

Chapter 14

Complex Evolutionary Pathways in Interacting Linguistic Communities

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Abstract We experiment with a linguistic change mechanism in a community of interacting agents and show the various phenomena that may emerge under different social constraints. We assume phonological and lexical learning and a semantic reference to external objects in the environment. Distinct groups of agents with initially different languages converge to a common language, with the relevant frequency of inter-agent interactions controlling which language dominates. Moreover, an initially monolingual community diverges due to social factors creating agent grouping, where agents interact more frequently with members of the same group. Additional cognitive features, like innovation and attention, lead to increased linguistic divergence between groups and word bistability. Finally, cultural learning leads to continuous linguistic change and occasional coexistence of multiple words, as well as revival of rare words. Overall, it appears that the initial community may evolve in arbitrary directions, and languages may dynamically form, split, mutate, and oscillate.

Keywords Language evolution • Multi-agent simulation

14.1 Introduction

The simulated evolution of language is concerned with understanding, among other things, the factors and the evolutionary forces that are responsible for the appearance of human language as well as for the dynamics of language change at the macro or population level [20]. Studies in the simulated evolution of language borrow the methodological concepts and tools that have been developed for the study of

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biological evolution [11, 18]. Thus the simulated evolution of language concerns issues such as the direction of language change, the sources of linguistic variation, the environmental pressure that biases and directs certain developments, and the evolution of linguistic complexity [4, 14].

The issue of linguistic complexity is not consensual by far. First of all, there exist many definitions of linguistic complexity and many debates over the role of typological comparison and criteria of judgement [13]. Linguistic complexity invariance has long been an axiomatic assumption in linguistics, but is now an object of serious doubt and refutation [7, 22]. Furthermore, unlike the biological domain, there is not a common linguistic ancestor or a proto-language that all or most linguists agree on [8]. One of the principal forces driving complexity change and linguistic evolution is proposed to be population and language contact [10, 12]. A study of language change dynamics and linguistic complexity could shed more light on issues such as linguistic speciation and the role of emergence of syntax or grammar. A number of theoretical proposals have appeared that discuss and relate language evolution, language change, and interaction or contact [6, 17, 21]. Phenomena of language change via population contact have also been studied with agent-based simulation. For example, Satterfield [23] has tested the hypothesis of incomplete second language learning in a creole environment, Beltran et al. [2] have studied language shift from a subordinate to a dominant language, and Castelló et al. [5] study bilingualism and linguistic competition in a social network.

Another domain in the simulated evolution of language is inspired by Wittgenstein's view that language is inseparable from its usage [3, 29]. Based on Wittgenstein's notion of language games, Parisi [19] describes several multi-agent simulations that demonstrate how linguistic forms are used by a population of individuals. A variety of models also exist in the literature, each one implementing a different computational technique that achieves success in language games or other basic cognitive games (for example, discrimination games). Steels views language as a complex adaptive system [26] and builds a model that implements a positive feedback loop between language use and success in use, leading to self-organized lexicons that are coherent among a population of agents [24, 25]. Other studies are concerned with the transmission of language between and/or within generations of speakers [1, 15].

We construct a model of language change that, first, combines both a lexical level (as in [2, 5]) and a phonological level (as in [16]) so as to have a more realistic two-factor device than the simple monofactor lexical one, and, second, is implemented in a general interaction context where many social configurations are available. Table 14.1 compares the features of the proposed model with some models found in the literature.

We perform experiments with a population of agents of a single or two distinct initial linguistic origins to capture different dynamics of interaction. One of our medium-term goals is to examine whether linguistic complexity may move in any direction from a certain starting point and under which circumstances. In what follows, we examine a few simple population scenarios that show linguistic convergence as well as differentiation, linguistic dominance as well as linguistic

Table 14.1 Comparative presentation of various models

Models	Lexicon	Grammar	Phonology	Scope
Beltran et al. [2]	N	N	N	Language shift in bilingual communities
Satterfield [23]	Y	Y	N	Pidgin genesis in multilingual communities
Oudeyer [16]	N	N	Y	Phonetic self-organization
Our model	Y	N	Y	Linguistic convergence, differentiation and innovation

mix, linguistic innovation, and continuous linguistic learning through cultural learning. All of these phenomena constitute landmark demonstrations of a bottom-up evolutionary process applied to the non-biological domain of language. All are also, by definition, complex phenomena, since their appearance cannot be predicted on the basis of the initial conditions of the population, but rather they constitute the contingent outcome of continuous social interaction. This way, the presented mechanism of linguistic change may serve as the basis of more situated work in historical linguistics and sociolinguistics and of more theoretical work in linguistic change and speciation. Although the language model is fairly primitive and lacks grammar, it succeeds in reproducing the phenomena of linguistic convergence, dominance, pluralism, etc.

In Sect. 14.2, we present the linguistic model and explain its function. In Sect. 14.3, we describe the simulation, and in Sect. 14.4 we present the experiments and discuss the results. In Sect. 14.5 we conclude the chapter and give some directions of future research.

14.2 Expanded and Revised Model of Language Change

In our previous work we have experimented with a fundamental model of linguistic change at a double level, phonological and lexical, and we have identified the cognitive and social parameters responsible for linguistic convergence in various environments [28]. In that model, the linguistic interactions were devoid of any external reference or other meaning, so as to isolate the effects of the various parameters studied. We expand this model of language change with the introduction of semantics to allow direct connection of uttered words to stable external references so as to be able to derive more meaningful conclusions. We also apply some changes to the core of the model, in order to make it clearer and more stable. In our language change expanded model a population of agents of N types (typically two: type0, and type1), participates in M types of social activities (typically three: activity0, activity1, activity2) and uses K types of objects (typically three: object0, object1, object2). All agents are equipped with a language device composed of a phonological and a lexical module as in the original model.

14.2.1 *The Artificial Language*

The basic phonological unit of the language is the syllable, which is composed of two phonemes. The former distinction between vowels and consonants has been considered to be of no real use to the model, so it was removed. Each syllable has an id and a weight (a real number from 0 to 1, which is called *PhonoStrength*) which represents the probability that the specific phoneme combination exists in the language. We introduce the concept of a neighborhood of syllables via a neighborhood factor: a value which describes how close a syllable is to another syllable, and is defined as

$$nf = 1 - d/D \quad (14.1)$$

where d is the distance of the ids of the two syllables and D is the maximum distance between the ids. So, two syllables are neighbors if their neighborhood factor exceeds a predefined threshold (*NThresh*). A word is composed of one or more syllables, and is associated with each object through a weight called *ObjStrength*, which is a real number from 0 to 1. Every agent comes with a predefined size lexicon (*LexiconSize*), which may grow and shrink during interaction.

14.2.2 *Social Activities and Agent Interaction*

In the experiments reported later, the social activities are defined as: type0-only, type1-mandatory, and type1-free, where the participation of type1 agents is forbidden, mandatory, and voluntary, respectively.

When an agent is selected as speaker, first an object is selected at random and then a word from the agent's lexicon is selected, also at random. If the selected word's *ObjStrength* for the selected object is greater than a predefined threshold (*LThresh*) and its *PhonoStrength* is greater than a predefined threshold (*PThresh*), then it is fed as input to all the other agents who participate in the activity (listeners), and lexical learning takes place (see below). If not, another word is selected at random and is checked as above. If no word can be found that fulfills the above criteria, a new round takes place where the agent decreases in turn the thresholds *PThresh* and *LThresh* and starts over.

A listener executes in two steps: First, for each syllable of the input it checks if the *PhonoStrength* of the syllable exceeds *PThresh*. If it does, the syllable is selected; otherwise, a search for the fittest neighbor (the closest neighbor whose *PhonoStrength* is greater than the threshold) is performed. Phonological learning (see below) takes place only if such a search is performed. Secondly, a search for the processed phonological input (perceivedWord) is performed in the lexicon, and if it is not found, it is added (with *ObjStrength* = 0 for all objects). Lexical learning is performed to learn the word that was either found or just added.

Table 14.2 Algorithm for the simulation cycle

```

random selection of activity
random selection of participants, based on activity rules
random selection of speakers from the participants
for the number of speech acts do
  word = speakers[i].speak(object)
  for the number of participants do
    if ( $j \neq 1$ ) then
      for Intensity do
        participant[j].listen(word,object)
      end for
    end if
  end for
end for

```

Table 14.3 Algorithm for the speaker

```

procedure speak(object)
word=selectWord(LThresh, PThresh, object, "LThresh")
//
function selectWord(LThresh, PThresh, object, lastDecreased)
for 1000 times do
  if (ObjStrength[randomWord, object] > LThresh AND randomWord.
PhonoStrength > PThresh) then
    selectedWord=randomWord
  end if
end for
if (selectedWord = null) then
  recursionsCount++
  if (lastDecreased = "LThresh") then
    selectedWord(LThresh, PThresh-0.1, object, "PThresh")
  else
    selectedWord(LThresh-0.1, PThresh, object, "LThresh")
  end if
end if
if (recursionsCount > 1) then
  executePLearning(selectedWord)
end if

```

An additional parameter called *Intensity* of interaction [9] controls the number of interactions between speaker and listener at each encounter and may vary for speakers of different type or even for different individuals. The *Intensity* of interaction may be thought of as the amount of attention an agent gives the speaker during interaction and corresponds to perceptual-processing speed of the linguistic imitation device. A more attentive agent is thus an agent that practically learns faster. Tables 14.2, 14.3 and 14.4 give the pseudocode of the algorithm for a simulation cycle.

Table 14.4 Algorithm for the listener

```

procedure listen(phonoInput, object)
// step1 : phonological processing
for each syllable in phonoInput do
  if (syllable.PhonoStrength > PThresh) then
    perceivedWord.Syllables.Add(syllable)
  else
    newSyllable =getFitterNeighbour(syllable)
  end if
  //phonological learning
  if (newSyllable ≠ syllable) then
    executePLearning(newsyllable)
  end if
  perceivedWord.Syllables.Add(newsyllable)
end for
// step2 : lexical processing
executeLLearning(perceivedWord, object)
//
function getFitterNeighbour(syllable)
maxstrength=-1
for each syl in SyllablesList do
  if (syl.PhonoStrength > PThresh AND syl.PhonoStrength > maxStrength)
  then
    if (NeighbourMatrix[syllable,syl] > NThresh) then
      maxStrength=syl.PhonoStrength
      returnSyllable=syl
    end if
  end if
end for
return returnSyllable

```

14.2.3 Learning Mechanisms

Lexical learning is accomplished by increasing *ObjStrength* of the target word for the specific object by a predefined value (*LRate*) and by decreasing the *ObjStrength* of the other words for the same object, and of the other objects for the specific word by another predefined value (*LInRate*).

Phonological learning is accomplished by increasing the *PhonoStrength* of all syllables of the phonological input by a predefined value (*PRate*), and by decreasing its neighbors' *PhonoStrength* by a predefined value (*PInRate*). Table 14.5 summarizes the model parameters.

14.3 Simulation Setup

In the experiments that follow, we use languages that are either created at random, or loaded from a previously saved simulation. There is a standard phonetic syllable alphabet, which is used as the base for all the languages created and tested.

Table 14.5 Model parameters

Parameter name	Explanation	Value
PopulationSize	Total number of agents	Default = 20
Perc0	Percentage of type0 agents	Variable
TotalSteps	Total number of simulation cycles = duration of the simulation run	Variable
LRate	Amount to add to the contextStrength of word to be learned (dominant)	Default = 0.02
LInRate	Amount to subtract from contextStrength of competitive words (subordinate)	Default = 0.01
PRate	Amount to add to the phonologicalStrength of the phonetic combination to be learned	Default = 0.02
PInRate	Amount to subtract from the phonologicalStrength of the competitive phonetic combinations	Default = 0.01
PThresh	Phonological threshold	Default = 0.6
LThresh	Lexical threshold	Default = 0.6
NThresh	Neighbor threshold	Default = 0.6
Intensity	Number of interactions between speaker and listener at each encounter	Variable
MaximumAgents	The maximum number of participants in an activity	Variable

First, each syllable is randomly assigned a *PhonoStrength* (value from 0 to 1). Next, words with syllables whose *PhonoStrength* exceeds the *PThresh* are randomly created. Finally, for each word and each object, a relation is created (*ObjStrength*) whose value is randomly initialized between 0 and 1. Each word also has a *PhonoStrength*, which is the average *PhonoStrength* of its syllables.

Activities are either created at random, or loaded from a previously saved simulation. An activity is characterized by its type and by the maximum number of participants (*MaximumAgents*). The actual number of participants can be lower, but is not allowed to be less than 2.

A simulation uses a newly created or loaded world (languages, activities, and agents) and executes for *TotalSteps* times. At each cycle an activity is selected at random, and is randomly assigned a number of agents (up to *MaximumAgents* for the selected activity) according to the activity's rules. Then, the number of speakers is randomly initialized with a value between 1 and the actual activity's number of agents. Next, for as many times as the number of speakers, an agent is selected at random to be the speaker and the rest of the agents act as listeners. Each listener executes *n* listening cycles, where *n* is the *Intensity* value the listener has for the speaker type.

14.4 Experiments

A typical experiment consists of several simulations using the same languages and variations of the model parameters. However, some parameters remained fixed across the experiments. Those were the parameters that guided the lexical and phonological learning process (by default $LRate = 0.02$, $LInRate = 0.01$, $PRate = 0.02$, $PInRate = 0.01$), the thresholds (by default $LThresh = 0.6$, $PThresh = 0.6$, $NThresh = 0.6$), and the $PopulationSize (= 20)$.

The initial languages used in the experiments reported below are given in Tables 14.6 and 14.7.

14.4.1 Linguistic Convergence and Dominance

In accordance with the findings in our previous work [28], the outcome of the competition among the words of the different types of agents is determined by the relative frequency of the interactions between the corresponding agents. The dominant language is the one that is spoken more frequently. For runs long enough, all simulations converge to a stable state, where all the agents share a common vocabulary. Because the system incorporates some random elements (for example, the selection of the reference object for each speaker), the stable state is not always the same. So for the same languages, depending on the random object selection, different words may end up meaning the same objects in different simulations. But the dominant language (the one appearing as the ancestor of the final language or the one that is represented better than others in the final language) is always the same and does not depend on the random initial conditions, but as already stated, only on the relative frequency of interactions between the agents of different types.

Table 14.6 Original lexicon for language0

Word	Object	PhonoStrength	ObjStrength
gmtm	0	0.727	0.319
ziau	0	0.721	0.607
kmno	0	0.860	0.131
fpup	0	0.821	0.973
rsup	0	0.765	0.901
gmtm	1	0.727	0.528
ziau	1	0.721	0.970
kmno	1	0.860	0.888
fpup	1	0.821	0.554
rsup	1	0.765	0.670
gmtm	2	0.727	0.251
ziau	2	0.721	0.438
kmno	2	0.860	0.514
fpup	2	0.821	0.538
rsup	2	0.765	0.803

Table 14.7 Original lexicon for language1

Word	Object	PhonoStrength	ObjStrength
rpsn	0	0.777	0.172
embk	0	0.805	0.381
upob	0	0.808	0.901
kenu	0	0.708	0.984
iuig	0	0.935	0.013
rpsn	1	0.777	0.193
embk	1	0.805	0.051
upob	1	0.808	0.465
kenu	1	0.708	0.839
iuig	1	0.935	0.695
rpsn	2	0.777	0.080
embk	2	0.805	0.356
upob	2	0.808	0.424
kenu	2	0.708	0.355
iuig	2	0.935	0.863

When agents are randomly assigned in each activity and *Intensity* of interaction is 1 for both types, the frequency of interactions is defined solely by the population composition. In a population with $Perc0 = 0.2$, all agents will interact approximately four times more with type1 agents than with type0 agents. As a consequence, the words of the resulting language will be closer, and in some cases directly copied, from the initial type1 language. Figure 14.1 shows the first 5,000 cycles of the simulation run (each chart shows the evolution in time (simulation cycles) of the *ObjStrength* of the words that were active (*ObjStrength* > *LThresh*) for some time during the simulation. Each word has a suffix which represents its origin (for example, 0 for language0)). Many words are simultaneously present in the lexicon of both type0 and type1 agents, but some of them die out because of competition, and after about 1,500 cycles the agents become monolingual, that is, all type0 and type1 agents converge to the same words, occasionally slightly mutated.¹ (All the following results are indicative, taken from a single simulation, and should be interpreted conceptually. In all cases tested the simulations stabilize at some time.²)

With an *Intensity* value relatively high for speakers of type0, and low for speakers of type1, the dominant language is type0, the one more frequently used. Figure 14.2 shows the results for *Intensity* = 10 for type0 speakers for all listeners and *Intensity* = 1 for type1 speakers for all listeners, in a population of $Perc0 = 0.2$ (four times as many type1 agents), *TotalSteps* = 2,000.

¹Mutations are introduced when the *PhonoStrength* of the perceived word is lower than *PThresh*, see Table 14.3.

²The actual time (number of steps) it takes for a simulation to stabilize depends on the initial languages and the interaction frequency.

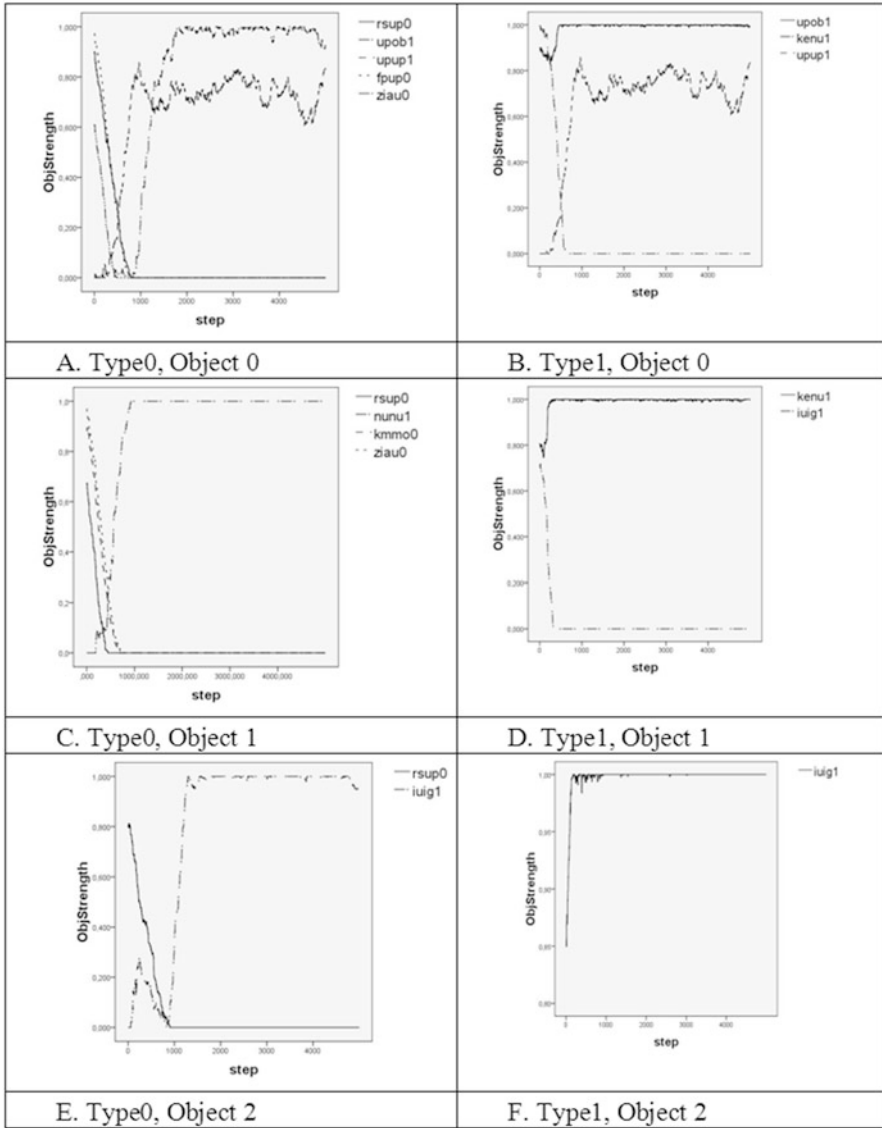


Fig. 14.1 Average *ObjStrength* for words used by agents type0 (charts **A**, **C**, **E**) and type1 (charts **B**, **D**, **F**), for objects0 (charts **A**, **B**), 1 (charts **C**, **D**), and 2 (charts **E**, **F**), by number of cycles, for *TotalSteps* = 5,000, *Perc0* = 0.2, *Intensity* = 1 for all speakers. In all cases the winning word comes from type1 language, the language of the initial majority. Interestingly, for object0, agents' lexicon (chart **A**, **B**) contains two words: the type1 "upob", and its mutation "upup". For object1 the winner word is *kenu* for type1 agents and its mutation *nunu* for type0 agents. For object2 the winner word is *iuig* for agents of both types

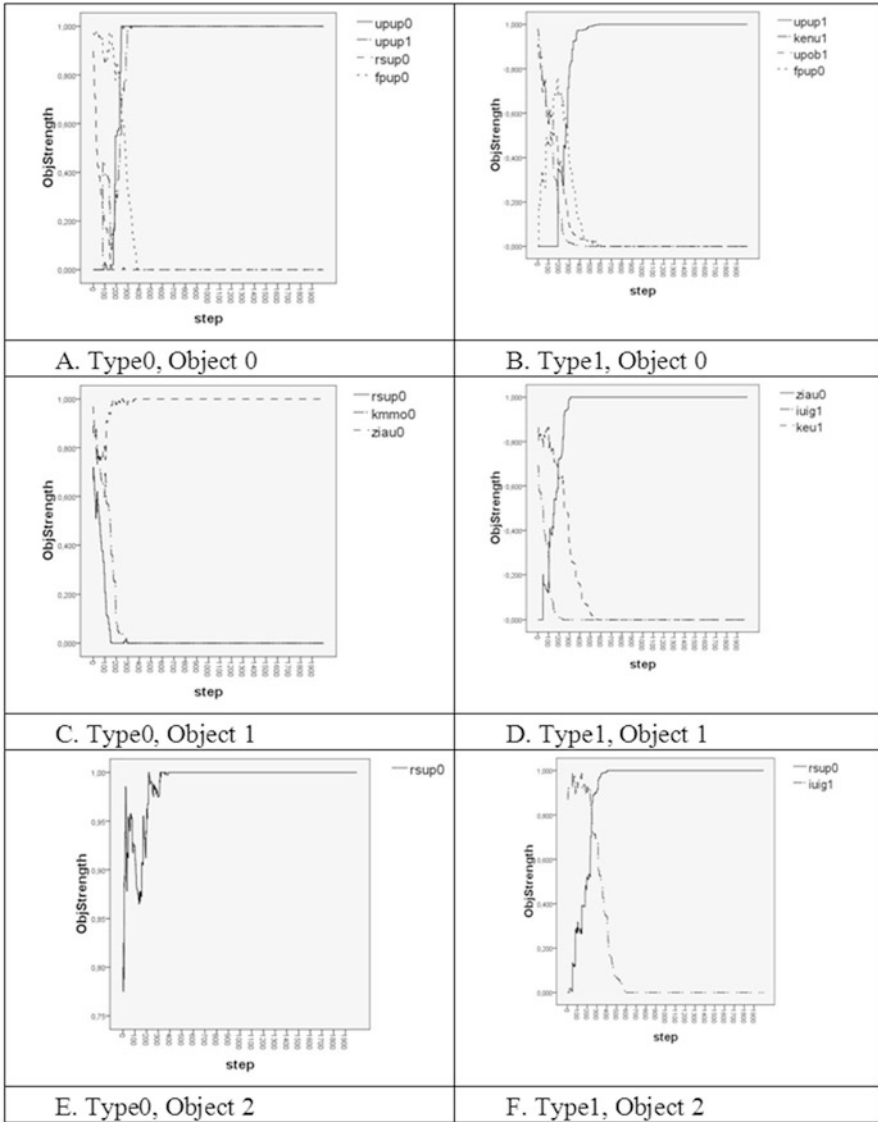


Fig. 14.2 Average *ObjStrength* for words used by agents type0 (charts **A**, **C**, **E**) and type1 (charts **B**, **D**, **F**), for objects0 (charts **A**, **B**), 1 (charts **C**, **D**), and 2 (charts **E**, **F**), by number of cycles, for *TotalSteps* = 2,000, *Perc0* = 0.2, *Intensity* = 10 for type0 speakers and 1 for type1 speakers. In all cases the winning word comes from object0 language. Note that for object0 (charts **A**, **B**), the winner “upup” is a mutation that came up in both languages independently (type0 : “fpup” → “upup”, type1: “upob” → “upup”). For object1 the winner word is “ziau” for agents of both types, and for object2 the winner is “rsup” also for both agent types

Table 14.8 Final words for all objects for all social groups, *Intensity* = 10 for speakers of the same group and 1 for speakers of other groups and *TotalSteps* = 2,000

Social group	Object0	Object1	Object2
0	fpup	kmno	rsup
1	fpup	ziau	rsup
2	fpup	ziau	rsup

Due to the formation of closed groups, the agents that belong to social group0 use the word “kmno” for object1, which is different from the word used by agents of social groups 0 and 2 (word “ziau”)

In all the experiments so far, a community of linguistically interacting agents converges to the use of a specific lexicon, generally consisting of a single word per object. The final words thus obtained are derived directly or indirectly from the language that dominates in number of interactions per agent, either because of the population composition or because of increased levels of attention to and interaction with some speakers. However, the exact final set cannot be predicted from the outset, and the linguistic evolution may follow many different pathways that share only a high resemblance to the original theoretically dominant language.

14.4.2 Linguistic Split and Stabilization

In the next experiment we modified the model to reproduce a different scenario: that of a linguistic community whose members, due to different social influences, diverge and end up using different words for the same object. We thus introduce the concept of a social group within a linguistic community. In the following simulations there are three different social groups with each agent allowed to be a member of only one of them. We changed the three types of social activities accordingly to accommodate the social group concept. In the following simulations, there are three types of social activities: social group 0-only, social group 0-excluded, and all groups allowed. Furthermore, each agent has *Intensity* 10 for members of the same group, and 1 for members of other groups. The initial language is type0 from the preceding experiment (Sect. 14.4.1). Table 14.8 displays the final words that each group uses for each object at the end of a simulation with *TotalSteps* = 2,000 and group sizes = 7, 7, 6 for the three groups respectively. This experiment demonstrates that a linguistic community may not only converge to a common language, but may also sometimes differentiate in cases of constrained contact rates. This observation leads to two immediate conclusions: first, that variations and dialects of a language, thus linguistic subspecies, may emerge in specific microenvironments, and, second, that the mechanism allowing linguistic differentiation is the same used for linguistic convergence and general language learning. Therefore, linguistic speciation does not seem to need any special apparatus, other than the regular device used for language learning.

Table 14.9 Algorithm for the speaker with the mutation function added

```

procedure speak(object)
word=selectWord(LThresh, PThresh, object, NThresh)
if (Innovation > IThresh) then
  mutate(word)
end if
executeLLearning(word, object)
//
procedure mutate(word)
if (RandomDouble > 0.5) then
  word.RandomSyllable=getFitterNeighbour(word.RandomSyllable)
end if

```

Table 14.10 Final words for all objects for all social groups. *Intensity* = 10 for speakers of the same group and 1 for speakers of other groups, *IThresh* = 0.4, *Innovation* (random) pseudonormal with mean 0.5 and *TotalSteps* = 2,000

Social group	Object0	Object1	Object2
0	fpup	ziau	rsup
1	fpup	kmno	zdup
2	zdor	rsrs	rsor

The groups diverge further, each one adopting its own mutated words for the majority of the cases

14.4.3 Linguistic Innovation

In the next experiment, we introduce a new feature in the speaker's cognitive mechanism called word mutation, which can slightly change the spoken word. This feature is controlled by a new parameter called *Innovation*, and there is also a new threshold (*IThresh*), so that when *Innovation* is greater than *IThresh* the spoken word mutates with a probability of 0.5. The mutation is not random, but is guided by the same algorithm the listener uses to parse phonologically weak syllables (see Table 14.4). Table 14.9 displays the modified algorithm for the speaker.

With *IThresh* = 0.4 (default) and *Innovation* taking value from a pseudonormal distribution with mean = 0.5, each group adopts its own mutations, as is clear from Table 14.10, which displays the results of a simulation with the same configuration as in Sect. 14.4.2.

Figure 14.3 shows the evolution in time (computational cycles) of the lexicon in social group2, for object2 for *TotalSteps* = 18,000. It is immediately noticeable that there is continuous evolution, where the appearance of new winner words doesn't seem to stop. Furthermore, the results show that the divergence between the groups increases, as each group produces its own mutations, which spread among its members faster than among members of different groups. In large time-scale

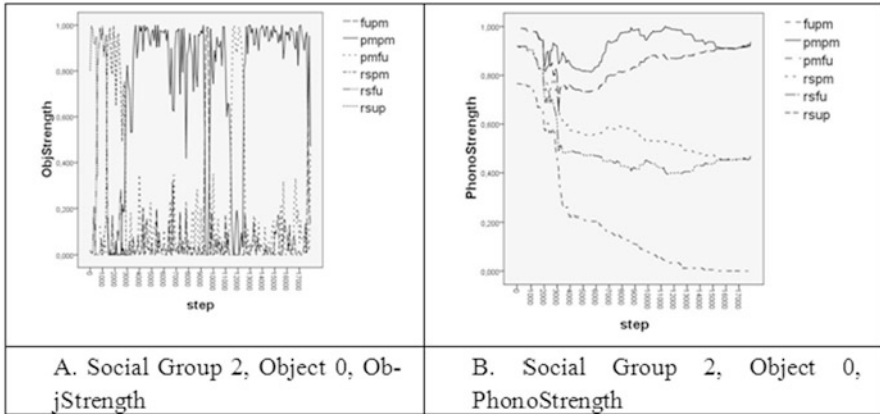


Fig. 14.3 Average *ObjStrength* (chart A) and *PhonoStrength* (chart B) for words used by social group2 for object0, by number of cycles, for *TotalSteps* = 18,000, *Intensity* = 10 for speakers of the same group and 1 for speakers of other groups, and *Innovation* is (random) pseudonormal with mean 0.5 and *IThresh* = 0.4. At some point on, the system seems to switch between two words (and their mutations): “pmpm” and “fupm” (mutation “pmfu”)

simulations, there seems to be a never-ending evolution where words continuously appear and disappear.

14.4.4 Linguistic Split and Convergence Controlled by Socio-Cognitive Factors

In the next experiment, we set up the simulation so that agents go through an attention shift at some point during the simulation. Thus, for *TotalSteps* = 10,000, *Intensity* takes the value 10 for speakers of the same social group, and 1 for speakers of a different social group for the first 5,000 cycles and the value 10 for speakers of social group0 and 1 for the other groups for the remaining cycles 5,000–10,000. Figure 14.4 shows the evolution in time of *ObjStrength* for object1 (for objects 0 and 2 there was early convergence in a common word for all groups).

The combined conclusions of possible linguistic convergence, differentiation, and mutation with one single mechanism may allow larger scale studies to be conducted, for example, to challenge some substrate approaches, because no substrate seems necessary to initially invent and later reinforce and share different linguistic subsets.

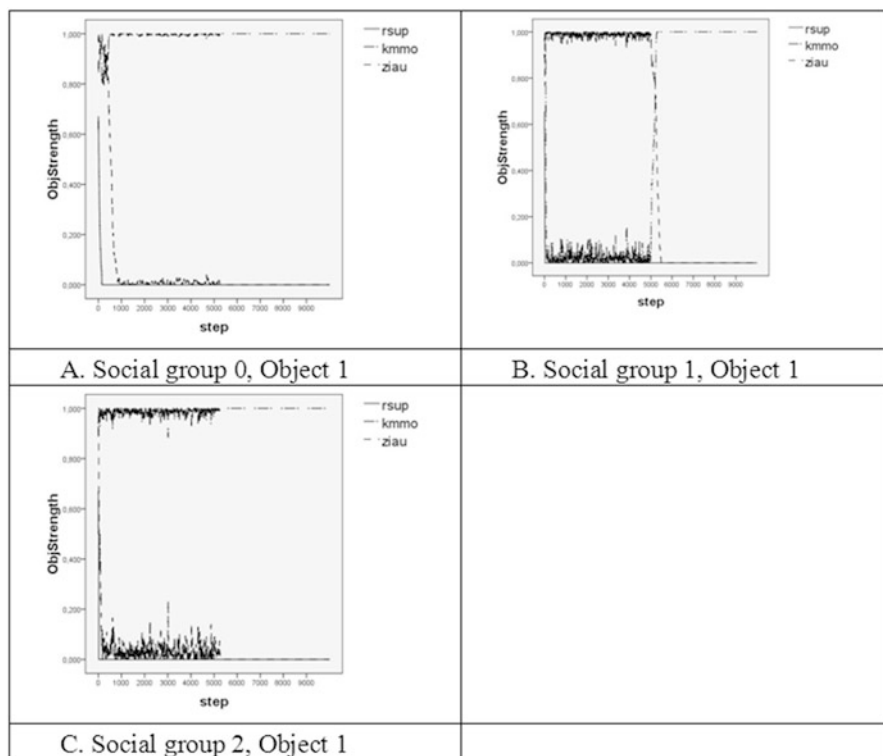


Fig. 14.4 Average *ObjStrength* for words used by social groups 0 (chart **A**), 1 (chart **B**), and 2 (chart **C**), for object 1 by number of cycles, for *TotalSteps* = 10,000. Innovation = 0 and *Intensity* = 10 for speakers of the same group and 1 for speakers of the other groups for the first 5,000 cycles and *Intensity* = 10 for speakers of social group 0 and 1 for speakers of the other groups. Social group 1 splits and uses “ziau” for object 1 for the first 5,000 cycles (chart **B**), but converges to “kmmo” soon after the attention shift to group 0 speakers. Also the fluctuations that exist for the first 5,000 cycles stop, and the model completely stabilizes

14.4.5 Cultural Transmission of Language Between Generations

In the final set of experiments we create a scenario of cultural transmission of the language between generations of agents. From time to time a newborn child is introduced in the population, i.e., an agent who has to learn the language by interacting with others in a pragmatic context [27].

To implement this, first the agents have to be modified in order to exhibit the feature of dying. We give them two new properties. The first one is called *age* and represents the age of the agent in simulation cycles. The second one, *maxAge*, represents the age at which the agent will die. At the end of each simulation cycle, all agents increase their *age* one unit and the agents whose *age* equals *maxAge* die.

For the new generation to emerge gradually, there is a *birth probability* (default = 0.2) that a child will be born at the end of each cycle. The newborn child will belong to one of the three social groups with equal chance. A child is a special kind of agent whose language device is not completely configured. Specifically, the lexicon is empty (the child knows no words) and all the *PhonoStrengths* are initialized to 0.65³ (it shows no tendency towards any specific phonological combination). Its other socio-cognitive abilities are equivalent to those of an adult.

If there are no distinct social groups, there must be a balance between the birth rate and the interaction rate for the language to be successfully transmitted culturally; otherwise, the language is lost. In the following experiment the simulation starts with a monolingual adult population with children gradually added as explained before and no social groups. *Innovation* is pseudonormal with mean 0.5 and *IThresh* = 0.4. Figure 14.5 presents the evolution in time of the *phObjStrength* of the various words that were used for *object2*, with variable *intensity* values for children or adult speakers and variable *birth probability*. It is shown that attention to adults (which is represented in the *Intensity* parameter) has to be high enough with respect to the birth rate for the parent language to be passed on to subsequent generations.

In the case where social groups exist and even in the absence of adult-specific attention, a language can also be culturally transmitted, but many other intricacies arise as well. For example, in the next experiment the simulation starts with a monolingual population and three social groups. *Intensity* takes the value 10 for speakers of the same social group, and 1 for speakers of a different social group, *Innovation* is pseudonormal with mean 0.5, *IThresh* = 0.4, and *birth probability* = 0.2. Figure 14.6 shows the evolution in time of the *Sum of speakers* (the actual number of agents that use the specific word) and of *ObjStrength* for *object2* and for social group2 for *TotalSteps* = 4,000.

The language is transmitted between the generations with no discontinuities, though it does not remain unchanged. There is a continuous evolution; several words coexist for one object, with some more persistent than others (for example, the words “rfaz” and “rpaz” last longer and are more widespread than “tata” or “pmif”). Analogous transitive phenomena are expected to arise when adult-specific attention coexists with group-specific attention.

14.5 Conclusion and Further Work

We presented a mechanism of phonological and lexical linguistic change in a community of interacting agents and have shown the various phenomena that may emerge under different social constraints. Distinct groups of agents that speak initially different languages and participate in different social activities may

³Which is above *pThresh* = 0.6.

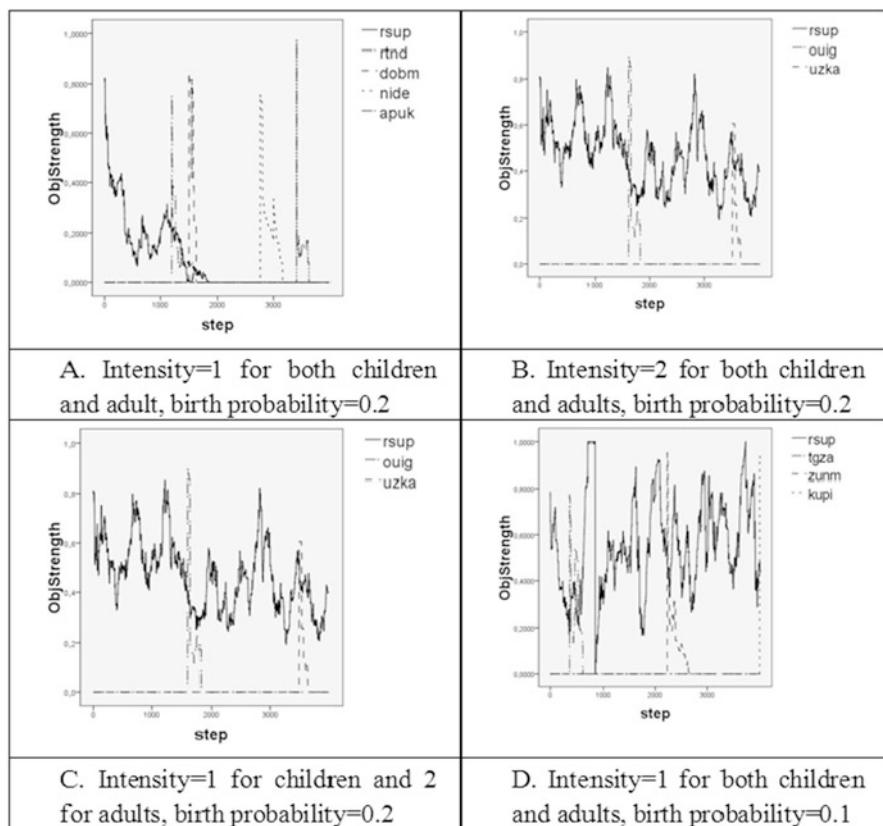


Fig. 14.5 Average *ObjStrength* for words used for *object2* by number of cycles, for *TotalSteps* = 4,000, *PopulationSize* = 20, *Intensity* = 1 for both children and adult speakers and *birth probability* = 0.2 (chart **A**), *Intensity* = 2 for both children and adult speakers and *birth probability* = 0.2 (chart **B**), *Intensity* = 1 for children and 2 for adult speakers and *birth probability* = 0.2 (chart **C**), and *Intensity* = 1 for children and 2 for adult speakers and *birth probability* = 0.1 (chart **D**). *Innovation* is (random) pseudonormal with mean 0.5 and *IThresh* = 0.4. In order for the language to be successfully transmitted between the generations (charts **B**, **C**, **D**), the *birth probability* cannot be too high in relation to the intensity, or the language is lost (chart **A**)

converge to a common language, where the relevant frequency of the interactions between agents of different types controls which parent language dominates the final population. On the other hand, an initially monolingual community splits to two or more groups in the presence of social factors that drive the agents to form closed groups, where the frequency of interaction is relatively higher between agents of the same group than between agents of different groups. Communities of agents equipped with an additional word mutation or innovation feature may exhibit increased linguistic divergence between the initial groups and bistability for dominant words. When a mechanism for cultural transmission of the language

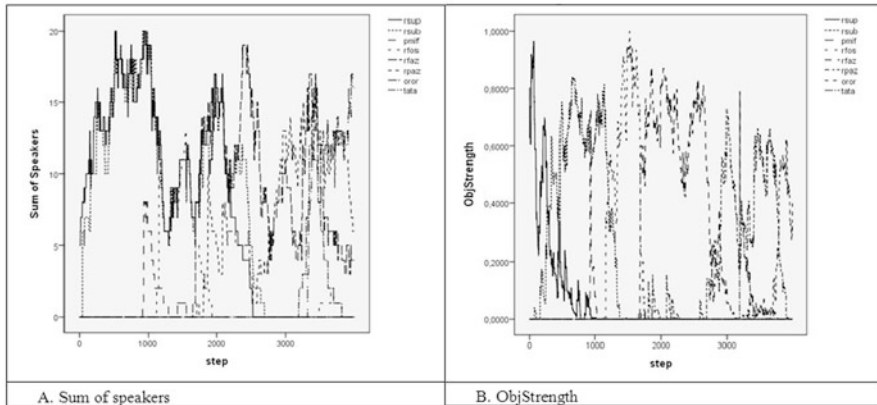


Fig. 14.6 *Sum of speakers* (chart **A**) and *ObjStrength* (chart **B**) for words used by social group2 for object2 by number of cycles, for *TotalSteps* = 4,000, *PopulationSize* = 20, *Intensity* = 10 for speakers of the same group and 1 for speakers of other groups, *Innovation* is (random) pseudonormal with mean 0.5, *IThresh* = 0.4, and *birth probability* = 0.2. Notice that the persistent word “rpaz” exists together with the transient words “oror” and “tata”

between generations of agents is implemented, the transmission carries on without discontinuities, as long as the birth rate is balanced by the interactions rate, and there are cases where several words are used for the same object, but not all of them are equally frequent or widespread among the population.

Overall, it appears that this linguistic mechanism allows the evolution of an initial community in arbitrary directions and especially allows languages to dynamically form, split, and mutate, depending on the social constraints on interactions between agents as well as on atomic parameters, such as attention. Other intricate and dynamic external conditions or interactions with external populations may drive an initial homogeneous or heterogeneous population to form clusters, dialects, pidgin-like simpler languages, and so on. Thus, our study shows that it might suffice to attribute any linguistic feature to a specific history of past interactions rather than to a spurious and hard-to-justify construct such as a universal or a substrate. Although our study is confined to phonological and lexical change, there is no reason why the same conclusions would not hold for any other kind of change, especially grammatical change, provided that the change/learning mechanism is similar. More importantly, we have demonstrated that this wealth of complex phenomena can be obtained in the absence of complex linguistic structures, such as grammar, and in the absence of development of linguistic references to external objects or categories.

Apart from grammarization, other envisaged directions of future research that appear promising at this stage are the coupling of linguistic and exo-linguistic interactions that influence one another, such as general cultural interactions, and the introduction of personal or group factors that alter the usual language learning procedure, for example, when an individual or a population “resists” phonologically or when agents demonstrate extreme openness, and so on.

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