu.hk).

James W. Minett is with The Chinese University of Hong Kong, Shatin, N.T., Hong Kong (e-mail: jminett@ee.cuhk.edu.hk).

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transmission could have such a high degree of orientation as assumed in this model.

In order to simulate a realistic cultural environment, an acquisition framework has to match several requirements.

First, it is necessary for this framework to involve both inter- and intra-generational transmissions and study their collective effects on language evolution.

Second, it is necessary for this framework to explicitly simulate different forms of cultural transmission. Only adjusting the probabilities for choosing a speaker or a listener is insufficient to clearly distinguish various forms of cultural transmission, and letting all agents to imitate a specific one is much too simplified to simulate inter- and intra-generational transmissions.

Finally, most of the contemporary models only focus on the effects of cultural transmission on the emergence of some linguistic universals, such as *compositionality* (in most languages, the meanings of complex expressions are determined by their lexical components) and *regularity* (in most languages, the structural features such as word order or morphology can affect the meanings of complex expressions). The maintenance of linguistic universals across generations is also important in present-day societies. A comparison of both the emergence and maintenance situations may provide further understanding of the individual learning mechanisms. Therefore, it is necessary for this framework to study the effects of cultural transmission on both language emergence and language maintenance.

Considering these, we propose a more realistic acquisition framework in this paper, and adopt our previous computational model on language emergence [7] to study language evolution in this framework. This acquisition framework involves inter-generational transmission between adults and children (adults as speakers, children as listeners, *AC-com*) and intra-generational transmission among children (children as both speakers and listeners, *CC-com*). By manipulating the parameters that adjust the percentage of AC-coms and CC-coms, we explore the roles of cultural transmission in two experiments. Exp. 1 focuses on the roles of CC-coms in language emergence and maintenance, and Exp. 2 focuses on the roles of AC-coms in language emergence and maintenance. Based on the simulation results in these experiments, we can systematically analyze the roles of these transmissions and explore the effect of *conventionalization* (a language user conforms his language to the language of the community; it is a social agreement that a particular utterance will have a particular meaning [4]) on language evolution.

The rest of the paper is organized as follows: the computational model is reviewed in Sec. 2; the acquisition framework is introduced in Sec. 3; the simulation results are discussed in Sec. 4; and finally, conclusions and future work are summarized in Sec. 5.

II. Model Review

The model adopted in this paper was originally designed to study the phylogenetic emergence of language in a population of language users. It shows that a population of interacting language-capable individuals can acquire a common set of lexical items and word orders as a result of some simple, local learning algorithms that are based on the abilities of sequencing lexical items and detecting recurrent patterns. Tow linguistic universals, compositionality (lexical items) and regularity (word order), co-evolve during the transition from an initial holistic signaling system to a compositional language.

Language in this model is treated as a set of meaning-utterance mappings. Individuals are exchanging two types of integrated meanings in communications: “Pr<Ag>”, such as “run<wolf>” meaning “a wolf is running”; and “Pr<Ag, Pat>”, such as “chase<wolf, sheep>” meaning “a wolf is chasing a sheep”. Here, ‘Ag’, ‘Pr’ and ‘Pat’ are semantic roles, in which ‘Ag’ represents the actor of an action; ‘Pr’, the action; and ‘Pat’, the entity that undergoes an action. These integrated meanings are mapped to utterances (strings of syllables).

A rule-based system is adopted in this model to represent individuals’ linguistic knowledge. Three types of linguistic rules are defined: *lexical rules* record mappings between integrated meanings and strings of syllables (*holistic rules*) or between semantic components and strings of syllables (*compositional rules*); *syntactic rules* record local orders (e.g., before or after, but not necessarily immediately before or after) between two strings of compositional rules in utterances; and *categories* that associate lexical rules encoding semantic components having the same semantic roles in integrated meanings.

The emergence of linguistic universals in this model is achieved by some domain-general abilities. Compositionality is developed by individuals through detecting recurrent semantic components and syllables in meaning-utterance mappings exchanged during communications, and mapping these recurrent patterns as compositional rules. Regularity is developed through a categorization process: When an individual observes that two (or more) meaning-utterance mappings involve a single lexical item that displays the same local order with respect to two lexical items having the same semantic role, he/she can assign these two lexical items to the same category. For convenience, we label categories with the syntactic roles to which they correspond in simple declarative sentences in English (i.e., ‘S’, Subject; ‘V’, Verb; and ‘O’, Object). The local order is also acquired as a syntactic rule between the first lexical rule and the newly formed category. Then, through reiterating local orders among the categories, individuals gradually acquire an emergent global word order to regulate lexical items. For instance, assume that an individual wants to express an integrated meaning “chase<wolf, sheep>” using the lexical items encoding “wolf”, “chase” and “sheep” from some S, V, and O categories, if the local orders in these categories are S before V and S before O, then these local orders lead to two global orders SVO or SOV, and the utterance produced by the individual could be either /WOLF CHASE SHEEP/ or /WOLF SHEEP CHASE/, here, the capitalized letters within "//" represent the syllables in utterances. In simulations, these syllables are chosen from an utterance space.

A dyadic communication is simulated in this model. In a communication, an individual is chosen as a speaker. He/She randomly selects an integrated meaning and codes it, based on his/her linguistic knowledge, into an utterance, and sends the utterance to another individual, the listener. The listener then tries to decode the utterance, based on his/her linguistic knowledge, into an integrated meaning. This comprehension process is sometimes assisted by some environmental information which might sometimes contain the speaker's intended meaning. Then, a confidence feedback is sent by the listener to the speaker, showing whether the listener believes he/she understands correctly, without directly checking whether the listener accurately interprets the meaning intended by the speaker. In the end, based on this feedback, both the speaker and the listener update their linguistic rules used in this communication.

The coevolution of compositionality and regularity takes place after iterated communications. Initially, all individuals in the population share a holistic language in which a limited number of integrated meanings can be expressed using holistic rules. Then, during iterated communications, through the above learning mechanisms, individuals first learn some lexical rules and induce some independent categories with which these lexical rules are associated. Then, based on the meaning-utterance mappings stored in their short-term memories, they acquire more lexical rules, expand the lexical and syntactic members of their categories, and gradually merge categories containing lexical items with identical semantic roles having the same usage. Finally, they develop a communal language in which all lexical items having the same semantic role belong to a single category. Moreover, by using syntactic rules to regulate local orders of lexical members of different categories, individuals form a common, emergent global word order. Together with the development of compositionality, the development of regularity in terms of global word order follows a 'bottom-up' routine based on the local and partial information contained in linguistic instances.

The simulation results on language emergence, the empirical basis of the learning mechanisms, and the implementation details of this model can be found in [6][7]. In this paper, we directly adopt this model to study language emergence and maintenance in an acquisition framework. In the simulations of language emergence, a holistic language is initially shared in the first generation of agents; in the simulations of language maintenance, a compositional language consisting of a set of lexical rules and two local order rules that produce a consistent global order is initially shared among the agents of the first generation. Agents in future generations have to develop their languages through cultural transmission with the agents in the previous generation in the acquisition framework.

III. The Acquisition Framework

An acquisition framework, as illustrated in Fig. 1, is adopted in this model to study the role of inter- and intra-generational transmissions on language emergence and maintenance. AC-coms and CC-coms are simulated in this framework. In each generation, first, some adults produce offspring (children) who initially have no linguistic knowledge. Then, the learning stage begins, during which a child can learn from an adult in an AC-com or interact with other child in a CC-com. During the learning stage, AC-coms and CC-coms are randomly interwoven. After that, these children become adults and replace their parents, and a new generation begins. In this framework, no global fitness is defined to guide children to learn from a specific adult. In addition, it adopts a discrete agent replacement (new agents are introduced after a certain number of communications) so that we can punctually trace the evolution of language in different generations.

In the simulations of this paper, the semantic space contains 64 integrated meanings (16 "Pr<Ag>" and 48 "Pr<Ag, Pat>" involving in total 12 semantic items). The population has 10 agents. After each generation, 5 adult are randomly chosen, and each of them produces one offspring. Then, these 5 offspring (children) interact with adults or other new offspring during the learning stage. After that, these children become adults and replace their parents, and a new generation begins. The total number of generations is 100.

Several indices are defined to evaluate the role of cultural transmission. *Understanding Rate* (*UR*), as calculated in (1), is defined as the average percentage of all integrated meanings that are understandable to each pair of agents in the community based on their linguistic knowledge only. A high value of *UR* indicates a high understandability of the communal language in the community.

$$UR = \frac{\sum_{i,j} \text{Understood integrated meanings between agents } i \text{ and } j}{\text{Number of pairs of } i, j \times \text{Number of integrated meanings}} \quad (1)$$

In addition, *inter-generation UR* (UR_{ser}) between agents in

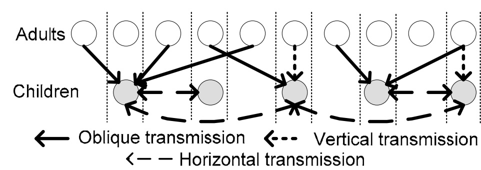


Fig. 1. The acquisition framework. Empty disks represent adults and filled disks represent children. Each type of cultural transmission is represented by a different type of line and arrow. In vertical and oblique transmission (AC-coms), adults speak and children listen. In horizontal transmission among children (CC-coms), children can be either speakers or listeners.

generations i and i+1, and *UR between the initial generation and later generations* (UR_{ini}) are measured. To measure UR_{ser}, all agents in generation i talk to all agents in generation i+1, and the percentage of accurately understood integrated meanings is calculated. To measure UR_{ini}, all agents in the first generation talk to all agents in the ith generation, and the percentage of accurately understood integrated meanings is calculated. A high value of UR_{ser} indicates a high understandability of the communal languages across generations, and a high value of UR_{ini} indicates a high possibility of maintaining an initial compositional language.

IV. The Simulation Results in the two experiments

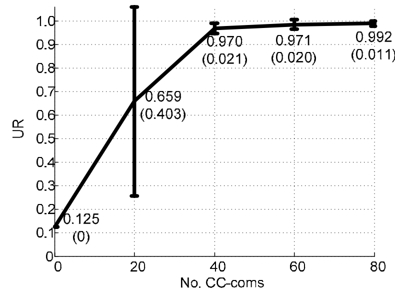
In this section, the simulation results for Exp. 1 and Exp. 2 are described. For the simulations on language emergence, the statistical results for 20 simulations in each condition are shown, including the average and standard deviation values of the highest *UR* in 100 generations, and the average and standard deviation values of the highest UR_{ser} in 100 generations. For the simulations on language maintenance, the statistical results include the average and standard deviation values of *UR* at the end of 100 generations, the average and standard deviation values of UR_{ser} in 100 generations (avg UR_{ser}) and at the end of 100 generations (last UR_{ser}), and avg UR_{ini} and last UR_{ini}. Based on these results, we examine the role of cultural transmission in both language emergence and language maintenance.

A. Exp. 1

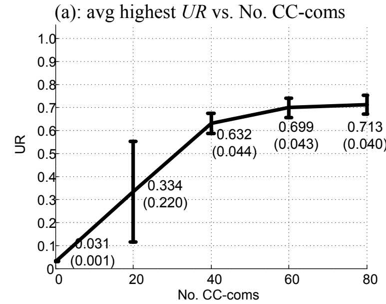
Exp. 1 studies the role of CC-coms. In each generation of the simulation, the number of AC-coms is set to 100 and the number of CC-coms is gradually increased from 0 to 80 with an increment of 20. The statistical results of Exp. 1 are shown in Fig. 2, in which panels (a)–(b) display the results on language emergence, and panels (c)–(e) display the results on language maintenance.

First, let us discuss the roles of CC-coms in language emergence. It appears in Fig. 2(a) that when the number of CC-coms is 0, no simulations produce a communal language with a high *UR*, which indicates that children cannot acquire a communal language after 100 generations of learning through only AC-coms. However, with the increase in the number of CC-coms, communal languages with high *UR*s emerge in most simulations. Furthermore, as shown in Fig. 2(b), with the increase in the number of CC-coms, the average UR_{ser} values are increasing, which indicates that more CC-coms can maintain a high understandability of the emergent communal language across generations. Similar results can also be obtained when the number of AC-coms is set to a different value (say, 200).

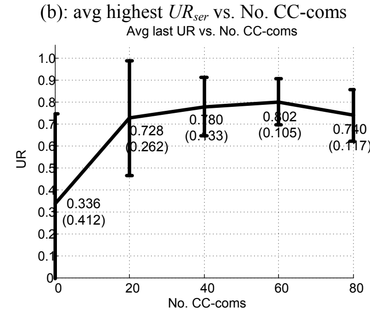
These results demonstrate two major roles of CC-coms. Given a certain number of AC-coms, CC-coms can: a) help to accelerate the emergence of a communal language, and b) help to maintain the understandability of the communal language across generations.



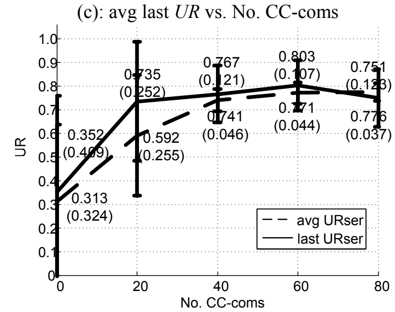
(a): avg highest *UR* vs. No. CC-coms



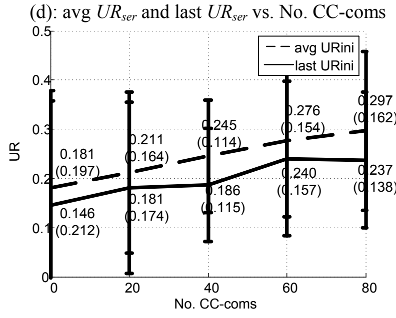
(b): avg highest UR_{ser} vs. No. CC-coms



(c): avg last *UR* vs. No. CC-coms



(d): avg UR_{ser} and last UR_{ser} vs. No. CC-coms



(e): avg UR_{ini} and last UR_{ini} vs. No. CC-coms

Fig. 2. The statistical results of Exp. 1 on language emergence (a)-(b) and maintenance (c)-(e). The numbers outside brackets are average values, and those inside brackets are standard deviation values.

Second, let us discuss the roles of CC-coms in language maintenance. In these simulations, agents in the first generation share a compositional language with a high *UR*. However, when there are no CC-coms, after 100 generations of learning only through AC-coms, the average *UR* value drops, as shown in Fig. 2(c). In addition, similar to the results on language emergence, with the increase in the number of CC-coms, the communal language can maintain a high understandability across generations, as shown in Fig. 2(d). However, whether this language is a newly-emergent one after the initial compositional language dies out or whether it maintains a high degree of similarity to the initial compositional language cannot be clarified only by looking at the *UR* or UR_{ser} value of this language. Therefore, UR_{ini} in these situations is calculated. As shown in Fig. 2(e), with the increase in the number of CC-coms, both the values of avg UR_{ini} and last UR_{ini} increase, though their values are not high (less than 0.5) compared with the UR_{ser} values. These results show that CC-coms can, to a certain degree, assist the maintenance of an initial compositional language. Similar results can be found when the number of AC-coms is set to a different value (say, 200).

These results on language maintenance not only reflect the roles of CC-coms summarized based on the simulation results on language emergence, but also introduce a new role of CC-coms: they can limitedly help to maintain a language across generations.

The roles of CC-coms are achieved as a result of a conventionalization process during CC-coms. During language emergence, in the early generations, most adults lack sufficient linguistic knowledge to express many integrated meanings. When talking to children, different adults tend to randomly create various expressions for their inexpressible meanings, and children just partially sample these salient expressions. CC-coms provide a means to converge toward some of these different expressions among idiolects. During CC-coms, the idiolects of the participants tend to conventionalize so that some common linguistic knowledge become shared among these idiolects. Therefore, a communal language can be triggered through CC-coms.

During language maintenance, after children randomly sample the adults' communal language, CC-coms provide a means to maintain and strengthen the shared linguistic knowledge in children's idiolects. Through CC-coms, part of the initial language transmitted through AC-coms can be maintained in the emergent language. In a sense, AC-coms also allow the speakers to strengthen their idiolects. However, in the acquisition framework, AC-coms usually happen between an adult speaker and a child listener whose linguistic knowledge could be immature. In such AC-coms, the speakers may not get sufficient information to update their idiolects. Therefore, the strengthening effect of AC-coms is weaker than that of CC-coms.

B. *Exp. 2*

Exp. 2 illustrates the role of AC-coms in language emergence and maintenance by studying the relations between AC-coms and CC-coms. In this experiment, the total number of AC-coms and CC-coms in the learning stage is fixed (200), and the ratio between them is adjusted. The considered ratios include 200:0 (200 AC-coms, 0 CC-coms), 160:40, 120:80, 80:120, and 40:160. The statistical results of Exp. 2 are shown in Fig. 3, in which panels (a)–(b) display the results on language emergence, and panels (c)–(e) display the results on language maintenance.

First, let us discuss the ratio between AC-coms and CC-coms on language emergence. It appears in Fig. 3(a) that when the number of CC-coms is 0, no simulations produce a communal language with high *UR*, which matches the simulation results in Exp. 1. In addition, with the increase in the percentage of CC-coms, communal languages with high *UR*s emerge in many simulations. This reflects the conventionalization process during CC-coms. However, when most communications are CC-coms, both the values of *UR* and UR_{ser} begin to drop. In a relatively extreme situation in which there are only 40 AC-coms, no simulations achieve a communal language with a high *UR* or UR_{ser}. Similar results can be found when the total number of AC-coms and CC-coms is set to a different value (say, 300).

All these results on language emergence illustrate an important role for AC-coms: without sufficient AC-coms, the understandability of the emergent language cannot be maintained across generations. These results also indicate that even though sufficient CC-coms may trigger a communal language in the child generation, if the number of AC-coms is low, this communal language that is mainly created and used among children is not understandable to adults and difficult to be maintained across generations.

Second, let us discuss the role of AC-coms in language maintenance. A similar tendency as before appears in these results. With the increase in the ratio of CC-coms, both *UR* and UR_{ser} increase. However, if the percentage of AC-coms is insufficient, both of them will drop. AC-coms also play a role in maintaining the initial compositional language. As shown in Fig. 3(e), with the decrease in the ratio of AC-coms, the similarity between the emergent language and the initial compositional language decreases. In the relatively extreme situation where the ratio of AC-coms to CC-coms is 40:160, no communal language emerges after 100 generations of learning, let alone the maintenance of the initial compositional language. Similar results can be found when the total number of AC-coms and CC-coms is set to a different value (say, 300).

Exp. 2 demonstrates the role of AC-coms in language emergence and maintenance, more precisely that a sufficient number of AC-coms are necessary for the emergence of a communal language and the maintenance of an initial compositional language across generations. Before children largely communicate with each other, without sufficient AC-coms for them to gain a broad sampling of the adults' language, what is conventionalized during CC-coms is a set of salient expressions randomly created by children themselves, instead of the adults' language. Therefore, in each generation, instead of maintaining the language of the previous generation, the new agents are creating their own idiolects. Similarly, after these children become adults, without sufficient AC-coms, they cannot transmit most of their idiolects to the new agents, who will therefore keep creating and conventionalizing their own linguistic expressions. At both levels, it is difficult to develop a communal language or maintain an available compositional language across generations, since in each generation, agents appear to create a new language due to insufficient sampling of the previous generation's language, and this newly-created language cannot be transmitted to the next generation.

C. Discussion

In the preceding two sections, language emergence and maintenance were studied based on an acquisition framework in two experiments. The simulation results are not restricted to the specific settings of the parameters, such as 100 generations, 10 agents or 64 integrated meanings. With the increase of the number of integrated meanings or the number of agents, given more communications within a generation, similar results can also be obtained.

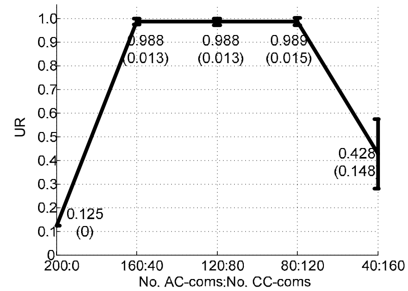
These studies explore the relative roles of AC-coms and CC-coms in the development of communal language.

First, AC-coms, in the form of vertical or oblique transmission between adults and children, can maintain the emergent language across generations by transmitting it directly to children. In the actual linguistic exchange between adults and children, adults may use simple examples, keep repeating the utterances and carefully manipulate the cues to help children accurately acquire their idiolects [5].

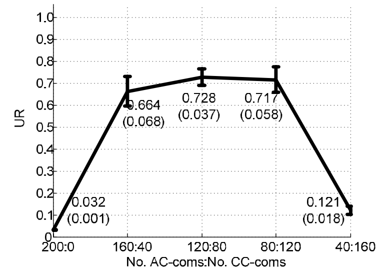
Second, CC-coms, in the form of horizontal transmission among children, can accelerate language emergence by conventionalizing different idiolects in the community. Instead of directly acquiring a language as in AC-coms, during CC-coms, children conventionalize the language already acquired from adults. And due to the insufficient sampling in AC-coms, during CC-coms, children need to invent expressions to convey otherwise inexpressible meanings, and these innovations can also diffuse in the community through conventionalization.

Considering the above two aspects, a *two-side effect* of conventionalization during CC-coms is shown. On the one hand, through conventionalization, a high understandability of the communal language is achieved, and if both AC-coms and CC-coms are sufficient, this effect is much explicit. On the other hand, after many generations, language change is inevitable, i.e., although the communal language maintains a high understandability across generations, the initial compositional language is not effectively maintained, especially when AC-coms are insufficient and CC-coms are redundant.

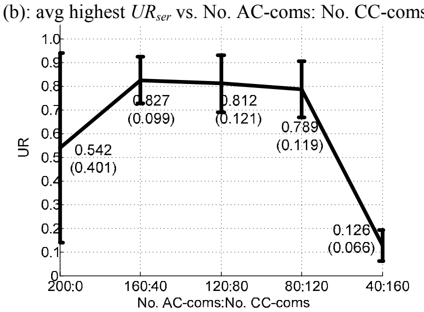
Apart from the values of UR, UR_{ini} and UR_{ser}, the two-side effect of conventionalization can also be observed by tracing



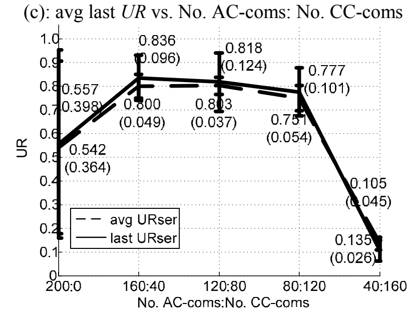
(a): avg highest UR vs. No. AC-coms: No. CC-coms



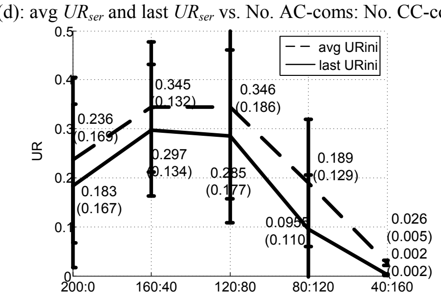
(b): avg highest UR_{ser} vs. No. AC-coms: No. CC-coms



(c): avg last UR vs. No. AC-coms: No. CC-coms



(d): avg UR_{ser} and last UR_{ser} vs. No. AC-coms: No. CC-coms



(e): avg UR_{ini} and last UR_{ini} vs. No. AC-coms: No. CC-coms.

Fig. 3. The statistical results of Exp. 2 on language emergence (a)-(b) and maintenance (c)-(e). The numbers outside brackets are average values, and those inside brackets are standard deviation values.

the shared lexical rules in the communal languages (see Fig. 4). In the experiments on language emergence (Fig. 4(a) and (c)), the initial communal language consists of only 8 holistic rules. Due to conventionalization, after a number of generations (say, 85), a compositional language consisting of several compositional rules gradually emerges, and it has a high understandability. In the experiments on language maintenance (Fig. 4(b) and (d)), the initial language consists of 12 compositional rules that can express all integrated meanings in the semantic space. Due to conventionalization, after a number of generations, this communal language changes though its understandability is still high; some lexical rules in it become different from those initial ones.

In the cultural environment of human language, there is no global fitness, so no particular communal language is fitter than any other except to the extent that communication with high *UR* is possible between randomly chosen individuals. We should not expect there to be a potential gain in fitness resulting from giving up the original communal language. The two-side effect of the conventionalization process is mainly caused by two factors. First, the under-sampling due to insufficient AC-coms and subsequent innovation during CC-coms provide fluctuations in the communal language. Second, conventionalization, taking effect based on the local information available in communications, makes it possible for diffusing some of these fluctuations and even making them as conventions in the communal language, thus introducing changes into the communal language.

The simulation results of this paper have shown that both AC- and CC-coms serve to maintain a high understandability of the communal language across generations. Meanwhile, the communal language is inevitably changing after many generations. In a sense, language evolution is a process of *dynamic equilibrium*: in the short run, the understandability of the communal language remains high; in the long run, language change is inevitable.

In addition, conventionalization is an essential reason to maintain this dynamic equilibrium. First, although the bottleneck during AC-coms triggers linguistic innovations among idiolects, whether these innovations can become conventions in the communal language is largely determined by conventionalization.

Second, even though the bottleneck is severe and the communal language of the previous generation is rarely transferred to the next generation, conventionalization during horizontal transmission is still able to maintain a relatively high understandability among the idiolects of the next generation. Conventionalization is continuously adjusting the idiolects, which helps to maintain a high understandability of the communal language across generations. Meanwhile, the slight adjustments in idiolects made by conventionalization can be accumulated to such a degree that the language in this generation can become quite different from the one that was spoken many generations ago. Similar to a tinkerer in the "tinkerer" view on evolution [8], conventionalization can be

```
Exp.1 on language emergence:
AC-coms (100), CC-coms (40);

Gen=  0:
UR= 8.00; URser= 8.00;
ComLex=8
Lex0( Hol)(1.00): '4<0>'<->/18 7 10 3 /
Lex1( Hol)(1.00): '5<1>'<->/2 20 18 11 /
Lex2( Hol)(1.00): '6<2>'<->/15 4 /
Lex3( Hol)(1.00): '7<3>'<->/29 /
Lex4( Hol)(1.00): '8<0,1>'<->/26 12 0 /
Lex5( Hol)(1.00): '9<1,2>'<->/0 28 22 3 13 /
Lex6( Hol)(1.00): '10<2,3>'<->/0 /
Lex7( Hol)(1.00): '11<3,0>'<->/24 0 3 7 11 /

Gen= 85:
UR=51.74; URser=55.70;
ComLex=8
Lex0(  Pr)(0.94): '7<#>'<->/12 /
Lex1(A|Pt)(0.93): ' 2 '<->/15 /
Lex2(  Pr)(0.94): '8<#,#>'<->/6 /
Lex3(A|Pt)(0.94): ' 0 '<->/26 /
Lex4(A|Pt)(0.94): ' 1 '<->/27 /
Lex5(A|Pt)(0.94): ' 3 '<->/18 /
Lex6(  Pr)(0.94): '6<#>'<->/19 /
Lex7(  Pr)(0.94): '4<#>'<->/4 /
```

(a): Exp. 1 on language emergence (AC-coms=100, CC-coms=40)

```
Exp.1 on language maintenance:
AC-coms (100), CC-coms (40);

Gen=  0:
UR=64.00; URini=64.00; URser=64.00;
ComLex=12
Lex 0(A|Pt)(1.00): ' 0 '<->/4 23 /
Lex 1(A|Pt)(1.00): ' 1 '<->/18 24 /
Lex 2(A|Pt)(1.00): ' 2 '<->/29 /
Lex 3(A|Pt)(1.00): ' 3 '<->/2 /
Lex 4(  Pr)(1.00): '4<#>'<->/0 /
Lex 5(  Pr)(1.00): '5<#>'<->/8 /
Lex 6(  Pr)(1.00): '6<#>'<->/24 6 /
Lex 7(  Pr)(1.00): '7<#>'<->/21 20 /
Lex 8(  Pr)(1.00): '8<#,#>'<->/25 /
Lex 9(  Pr)(1.00): '9<#,#>'<->/1 18 /
Lex10(  Pr)(1.00): '10<#,#>'<->/19 /
Lex11(  Pr)(1.00): '11<#,#>'<->/22 /

Gen= 85:
UR=57.90; URini=22.65; URser=57.63;
ComLex=8
Lex0(  Pr)(0.94): '10<#,#>'<->/26 /
Lex1(A|Pt)(0.94): ' 3 '<->/2 /
Lex2(  Pr)(0.93): '4<#>'<->/0 /
Lex3(A|Pt)(0.94): ' 2 '<->/29 /
Lex4(  Pr)(0.93): '11<#,#>'<->/22 /
Lex5(  Pr)(0.94): '8<#,#>'<->/25 /
Lex6(A|Pt)(0.94): ' 1 '<->/24 /
Lex7(A|Pt)(0.94): ' 0 '<->/4 /
```

(b): Exp. 1 on language maintenance (AC-coms=100, CC-coms=40)

```
Exp.2 on language emergence:
Total Com (200), AC-coms: CC-coms (120:80);

Gen=  0:
UR= 8.00; URser= 8.00;
ComLex=8
Lex0( Hol)(1.00): '4<0>'<->/20 29 13 8 /
Lex1( Hol)(1.00): '5<1>'<->/16 /
Lex2( Hol)(1.00): '6<2>'<->/29 15 28 0 /
Lex3( Hol)(1.00): '7<3>'<->/28 /
Lex4( Hol)(1.00): '8<0,1>'<->/10 20 24 5 19 1 19 0 /
Lex5( Hol)(1.00): '9<1,2>'<->/0 /
Lex6( Hol)(1.00): '10<2,3>'<->/9 2 8 4 19 15 28 3 /
Lex7( Hol)(1.00): '11<3,0>'<->/15 9 18 10 2 22 17 /

Gen= 85:
UR=61.47; URser=61.06;
ComLex=12
Lex 0(A|Pt)(0.94): ' 0 '<->/8 /
Lex 1(A|Pt)(0.94): ' 3 '<->/7 /
Lex 2(  Pr)(0.94): '7<#>'<->/11 /
Lex 3(  Pr)(0.91): '5<#>'<->/23 /
Lex 4(A|Pt)(0.94): ' 1 '<->/9 /
Lex 5(  Pr)(0.94): '6<#>'<->/29 /
Lex 6(A|Pt)(0.94): ' 2 '<->/26 /
Lex 7(  Pr)(0.94): '9<#,#>'<->/13 /
Lex 8(  Pr)(0.93): '10<#,#>'<->/6 /
Lex 9(  Pr)(0.93): '11<#,#>'<->/22 /
Lex10(  Pr)(0.94): '8<#,#>'<->/5 /
Lex11(  Pr)(0.94): '4<#>'<->/25 /
```

(c): Exp. 2 on language emergence (AC-coms:CC-coms=120:80)

```
Exp.2 on language maintenance:
Total Com (200), AC-coms: CC-coms (120:80);

Gen=  0:
UR=64.00; URini=64.00; URser=64.00;
ComLex=12
Lex 0(A|Pt)(1.00): ' 0 '<->/28 14 /
Lex 1(A|Pt)(1.00): ' 1 '<->/27 /
Lex 2(A|Pt)(1.00): ' 2 '<->/25 12 /
Lex 3(A|Pt)(1.00): ' 3 '<->/15 /
Lex 4(  Pr)(1.00): '4<#>'<->/22 /
Lex 5(  Pr)(1.00): '5<#>'<->/19 18 /
Lex 6(  Pr)(1.00): '6<#>'<->/9 /
Lex 7(  Pr)(1.00): '7<#>'<->/26 27 /
Lex 8(  Pr)(1.00): '8<#,#>'<->/4 /
Lex 9(  Pr)(1.00): '9<#,#>'<->/28 24 /
Lex10(  Pr)(1.00): '10<#,#>'<->/13 /
Lex11(  Pr)(1.00): '11<#,#>'<->/5 17 /

Gen= 85:
UR=56.26; URini=22.90; URser=52.56;
ComLex=12
Lex 0(A|Pt)(0.93): ' 3 '<->/15 /
Lex 1(  Pr)(0.92): '11<#,#>'<->/17 /
Lex 2(A|Pt)(0.93): ' 0 '<->/28 /
Lex 3(A|Pt)(0.93): ' 1 '<->/27 /
Lex 4(  Pr)(0.92): '4<#>'<->/22 /
Lex 5(  Pr)(0.93): '6<#>'<->/9 /
Lex 6(  Pr)(0.93): '5<#>'<->/18 /
Lex 7(  Pr)(0.93): '9<#,#>'<->/19 /
Lex 8(  Pr)(0.93): '7<#>'<->/26 /
Lex 9(  Pr)(0.90): '8<#,#>'<->/24 /
Lex10(A|Pt)(0.93): ' 2 '<->/12 /
Lex11(  Pr)(0.93): '10<#,#>'<->/13 /
```

(d): Exp. 2 on language maintenance (AC-coms:CC-coms=120:80).

Fig. 4. Some examples of the shared lexical rules in the communal languages in Exp. 1 and Exp. 2. "Gen" denotes the number of generations, "ComLex" denotes the number of shared lexical rules, and "Lex" represents these shared lexical rules. "A", "Pt", and "Pr" in the brackets represent the semantic roles of compositional rules: Ag, Pat, and Pr. "Hol" represents holistic rules. "#" represents unfilled semantic items. The numbers inside brackets are average rule strengths, those within "''" are different semantic items, and those within "//" are different utterance syllables.

viewed as a self-organizing property of the human communication system that drives language evolution.

These conclusions and discussions of the relative roles of inter- and intra-generational transmissions and the conventionalization process during intra-generational transmissions provide some revisions on the bottleneck effect and the conclusions drawn from other models addressing similar questions.

First, in the cultural environment, innovations can occur quite early during CC-coms. And in the multi-agent scheme, the bottleneck in AC-coms is much less explicit, since it can be partially compensated by CC-coms, e.g., what we did not learn from our parents can be compensated by communicating with other playmates in kindergartens or schools. Considering the heterogeneous communication histories of different individuals, it is also impossible to manipulate the bottleneck in AC-coms in the multi-agent scheme. Furthermore, as pointed out by Vogt [14], horizontal transmission also has an 'implicit' bottleneck. The insufficiency of linguistic instances manifests as the bottleneck not only in inter-generational transmissions, but also in intra-generational transmissions.

Second, in the multi-agent scheme, during AC-coms, the bottleneck effect is independently applied on individual child when he/she listens to an adult. Without sufficient CC-coms, compositionality only emerges at the idiolect level, but not at the community level. In other words, communal compositionality (i.e., high UR) requires sufficiently many CC-coms, especially when the number of AC-coms is low.

Finally, cultural transmission in [1] was simplified as the imitation from a specific agent. In that situation, CC-coms seemed to be useless in a rarely changing environment. However, in my model, CC-coms are crucial for the emergence of communal language. Considering the cultural environment of human language, no global fitness is available for agents to determine which is the "best" in their or previous generations, and factors such as group size or social structure may restrict them from easily learning from others. Then, without CC-coms to conventionalize their idiolects, a communal language is difficult to be maintained.

To summarize, adopting a multi-agent scheme to simulate the cultural environment of language evolution is more appropriate than assuming that each generation only contains a single agent. An integrative study of the relative role of various forms of cultural transmission is more realistic than an isolated study covering only one form of cultural transmission. Combining internal learning mechanisms with an external cultural environment can provide a more comprehensive perspective on linguistic questions than is possible by only focusing on the external factors.

V. CONCLUSIONS AND FUTURE WORK

This paper presents a simulative study on the role of cultural transmission in language evolution. An acquisition framework is introduced to simulate some major forms of cultural transmission. We analyze the effects of these transmissions on language emergence and maintenance in two experiments, and examine the conventionalization process as a driving force for language evolution.

Future refinements of a cultural framework for language evolution should include not only adult-to-child and child-to-child communications, but also adult-to-adult and even child-to-adult communications. It should also adopt a continuous generation replacement as in human societies. Furthermore, the genetic relations between adults and children may constrain the selection of participants in transmissions, thus affecting language evolution.

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