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From Changes in the World to Changes in the Words

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This paper deals with the evolution of the lexicon in a changing environment. We adopt Mufwene's (2001) metaphor of "language as species" that explains evolution of languages as differential selection of features in languages' feature pools. We propose a multi-agent model and use it to explore the role of different constraints on the feature selection process. We show that constraints are indeed competing and that one of them is the major constraint in natural selection, viz., fitness to the environment.

Keywords: language evolution, feature pool, evolutionary linguistics, conceptual spaces.

1. Introduction

According to the myth of Babel, diversity in human languages is due God's anger toward the arrogance of humans that were trying to build a tower high enough to reach heaven. Such defiance against divine power being unacceptable, God broke mankind's linguistic unity. Unable to understand each other and thus divided, humans gave up with their tower project and populations spread over the world, leaving intact the domination of God on heaven.

This myth broke down in favor of evolutionary views of language as early as the mid-18th century, decades before the diffusion of evolutionarism into natural sciences and thus long before Darwin's theory (Tort 1980). This anteriority had a double consequence: on the one hand biologists, aware of linguists' interests in evolution, used the language metaphor to explain natural evolution of species (Darwin 1859), while on the other, linguists, seeking a formalization of language evolution, followed developments of the biological theory (Schleicher 1863; see Ben Hamed *in press* for a review).

When one mentions the evolution of language, a distinction has to be made between the evolution of the language faculty and the evolution of languages. The evolution of the language faculty is a field of research seeking to ascertain when, how and why our species has developed this unique and complex communication system, viz., Language. This field is growing rapidly and relies strongly on neo-Darwinism since Pinker and Bloom (1990) argued for the necessity of referring to natural selection in explanations of language origin. This biological evolution has nothing to do with the evolution of languages, which is a cultural process taking place on timescales which are insignificant to natural evolution. Nevertheless, parallels between biological and cultural evolutions may be drawn and metaphors formulated since similar mechanisms drive both evolutions. This use of a biological metaphor for language evolution can be found in Mufwene (2001) who considers languages as species and idiolects as individuals. Each language has a feature pool similar to species' gene pool in which idiolects pick out their characteristics. Language evolution is then due to the selection by learners of features in competition from the feature pool (learners may modify features, providing then new features to the pool, with the consequence that this evolution falls into the Lamarckian paradigm). Selection criteria proposed by Mufwene are primarily frequency of the features and cognitive and structural constraints. The main thesis of this paper is that when we look at lexical items, there is a very specific constraint on the selection: selected items are items that best fit speakers' environment.

The rest of the paper is organized into four sections: in the following section we describe the semantic framework upon which our work is grounded. Then we describe the model we developed in order to study dynamics of the lexicon. The next section relates four simulations run with the model, and in the final section the results obtained are discussed.

2. Semantics, categories and concepts

2.1 Semantics

Providing an account of how words get their meaning is a problem far from trivial. The 20th century has seen broadly three attempted solutions coming from three different fields: philosophy, linguistics and psychology.

The philosophical account of semantics, called formal semantics or veri-conditional semantics, is due to the revolution of logic that happened at the end of 19th and the beginning of the 20th centuries when Frege and others realized that Aristotle did not say all that can be said about logic. Assimilating formal and natural languages, they faced the problem of how the symbols of their expressions refer to something. The answer that formed the groundwork for formal semantics was provided by Wittgenstein (1922): the meaning of an expression is its truth conditions, *i.e.* how the world should be so that the expression is true. This semantic tradition is still very active and its most achieved proposition is probably Montague's semantics (Montague 1973).

Linguists' interest in semantics is clearly natural. The Saussurian structural wave (de Saussure 1915) that flooded linguistics and more generally humanities (at least in Europe) reached semantics and inspired structural semantics. According to the structural account, a language is a closed system and a sign, composed of a *signifié* and a *signifiant*, receives its meaning from the relations the *signifiant* maintains with the other *signifiants* of the language.

The psychological account of semantics, viz., cognitive semantics, has also been proposed by linguists. It is much more recent since the pioneering contributions are only a quarter of a century old (Fillmore 1982; Langacker 1987; Lakoff 1987). It is psychological in the sense that meaning of words and expressions are mental entities. Cognitive semantics belongs to the more general stream of cognitive linguistics that rules out the independency of language and embeds it firmly into cognition. Our cognitive apparatus allows us to form mental representations of the world which may serve as meaning of words and expressions. This approach is summarized in Sweetser (1989: 1): "*Language is systematically grounded in human cognition and cognitive linguistics seeks to show exactly how. The conceptual system that emerges from everyday human experience has been shown [...] to be the basis for natural-language semantics [...]*". This is the line of semantics which we adopt here. The notions of categories and concepts are thus critical for us, and consequently the following section aims at detailing them.

2.2 Categories and concepts

2.2.1 The Classical view

Grouping things together is an activity that we cannot avoid doing. We cannot see a bed without thinking that it is a bed, we cannot write with a pen without knowing that we are using a pen. Categorization is one of our basic cognitive skills and is used in most (if not all) of our activities.

Our ability to recognize objects of the world as members of categories is so automatic and unavoidable, that people have long thought that objects really belong to categories which somehow exist independently of us. This view is known as the classical view and can be traced back to Aristotle. Aristotle's conception of the world was hierarchical: things belong to categories, which are in turn grouped into supercategories, and so on, with the category "Being" at the top of the hierarchy. At any level of this taxonomy, categories are mutually exclusive and they sum up together to form the universe: an object belongs to one and only one category. It follows that given an object and a category, either this object belongs to this category, or it does not. A category is defined in term of the characteristics that all of its members have in common. Each of these characteristics is necessary for an object to belong to the category, and they are all together sufficient to provide the membership to the category.

2.2.2 The Roschian revolution

This view of categories prevailed for almost 23 centuries. The first major claim against the classical view came from philosophy with Wittgenstein (1953). Wittgenstein noticed that it is not always the case (almost never in fact), that membership is due to a set of common characteristics shared by all the members of a category and only them. He illustrated this fact with the famous example of the category GAME. If we look at the characteristics of games, we find that many of them are shared by many games, but none is present in all the games. Most games involve different players, but not all; some games rely on particular skills, others on chance and others on both; many games finish with a winner, but for others the notion of "winning" is meaningless. Rather than a set of common characteristics, what characterizes the members of a category is what Wittgenstein called *family resemblances*. Members of a category are similar to each other in many ways, but none of this ways make them similar all together. As a consequence of the Wittgensteinian view of the categories, we are no longer provided with a criteria (a set of necessary and sufficient conditions) to decide whether an object belongs to a category or not. It follows that the boundaries of the categories are not clear as in the classical view but fuzzy and extendable. An illustration of the fuzziness of boundaries can be found in the beginnings of surrealism which was accepted as art by some, while strongly refused by others. And to illustrate the extendableness of boundaries, it is interesting to note that the debate of membership of surrealism to art is long over and is now considered a typical art form of the first half of the 20*th* century. One fundamental implication of Wittgenstein's conception of categories is that they are no longer seen as abstract entities that exist independently of us. The fuzziness of their boundaries and the impossibility to define objective means to make judgment about membership clearly establish categories as psychological entities.

The next major attack against the classical view (and probably the most important) marked the shift of categorization from philosophy to psychology with the empirical work of Eleanor Rosch (Rosch 1975). Rosch's contribution to categorization, known as *prototype theory*, addresses both the status of certain members within categories and the status of certain categories within the taxonomy. In Aristotle's hierarchy of categories, no level is given particular consideration. A dog is equally a Dalmatian, a dog, a mammal, an animal, and so on. What Rosch pointed out, is that it not the case at all. Before being a Dalmatian or a mammal, a dog is a dog. The category DOG has a special cognitive status. It is a *basic level* category. These categories, like CHAIR, TREE, are more naturally used when we categorize things. They are learned and remembered more easily, we have motor actions associated with them and we can form mental images of them. A theory of categorization must account for that, but the classical view cannot.

Rosch also established that we do not treat all the members of a given category equivalently: some of them are more representative of the category than others; members differ in their *typicality*. For example, in the category BIRD, *robin* is a better example than *chicken*, which is a better example than *penguin*. Best examples of a category are called *prototypes*. Effects of prototypicality have been shown in many different kinds of tasks (direct rating, mental chronometry, and so on, cf. Lakoff 1987: ch. 2, for a review). The classical view cannot give any account for these prototype effects, given that the set of necessary and sufficient conditions which defines membership does not give a special status to any member.

One consequence of abandoning the classical view is that categories have to be attributed a new ontological status. Categories are not objective and external entities, but subjective and internal. There is no objective category BIRD that exists independently of cognitive organisms (which does not mean that the world has no structure). Cognitive organisms create concepts, *i.e.* representations of the world, which capture the similarities of the world they live in. The world is continuous and concepts try to give a discrete account of it. Objects more or less match the concepts, causing the prototype effect.

Let us consider an entity that we categorize as BIRD; we would categorize the parents of that entity as BIRD too, as we would do with the parents of the parents, and with the parents of the parents of the parents, and so on. But if we consider the ancestors of that entity that lived 200 millions years ago, we would categorize them as DINOSAUR. There is a continuum between the entity that lives now and its ancestors. There is no necessary and sufficient condition for being a bird that one entity would not have verified (and hence been a dinosaur) and that its child would have verified (and hence been a bird). Instead of one absolute and objective category, there are as many subjective categories as cognitive organisms are able to develop. These categories represent the world in which the organism does live, and that is why Archaeopteryx is a rather non typical bird.

3. Model of lexical evolution

In this section, we present our model of lexical evolution which falls into the evolutionary linguistics framework. Evolutionary linguistics aims to explain language origin and evolution by simulating community of interacting speakers. From their interactions, emerge and evolve particular aspects of language such as lexicon (e.g. Steels 1998), phonology (e.g. de Boer 2000), syntax (e.g. Kirby 2000), … (See Cangelosi and Parisi 2001 for general introduction to evolutionary linguistics.) In particular, our model is related to works of Steels (1998), Vogt (2003) and Smith (2003). (See Discussion for details).

In order to fully describe the model, we have to specify how the speakers, their interactions, their social relationships, and their environment are modeled.

3.1 Cognitive architecture of the speakers

3.1.1 Conceptual spaces

Let us take four balls, two blue, a big one and a small one, and two red, a small one and a big one as well. When we turn to the relations of similarity between these 4 objects, we face a dilemma: would we judge the similarity according to the size, grouping together the big balls on the one hand and the small ones on the other? Or would we group according to the color, having the two red balls in one group and the two blue in the other?

This example reveals the (trivial) fact that there are many ways of judging similarity between objects. Gärdenfors (2000) has named these different ways *quality dimensions.* We have seen that shape and color are quality dimensions[1], but we could cite many others: weight, time, and so on. Quality dimensions may vary on their topological structure: weight is isomorphic with the nonnegative real numbers, while the hue dimension of colors is isomorphic with a circle. Some quality dimensions are innate (*i.e.* biology based), others are acquired (*i.e.* culture based): perception and representation of colors are universal (Berlin and Kay 1969), while representation of time is linear in some cultures but circular in others.

Together, quality dimensions form *conceptual spaces.* The conceptual spaces framework allows us to define some crucial notions for our problem. Perception of an object is defined as the act of determining the value of that object on each quality dimension, *i.e.* forming a point in the conceptual space that represents the object. A concept (*i.e.* a mental representation that determines the categorization of a perceived object) is a region of a conceptual space. Learning is creating a new concept, or modifying an existing one.

3.1.2 Concepts

In this section, we review the technical details of concept modeling in a conceptual space, which differ from Gärdenfors (2000). In the rest of this paper, all quality dimensions are isomorphic to the real numbers, and thus conceptual spaces are multi-dimensional Euclidian spaces.

As we have seen in section 2, categories are not clear cut sets of objects. Members of categories vary in their typicality, ranging from objects that are prototypes of the category, to objects for which membership is not an easy question. Mathematics provides us with a very useful tool for handling this kind of set: the fuzzy sets theory. More precisely, fuzzy arithmetic will be our scalpel to shape concepts in conceptual spaces. Fuzzy numbers have been introduced to model expressions such as "about 50" (Dubois and Prade 1978; Kaufman

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[1] Color is actually composed of three dimensions: hue, saturation and brightness.

and Gupta 1984; Mareš 1994). 50 is certainly “about 50”, 49 and 51 are very likely to be “about fifty”, but -65 and 842 are probably not “about 50” (what exactly is “about 50” depends on what we are talking about). In fuzzy arithmetic, a fuzzy number F is defined by its characteristic function $\mu_F : \Re \rightarrow [0;1]$. In our case, we will consider an extension of fuzzy numbers in n-dimensional spaces, *i.e.* we will consider fuzzy vectors. The characteristic function of a fuzzy vector has to verify the following properties:

(i) $\exists x_0 \in \Re^n, \mu_F(x_0) = 1$,

(ii) $\forall x_1, x_2 \in \Re^n, \forall \lambda \in [0;1], \mu_F(\lambda \cdot x_1 + (1-\lambda) \cdot x_2) \leq \max(\mu_F(x_1), \mu_F(x_2))$,

(iii) $\{x \in \Re^n, \mu_F(x) \neq 0\}$ is bounded.

In the framework of concept modeling, the μ_F function indicates the membership of objects. If for an object x, $\mu_F(x) = 1$, x is then a prototype of the category. If $\mu_F(x) = 0$, x does not belong to the category. Intermediate values indicate the degree of typicality. Property (*i*) may be interpreted by the fact that each concept has a prototype which is an object with a certain membership. Property (*ii*) expresses that if an object x_1 is more similar to the prototype than an object x_2, then x_1 is more typical that x_2. Property (*iii*) expresses that if an object is dissimilar enough from the prototype, it does not belong to the concept. Figure 1 illustrates a characteristic function in $\Re$.

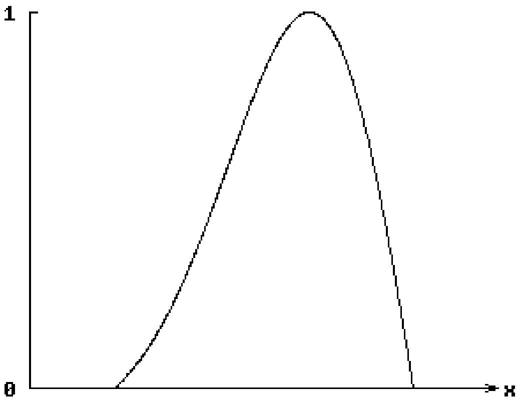

Figure 1: A characteristic function of a fuzzy number.

Directly handling or modifying the characteristic function of a fuzzy number is not very practical. For that reason many ways of representing fuzzy numbers have been introduced. Here, we will use an approach proposed by Kaufman and Gupta (1984), which relies on the notion of *α-cut*. F_α is the α-cut of F if and only if $F_\alpha = \{x \in \Re, \mu_F(x) \geq \alpha\}$. A fuzzy number F can be defined by the set $\{F_\alpha, \alpha \in]0;1]\}$. Moreover, any set of N pairs:

$$\{([x_n; x'_n], \alpha_n), 0 \leq n < N, [x_{n-1}; x'_{n-1}] \subset [x_n; x'_n], 0 < \alpha_{n-1} < \alpha_n \leq 1, \alpha_{N-1} = 1\},$$

define a fuzzy number F which step-shaped characteristic function is (see figure 2):

$$\mu_F(x) = \begin{cases} 0 \; if \;\; x \notin [x_0; x'_0] \\ 1 \; if \;\; x \in [x_{N-1}; x'_{N-1}] \\ \alpha_n \; if \;\; x \in [x_n; x'_n] \quad \& \quad x \notin [x_{n+1}; x'_{n+1}] \end{cases}$$

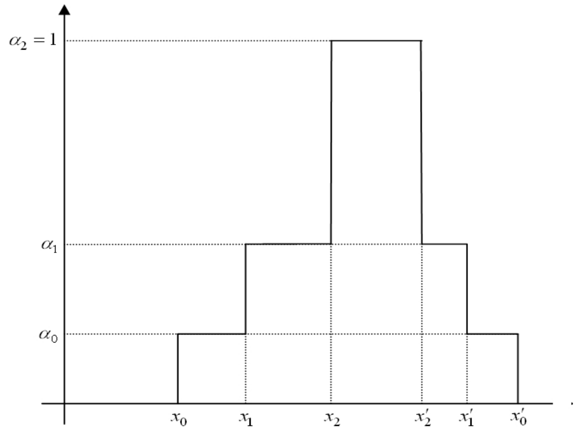

Figure 2: Characteristic function μ_F of a fuzzy number *F* defined by

$$\left\{ \left(\left[x_0 ; x_0' \right], \alpha_0 \right), \left(\left[x_1 ; x_1' \right], \alpha_1 \right), \left(\left[x_2 ; x_2' \right], \alpha_2 \right) \right\}.$$

Fuzzy numbers defined by the mean of α-cut can easily be generalized to fuzzy vectors in N-dimensional spaces by using N-dimensional hyperspheres instead of intervals. Each α-cut is then defined by a center and a radius. This is how concepts are represented in our model. The number of α-cuts used for representing the concept is a parameter of the model (in subsequent simulation, α is set to 10). Each concept C is given a confidence degree, $U_C \in [0;1]$, which represents the confidence of the speaker in the usefulness of the concept. Each concept is also tagged with a word, w_C, and stands for the meaning of that word. We will use the term “conceptual structure” to refer to a speaker’s conceptual space and concepts together. In all the simulations presented in this article, speakers are endowed with a two dimensional conceptual space.

3.2 Interactions

In our model speakers communicate about the objects around them and from their interactions emerges and evolves a lexicon. This is made possible because after each interaction, speakers modify their conceptual space in order to take into account the result of the interaction. Let us first describe the protocol of communication between speakers, and then how they modify their concepts.

3.2.1 Protocol

Interactions take place between two members of the population. When two of them are chosen to interact, they are given specific roles. One of them is designated as the teacher, while the other is the learner. The teacher chooses one of the objects of the world, and indicates its choice to the learner by pointing to the object. The learner’s goal is then to perceive, categorize and name the object indicated by the teacher.

Once the object is placed in the learner’s conceptual space, she[2] must categorize it. A concept C may be used to categorize an object 0 if $\mu_C(O) \geq 0$. The learner can thus have many concurring concepts during the categorization process. The concept C_k that results of the categorization is stochastically determined with the probability:

$$p(C_k) = \frac{\mu_{C_k}(O) \cdot U_{C_k}}{\sum_i \mu_{C_i}(O) \cdot U_{C_i}}$$

The more the object is prototypical of the category represented by the concept and the more the learner has confidence in the usefulness of the concept, the more likely is the

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[2] Speakers are asexual entities. We nevertheless choose to refer to them with the pronoun *she.*

concept to be the result of the categorization process. The last step for the learner is to name the object, and this is done with the word w_C associated with the concept.

The teacher has then to inform the learner whether she agrees with the word used to name the object. To achieve this, she just checks if one of her concepts is associated with the learner's word, and if this concept C is such that $\mu_C(O) > 0$. If she does agree, the interaction is successful. In that case, the learner refines the concept she used for the categorization in order to make the object more prototypical. She also increases her confidence in the concept (these two actions are described in the next section). But in several other scenarios the interaction fails.

The first problem that can occur is a failure on the part of the learner to categorize the object, because none of her concepts verifies $\mu_C(O) > 0$. In that case, if the teacher is able to give the learner a word for the object, then the learner acquires it. This learning can take different aspects. If the learner does not know the word used by the teacher, she creates a new concept on the basis of the object, and tags it with the teacher's word. If she already knows the teacher's word, either the associated concept was one of the concurring concepts during the categorization process ($\mu_C(O) > 0$), or it was not ($\mu_C(O) = 0$). In the first case, the learner refines her concept, and in the second she expands it in order to make its characteristic function such that $\mu_C(O) > 0$. But it might be the case that the teacher is unable to name the object. When this happens, they both create a new concept, and tag it with a word that the teacher invents. When a teacher invents a new word, it is always a completely new word: no other member of the population knows it.

When the learner manages to name the object, it is still possible that the teacher disagrees with that name. This disagreement can have two different causes: either the teacher does not have any concept C tagged with the learner's word such that $\mu_C(O) > 0$, or she simply cannot categorize the object. In both cases, the learner decreases the confidence of the concept she used. But in the first case, the teacher names the object and the learner learns the teacher's word (all the different cases of learning discussed in the previous paragraph are possible here too).

We have seen that in response to their interactions, speakers modify their conceptual structure. They may learn new words, extend or refine their concepts and/or modify the degrees of confidence toward their concepts. Let us examine how these operations are done.

3.2.2 Word acquisition

Acquiring a new word happens when the student is told by the teacher a word he had never heard before. Learning a new word means creating a new concept. The speaker does not know anything about the word but that it stands for the object chosen for the interaction. The concept created is defined as follow: all the α-cuts are centred on the object (it is the prototype of the new concept). The radius of the α-cut C_{α_n} is $\frac{R_{new}}{n+1}$, where R_{new} is a parameter of the model. The initial confidence degree of a new concept is another parameter of the model, U_{new} (in the rest of this paper, R_{new} is set to one thirtieth of the size of the conceptual spaces, and U_{new} to 0.5).

3.2.3 Concept extension

Speakers have to extend a concept when they are told that a word (which they already know) is usable for an object that is not in the scope of the concept yet. All of the α-cuts are modified. The different factors involved in the modification of C_{α_n} are the position of its center *P*, its radius *r*, the position of the object *O*, α_n and the concept degree of confidence *U*. When a member of the population is told about the association of a word she knows and an object, she may consider this object rather peripheral according to the category associated with a word. It would be surprising if a new example of a category modified radically the prototype of the category. So the closer α_n is to 1, the less C_{α_n} is modified. It would also be surprising if a speaker modified a concept that has been very useful in the past and thus in which she has a high degree of confidence. So the more U is close to 1, the more the speaker is confident in her knowledge, and the less the concept is modified.

If d is the distance between the center of C_{α_n} and the object, the new radius r' of C_{α_n} is:

$$r' = r + \frac{d-r}{2} \cdot (1-U) \cdot (1-\alpha_n)$$

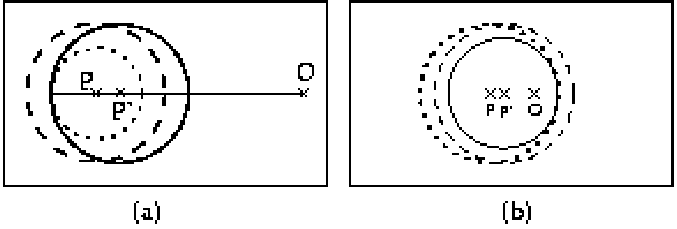
The center P is moved in the direction of the object in order not to generalize in the opposite direction of the object (see figure 3a). In vectorial notation, we have:

$$P' = \frac{\beta_1 \cdot P + \beta_2 \cdot O}{\beta_1 + \beta_2}, \text{ with } \beta_1 = r' - r = \frac{d-r}{2} \cdot (1-U) \cdot (1-\alpha_n),$$
$$\text{and } \beta_2 = d - \beta_1$$

In addition to this modifications, there is a constraint such that the radius cannot be increased nor the center be moved in a way such that $C_{\alpha_n} \not\subset C_{\alpha_{n-1}}$.

3.2.4 Concept refinement

Concept refinement occurs when a speaker has to tune a concept according to the information given by the position of an object that has already been categorized by this concept. When an object is categorized by a concept, the point that represents this object belongs to some of the α-cuts of the concept, maybe all, maybe not, depending on the typicality of the object. α-cuts are not modified in the same way when they contain the object or not. α-cuts that do not contain the object are modified in the same way than in the case of extension of concepts. α-cuts that do contain the object are recentered around the object. As in the case of extension, the higher the degree of confidence of a concept is, the less its α-cuts are modified. But the more the object is typical, *i.e.* the more the α-cuts in which it falls down have high α_n, the more it gives information to the category formation. So the higher α_n is, the more the α-cut is modified. If an α-cut C_{α_n} with center P and radius r is refined according to an object represented by the point O, its new centre P' is the barycenter of the points O and P with respective weights $\alpha_n \cdot (1-U_C)$ and $1-\alpha_n \cdot (1-U_C)$. The radius is then modified so that the α-cut after modification is included in what it was before: $r' = r - d_{PP'}$, where $d_{PP'}$ is the distance between the old position of the center and the new one (see figure 3b).



(a) (b)

Figure 3: (a) α-cut C_{α_n} before extension (dotted line), after modification of the radius (dashed line) and after modification of the center (plain line); (b) α-cut C_{α_n} before refinement (dotted line), after modification of the center (dashed line) and after modification of the radius (plain line).

3.2.5 Modification of the degree of confidence

A speaker increases (decreases) the degree of confidence of a concept when an object has been successfully (unsuccessfully) named by the word associated with the concept. At the same time when a speaker increases (decreases) the weight of a concept, she decreases

(increases) the degree of confidence of all the concepts that were concurring in the categorization process for this object. The more the object is typical, the more the degree of confidence is modified. If a speaker has a high (low) degree of confidence in a concept, it will not decrease (increase) remarkably after one successful (failed) interaction.
When the degree of confidence U is increased given an object O it becomes U' :

$$U' = U + \min(U, (1-U)) \cdot \mu(O) \cdot \delta \ ,$$

and when it is decreased:

$$U' = U - \min(U, (1-U)) \cdot \mu(O) \cdot \delta \ ,$$

where δ is a parameter of the model. In all the following simulations, δ is set to 0.2.
If a speaker has have a very low degree of confidence for a concept (under U_{min}, a parameter of the model set to .1), she forgets the concept (and the associated word).

3.3 Social relations

Our population is not an unstructured set of speakers. Not everybody can be the teacher of anybody. At each instant, the population is composed of two generations, an old one and a young one. Every T_{gen} interactions, the old generation disappears, the young generation becomes old, and a new young generation of speakers is created (T_{gen} is set to 15,000 for the rest of the paper). A newborn speaker does not have any knowledge, *i.e.* any concept. It then would not make any sense to have such a speaker as a teacher. The teacher is thus always from the old generation. The learner may be from one generation or the other. As a consequence, transmission of knowledge occurs both vertically and horizontally. In the simulations presented here, each generation is composed of 30 speakers.

3.4 Environment

The population's environment consists of the set of objects they can choose from for their interactions. The only thing they can do with these objects is to perceive them. As we explained in section 3.1.1, perception of an object consists in determining its coordinates in the conceptual space. We assume that all speakers have the same perceptual apparatus. So a given object has the same coordinates in every speaker's conceptual space. Objects are thus only defined by their coordinates in speakers' conceptual spaces.

As in the world in which we live in, the environment in the simulation we report here is not a simple pack of objects. It is on the contrary structured. Structured environments have been shown to increase communication (Smith 2003). The initial conditions of all the simulations are the following: 90 objects are distributed in 9 clusters. Figure 4 shows the repartition of the clusters in speakers' conceptual spaces. The size of the clusters is R_{new} (we suppose that speakers have phylogenetically evolved in such a way that they create new concepts with a size that matches their environment's regularities).

This world is not static: both the positions of the clusters and the positions of the objects within the clusters change. The evolution of the positions of the cluster is one of the parameters that will vary in the following simulations, and will be described when necessary. Within each clusters objects are changed every R_{obj} interactions. For the rest of the paper, R_{obj} is set to 500.

4. Simulations

4.1 Measurements

In order to describe the processes going on in the population, we need to define some informative quantities. The first that will be of interest is *success.* Success is simply the ratio of successful interactions over a fixed number of interactions (1,000 for all the simulations).

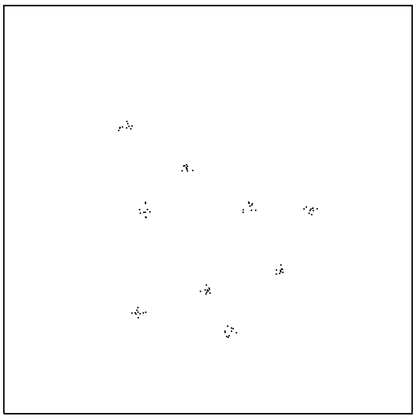


Fig.4: Initial positions of the clusters of objects as the speakers perceive them through their conceptual space.

Coherence and *stability* are also of important interest. These two measurements are computed when a generation dies. They are both defined with reference to speakers' similarity. The similarity $Sim_{1,2}$ between two speakers S_1 and S_2, is computed as follow: for each word, we compute the volume of the intersection of the associated fuzzy vectors of the speakers (this intersection is null if one of the speakers does not know the word). The sum over all the words is the volume $V_\cap$ of the intersection of their conceptual spaces. Let V_1 and V_2 be the volume of the conceptual space of S_1 and S_2 respectively (*i.e.* the sum of the volume of the fuzzy vectors). $V_\cap / V_1$ (respectively $V_\cap / V_2$) is that part of the knowledge of S_1 (respectively S_2) also known by S_2 (respectively S_1). We define the similarity $Sim_{1,2}$ between S_1 and S_2 as $Sim_{1,2} = \frac{1}{2}\left(\frac{V_\cap}{V_1} + \frac{V_\cap}{V_2}\right)$.

When a generation dies, for each of its speakers S_i, we measure the mean similarity Sim_i^0 with all the speakers of its generation and the mean similarity Sim_i^{-1} with all the speakers of the previous generation (*i.e.* the generation that died T_{gen} before and that has transmitted its knowledge vertically to the dying generation). The mean over all the speakers of the dying generation of Sim_i^0 gives the coherence of the population, and the mean over all the speakers of Sim_i^{-1} gives the stability with respect to the previous generation.

4.2 Simulation 1, Emergence of a lexicon

In this first simulation, the positions of clusters do not vary. It is aimed to present the general dynamics of the model and to give an answer to the following problem: we said that the young generation does not provide teachers since when speakers arrive in the population they are without any knowledge. But what about the first generation? As it is the first one, there is no old generation from which to obtain knowledge. This simulation shows that if we make an exception to our rule for the first generation and permit teachers to be from the young generation (the only one at this point), a lexicon emerges from the interaction.

Figure 5 shows the evolution of the success, coherence and stability for 500,000 interactions. Several remarks can be made: after 100,000 interactions the plot of success oscillates around 0.95, with regular abrupt downfalls. These downfalls occur indeed every 15,000 interactions and correspond to generation replacement: as explained in section 3.3, newborn speakers do not have any knowledge and thus fail to communicate during their first interactions. But they learn very quickly, and subsequent interactions are generally successful. Coherence and stability have similar shape, oscillating around .45, except at the beginning of the simulation, before success stabilizes, indicating that speakers always differ in their conceptual structure, and thus explaining why success never reach 1.

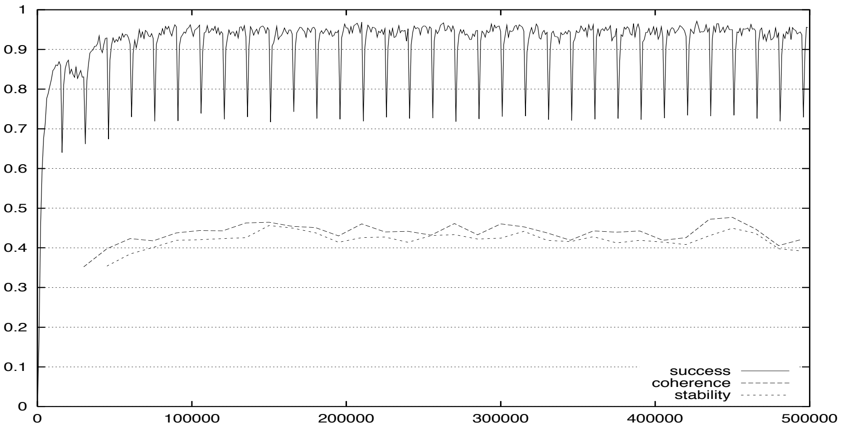


Fig. 5: Plots during 500,000 interactions of the success, the coherence and the stability of a population of 30 speakers per generation in a stable environment.

If we turn to the lexicon used by the population, we learn (see figure 6) that after an adjustment period, it oscillates between 40 and 60 words. Each word stands on average for 9.5 objects, all from the same clusters: speakers use words that refer to clusters of objects. Given that there are 9 clusters of objects in speakers' environment, such a lexicon would imply a large amount of synonymy (more than 5 words on average per cluster). But this view is not very precise, and looking at each speaker's private lexicon rather than at the pool of lexical items is more informative: the last generation of speakers only know 13.03 words out of the 49 spread in the population at this time, and while 9 words of the lexicon were created before the 500th interaction, the 40 others were created after the 440,000th one. Moreover, every speaker knows the 9 old base words with a high degree of confidence in the associated concept (*i.e.* in the meaning of the word), while degrees of confidence are always less than .5, their initial value, for the other words. The population uses in fact one word per cluster: speakers have on average between 1 and 1.5 different ways of categorizing the object of interactions (see figure 6). "Satellite" words are permanently created. They stay in the population for a few generations (a word created at the 440,000th interaction and still present at the 500,000th has been used for 6 generations), and then disappear. These words are not very widespread in the population since each speaker only knows 13.03 words including the 9 base words.

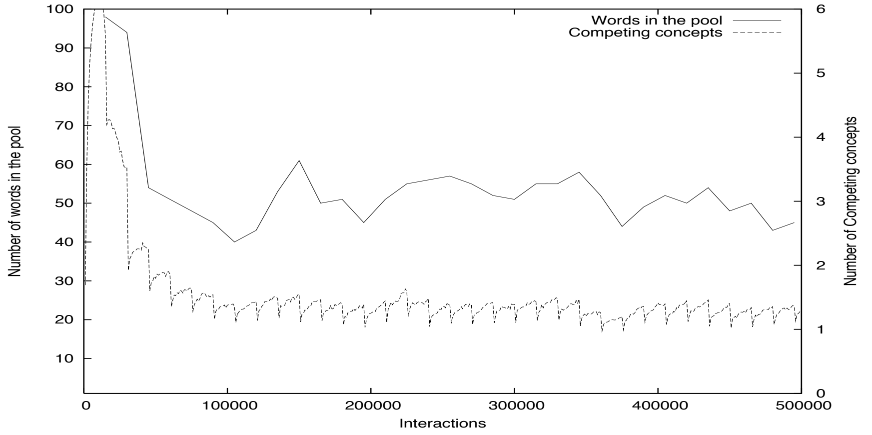


Figure 6: Plots during 500,000 interactions of the number of words in the pool and the number of competing concepts during the categorization process in a population of 30 speakers per generation in a stable environment.

One of the goals of this simulation was to investigate whether in our model the population is able to develop a lexicon from scratch. When looking at the results, no doubts can be cast on this. This "phylogenic" acquisition of a lexicon is similar but nevertheless distinct from the ontogenic one which occurs when a new generation arrives in the population. Whereas a new generation acquires the conceptual structure and the associated lexicon very quickly, emergence of shared conceptual structure and lexicon is a longer process, lasting over several generations. Our model relies on the strength of cultural transmission of acquired knowledge from one generation to the following one.

4.3 Dynamics of the lexicon in a changing environment

Contrary to other aspects of language such as phonology or syntax that are constrained only by speakers' physiological or cognitive structures, the lexicon is constrained by the environment it refers to through mental representations. Consequently, as the environment changes, speakers must modify their conceptual structures and thus their lexicon. This is the process to which we will now turn. As mentioned in section 3.4, the environmental evolutions that we will consider are changes in the position of clusters. In order to keep things tractable, the position of only one cluster will be changed here. The parameter we will vary is the speed of the transition from the initial to the final state which is represented in figure 7.

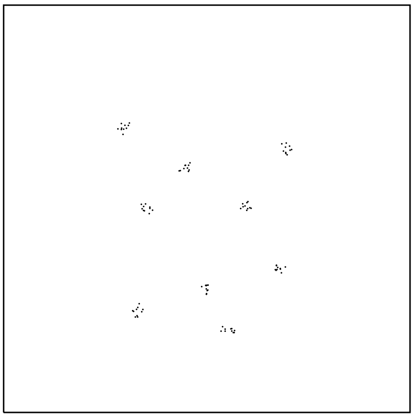


Figure 7: Final positions of the clusters after the change.

4.3.1 Simulation 2

In this simulation, the population is placed in an environment that will change from the initial to final conditions in 10,000 interactions, from the 100,000th to the 110,000th. Figure 8 shows the evolution of the success and the transmitted knowledge for 300,000 interactions.

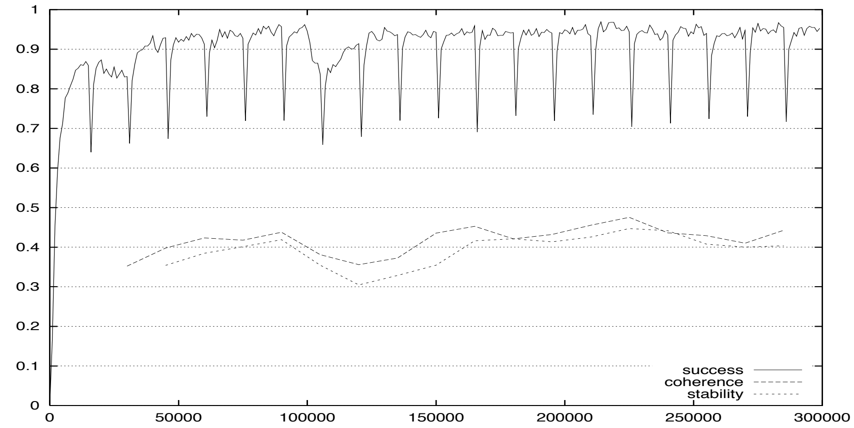


Figure 8: Plots during 300,000 interactions of the success, the coherence and the stability of a population of 30 speakers per generation in an environment changing in 10,000 interactions.

In these conditions success is perturbed during the cluster position transition but recovers its prior level just after the transition. Coherence drops from the 105,000th interaction to the 135,000th, as does stability from the 105,000th to the 150,000th. Coherence is low for the 3 generations that experienced the transition,

Figure 9 presents the mean conceptual space of the generations that died at the 90,000th, 105,000th, 120,000th, 135,000th and 150,000th interactions.

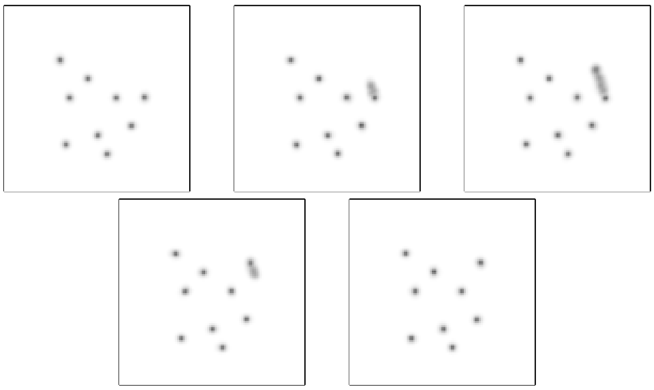


Figure 9: Mean conceptual space of the generation that died at the 90,000th, 105,000th, 120,000th, 135,000th and 150,000th interactions.

Even if the transition is shorter than a generation's lifetime, three of them have experienced it, and this perception has marked their conceptual structure. These marks of transition indicate the transition long after it ends, and much longer than the communicative success does. Because of these traces of an environment that does not exist anymore, speakers cannot develop a conceptual structure similar to their parent's, and this causes the stability to drop.

The lexicon of the population is again composed of 9 basic words shared by all the speakers, and a set of satellite words. The basic word used for the changed cluster at the end of the simulation is created between the 108,000th and 108,500th interactions. As long as the transition is going on the population invents new words, and lexicalizes one of them only after the transition it is over. Figure 10 shows the average number of competing concepts during categorization and the number of word in the pool. It indicates that this lexical innovation period is also characterized by a higher synonymy level, which is the cause of the low coherence.

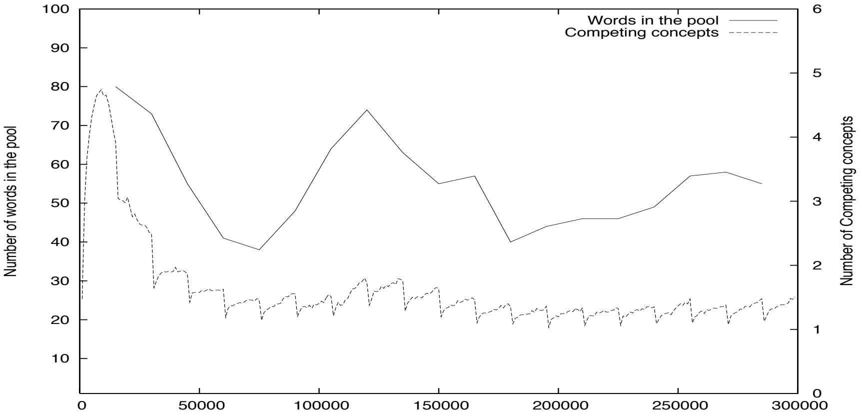


Figure 10: Plots during 300,000 interactions of the number of words in the pool and the number of competing concepts during the categorization process in a population of 30 speakers per generation in an environment changing in 10,000 interactions.

4.3.2 Simulation 3

The next simulation is exactly identical to the previous one, except that the transition between the initial and final position of the cluster is not as rapid. We still seek semantic change, *i.e.* changes of the representation associated with a word, and neither word loose nor lexical innovation as observed in the previous simulation fall into this category. The hypothesis behind this simulation is that if the transition is stretched over several generations, semantic change may occur. Figure 11 shows the evolution of the success and the knowledge transmission for 500,000 interactions with a transition occurring between the 100,000th and the 200,000th interactions.

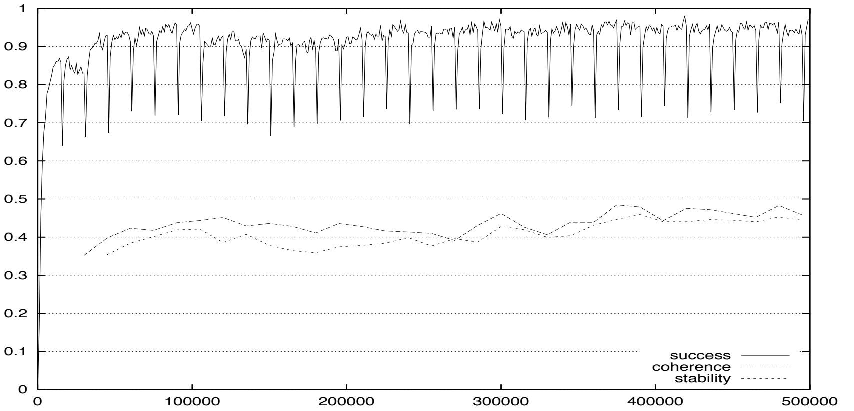


Figure 11: Plots during 500,000 interactions of the success, the coherence and the stability of a population of 30 speakers per generation in an environment changing in 100,000 interactions.

Success and stability are both lower than their normal level during transition. Coherence is less affected.

The lexicon at the end of the simulation has a similar pattern than in the previous: 9 basic words are shared by all the speakers. Figure 12 is a plot of the synonymy in the population. Again the transition induces more synonymy in the lexicon. The word for the changed cluster appears in the population between the 173,000th and 173,500th interaction, the population opting again for lexical innovation rather than changing the meaning of the word used for the cluster before the transition. Nevertheless, at the 173,500th interaction, the position of the cluster was not the final one, and thus representations associated to the word at this moment were different from these associated to it after the transition. This is a case of semantic change.

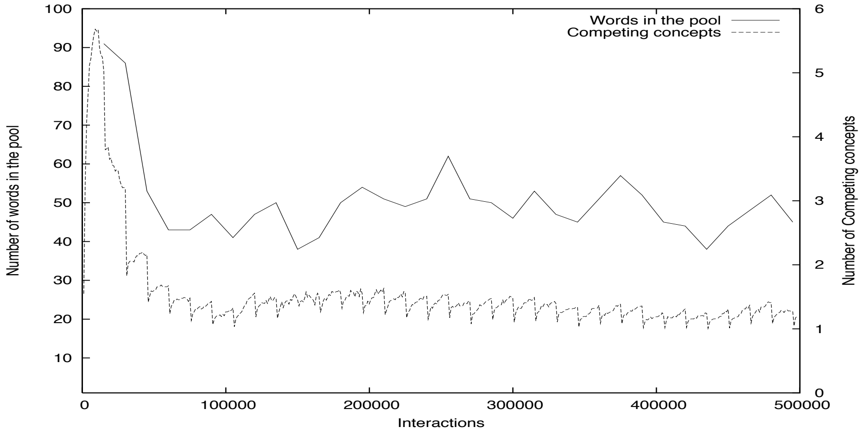


Figure 12: Plots during 500,000 interactions of the number of words in the pool and the number of competing concepts during the categorization process in a population of 30 speakers per generation in an environment changing in 100,000 interactions.

4.3.2 Simulation 4

This last simulation with simple environmental evolution is similar to the two previous in all respects, expect for the number of interactions needed for the transition, which is now set to 500,000. Figure 13 shows the evolution of the success and the transmitted knowledge for 700,000 interactions with a transition occurring between the 100,000th and the 600,000th interactions.

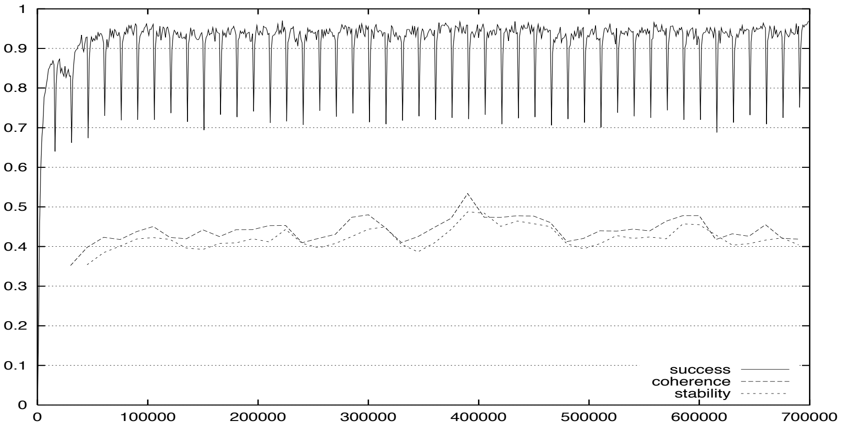


Figure 13: Plots during 700,000 interactions of the success, the coherence and the stability of a population of 30 speakers per generation in an environment changing in 500,000 interactions.

Success, coherence and similarity are not affected by the transition. The reason is that the change is so gradual that speakers are not aware of it. Figure 14 present the mean conceptual space of generations that died at the 105,000th, 300,000th and 600,000th interactions. Contrary to Figure 9, no traces of environmental changes are observed.

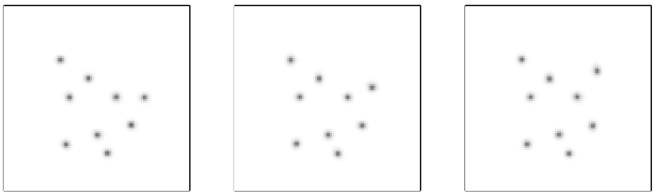


Figure 14: Mean conceptual space of the generation that died at the 105,000th, 300,000th and 600,000th interactions.

If we turn to the lexicon of the population at the end of the simulation, the situation differs from the previous simulation. There are still 9 basic words plus satellite words, but the basic word used for the changed cluster is created before the 500th interaction, *i.e.* at the very beginning of the simulation, simultaneously with the other basic words: the concepts associated with it in the successive generations represent the different stages of the evolution of the cluster, evolving with it. As figure 15 indicates, synonymy is not affected by this transition.

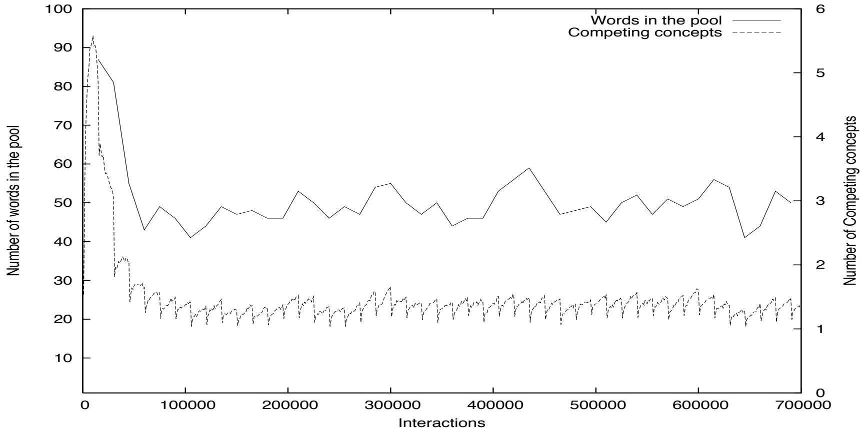


Figure 15: Plots during 700,000 interactions of the number of words in the pool and the number of competing concepts during the categorization process in a population of 30 speakers per generation in an environment changing in 500,000 interactions.

4. Discussion

4.1 The model itself

Evolutionary linguistics, *i.e.* computers simulations for the evolution of language, is an approach that has exponentially grown in the last few years. It uses the power of computers to allow us to build virtual labs in which we can test hypothesis that would have been only speculation otherwise.

Our model follows along the same lines as many others related models that include some semantics (Steels 1998; Hashimoto 1998; Hurford and Kirby 2001; Smith 2003; Vogt 2003). However, most of these models suffer from a double grave vice already mentioned by Smith (2003) and Vogt (2003): communication acts upon a predefined semantics and meanings are explicitly transmitted. However, as explained in section 2, not only meaning is grounded and then not predefined, but it is also private to speakers and cannot then be explicitly transmitted without some kind of mind reading or telepathy. This telepathical prerequisite is a hypothesis put in the models that obviously contradicts reality. Moreover, as noted by Smith (2003), if both the meaning and the signal are explicitly transferred in communication, then the signal does not convey the meaning anymore, and thus becomes useless.

According to Smith (2003), in order to obtain a communication without explicit meaning transfer

> “there must be at least three separate levels of representation in the model: the external, public world, a private, agent-specific internal semantic representation, and a set of signals, which can again be publicly observed. The mapping between the public and the private sections of the model must be specific to each agent and unobservable to the others […].”

Our model meets these requirements, and to our knowledge, only few models (Steels 1998; Smith 2003; Vogt 2003) do, exhibiting as in our case a co-evolution of lexicon and conceptual structure.

However, all these models build private meanings by successive division of the meaning space, leading to concepts that represent clear cut classical categories, without any possible way of exhibiting prototype effects. This drawback is not present in our model in which speakers build the semantics of their lexicon in a Roschian way.

We have here a model that both avoids the mind reading problem[3] found in most of models and represents categories in a much more natural way than the models discussed above.

4.2 The simulations

The results from the simulations we ran with our model show that populations can build a lexicon from scratch and can transmit it from generation to generation. This lexicon is efficient and permits successful communicative interactions between the members of the population.

In all the simulations, the lexicon that is developed is composed of two sets of words: basic words, shared by all the speakers and transmitted through generations, and satellite words, used only by a part of the population and that have a limited lifetime in the lexicon. Together, all these words constitute a lexical pool in which new speakers select their vocabulary. Given that the concepts which are developed by speakers match clusters of objects, and given the number of words in the pool (typically 50) and the number of clusters (9), there is a considerable amount of synonymy in the pool, and thus considerable competition for the selection by the speakers.

Several factors can explain how this selection operates. First, it is worth noting that speakers select a limited number of words out of the pool. This is due to the cognitive architecture of the speakers, and more specifically to the *winner-takes-all* strategy of rewarding successful concepts. When an agent has many competing concepts for the categorization of an object, the winner, if the communication is successful, has its degree of confidence increased, while other competing concepts have their degree of confidence decreased. The winner is then more likely to win the next categorization, decreasing again the degree of confidence of others competitors, which may finally be forgotten by the speaker. Synonymy is thus rejected by the members of the population, who do not select all the words of the pool. A similar result has been obtained by Hurford (2003) who argued that synonymy is rare because of production constraints rather than on comprehension constraints.

Another factor that explains the selection of lexical items by speakers is their frequency. As soon as the set of basic words is established, since all speakers know them they are used much more frequently than satellite words with more restricted diffusions. This frequency bias toward basic words makes them much more likely to be learnt.

As mentioned in section 4.3, lexicon is not only shaped by structural, cognitive or even physiological constraints as phonology or syntax are, but also by the environment it refers to. As simulations 2 and 3 have shown, when the environment is changing, it may be the case that words in the pool are used by speakers with meanings that no longer represent the world appropriately. This fitness constraint can be strong enough to influence speakers so that they do not select those words, with the consequences that the basic vocabulary is not entirely transmitted across generations and that synonymy increases, overriding then both the cognitive constraint against synonymy and the frequency bias.

However, all these factors are in fact competing during selection, and simulation 3 and 4 give insights on this factor competition. In simulation 3, we saw that the word for the moved cluster is introduced in the lexicon at ¾ of the trajectory of the cluster. This means that during the last quarter of the trajectory, even if the meaning of this word never fits perfectly its referents that are still changing, it is still selected from the pool by the learners. The

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[3] Our model avoids mind reading in the sense that it evacuates explicit meaning transfer. But in fact, it faces the mind reading problem in the sense of Quine (1960): we assume that the learner automatically identifies the referent indicated by the teacher, while in real world this ambiguity about the referent is in fact present in many cases.

meaning they associate to this word is then different from their parents', adapting their conceptual structure to their environment. The word experiences then a semantic change.

In simulation 4, the change is so slow that the word that refers to the cluster always fits its referents quite well. The pressure of the fitness constraint is then very weak, and the frequency bias makes the learner select the basic word. They nevertheless build a meaning for it slightly different from their parents', the word experiencing then a semantic change too.

5. Conclusion

It seems that the universe is such that the complex entities which it harbors cannot be stable and have to evolve. These evolutionary processes are fascinating when we look at complex systems such as life, language or culture. It is amazing to see that even if these processes are definitely distinct, robust parallels can be drawn between them.

In this paper, using Mufwene's (2001) metaphor *language as species,* we have shown that the very cultural process of language evolution is affected by the major constraint in natural selection, viz., fitness to the environment. In the case of language, it is just one constraint among others, and all compete to drive language evolution.

The model we developed solves the explicit meaning transfer problem, speaker's concepts being completely private. Moreover their concepts have a structure that takes into account the Roschian insights about categorization. But this model is nevertheless far from perfect since it lacks important aspects of language such as polysemy or compositionality. It has its own features that now belong to the models' feature pool, and we hope that evolution will play its role and that future models will select the good ones.

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