

Language evolution: Computer models for empirical data

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Abstract

This methodological article serves as an introduction to this special issue, whose aim is to encourage more and better interaction between empirical studies and computer modeling with regard to the study of language evolution. We argue that research into the field of language evolution is so complex that computer modeling forms an essential tool to generate predictions based on some, possibly descriptive, theory in order to falsify that theory. Falsification should be carried out by comparing the generated predictions with empirical data. In order to improve the quality of the predictions and thus the reliability of the falsification process, we stress the importance of initializing the computer model with empirical data. The papers in this special issue provide some concrete examples and new proposals of applying the suggested methodology.

1 Introduction

Computer modeling of the evolution of language has come a long way since the first attempts in the seventies and eighties (Lieberman & Crelin, 1971; Hurford, 1989; Werner & Dyer, 1991). In language evolution three complex processes interact: the human ability for producing, perceiving and learning language, the dynamics of language in a population, and the biological evolution of our ability to use language (Kirby & Hurford, 2002). Language evolution therefore involves both biological and cultural evolution, as well as co-evolution between biology and culture. Computer models have proved to be an indispensable tool to get a grip on this complexity. The aim of this paper, and of the other papers in this special issue is not so much to give an overview of the state-of-the-art; better sources for this exist, such as Cangelosi and Parisi (2002), Christiansen and Kirby (2003), Kirby (2002), Vogt (2006), and the proceedings of the evolution of language conferences. Nor do we aim to provide guidelines on what types of formal model one should select; this is covered in a recent

review on the interaction between demography and language evolution (Vogt, 2009). Our aim is to encourage more and better interaction between empirical studies and computer modeling.

In this special issue, a number of examples will be presented of research in which computer modeling and empirical data interact. The special issue is the result of the Advanced Studies Initiative of the Netherlands Organization for Scientific Research on ‘Language evolution: computer models for empirical data’, held in Noordwijk, the Netherlands in June 2007. In this workshop a group of computer scientists and researchers from relevant empirical disciplines, such as biology, psychology and linguistics, worked in small groups for one week on a number of topics relevant to language evolution in the broadest sense (i.e. evolution of communication, emergence of language, evolution of languages and language change). Each group contained at least one computer modeler and one researcher from the empirical disciplines and they were given the request to write a joint article on their own specialist topic. The result of this work is collected in this special issue. The articles may be slightly unconventional for the *Adaptive Behavior* journal, but this is partly due to the fact that most groups were formed from researchers who had not worked with each other before and who – in some cases – did not even know each other. Yet, we believe that, even though the subject area is language evolution, the issues raised in this volume are relevant to the use of synthetic approaches to study adaptive behavior in general.

Before presenting an overview of the papers published in this special issue (Section 4), we will briefly review some of the main issues on language evolution (Section 2) and provide some of our methodological views on how empirical data and computer modeling should interact (Section 3). The aim of the methodological section is to provide guidelines on how to use computer models to generate and test hypotheses based on and using empirical data and methods.

2 The complexity of language evolution research

Language is a behavior that not only distinguishes humans from other animals, but that also allows us to have culture and complex societies. It is therefore understandable that humans have always been interested in how humans got language and how language became so diverse. Due to the complexity of human behavior in general and of language in particular, and due to the complexity of historical and evolutionary processes, the origin of language and languages is a very difficult problem. Recently, however, the questions have begun to yield some answers.

Many of these answers have come from disciplines that tend to use empirical methods, such as linguistics, psychology, biology, anthropology and archaeology. For instance, modern sources generally propose that modern thought and language emerged at the latest about 40–50 thousand years (ka) ago (Klein, 2000). This is when modern expressions of symbolic art, such as cave paintings and complex statues first appear in the archaeological record. Although

more recently artifacts have been found that would push this date backwards to about 70–80 ka ago (Henshilwood et al., 2002), the basic idea remains the same: we can only be sure about the presence of language when artifacts with symbolic function appear in the archaeological record (McBrearty & Brooks, 2000). Given the relatively sudden emergence of such symbolic artifacts, there is also a certain correlation between this point of view and the idea that (complex) language has emerged relatively quickly.

Arguments based on biological, genetic and fossil evidence generally take a rather different perspective. As Neanderthals and *Homo sapiens* fall into the same category for both anatomical (e.g., Arensburg et al., 1989; MacLarnon & Hewitt, 1999; Martinez et al., 2008) and genetic properties, such as the FOXP2 gene (Krause et al., 2007) for speech and language, it is assumed that adaptations for speech must be as old as the latest common ancestor with Neanderthals, which lived around 500 ka ago. This gives a rather large range of possible time depths for the biological emergence. It must be noted, however, that these different perspectives are not in complete contradiction with each other. Evolution of our abilities for language and speech must have been a gradual process, and it is quite likely that different degrees of linguistic ability are represented in the fossil and archaeological record (e.g., McBrearty & Brooks, 2000). Some researchers (e.g., Mithen, 2007) have even proposed that Neanderthals had a relatively similar ability for speech, but a completely different symbolic ability.

Data on historical linguistics sheds light on the cultural evolution of language, though only based on recent history (up to 5–10 ka). Such data indicate that the rate of language change is so rapid that one can only explain this on a cultural account (Croft, 2000). Similar arguments have been made regarding the cultural evolution of creole languages (Mufwene, 2001) and sign languages (Senghas, Kita, & Özyürek, 2004). Also research on child language has indicated that Chomsky's (1980) *poverty of the stimulus* argument may be flawed, because data suggest that constructions produced by children reflect the input they have received (e.g., Lieven, Behrens, Speares, & Tomasello, 2003). This is important, since the poverty of the stimulus argument was the foundation on Chomsky's proposal for an innate Universal Grammar. However, these recent observations have been obtained by observing populations of humans that already have evolved a capacity for language. The question thus remains whether this capacity is a general cognitive capacity, potentially shared with other animals (e.g., Tomasello, 2003) or whether such a capacity is unique to language and therefore also to humans (e.g., Pinker & Bloom, 1990; Jackendoff, 2002). The two different perspectives make very different predictions about the interaction between biological evolution and cultural evolution.

The problem with both biological and cultural evolution is that they are historical processes, and therefore to a certain degree unpredictable and prone to loss of information over time (e.g., Gould, 1989). This means that it is impossible to know exactly how language evolved. The situation is exacerbated by the fact that language does not directly leave any physical traces in the fossil record. But does it also mean that it is impossible to say anything scientific about the evolution of language?

Nowadays, scientific knowledge about the issues relevant to the evolution of language has increased enormously. Equally important is the fact that, due to improved information technology, knowledge of these different disciplines can be much more readily shared between disciplines. These two factors have recently led to a renewed interest in the question of language origins. However, even though much more (interdisciplinary) data is available, it still remains a necessary but difficult issue to identify the questions that can reasonably be answered.

In order to give direction to research it is useful to have frames of reference. An example is Hockett's (Hockett, 1960) list of design features of language. These are defining characteristics of human language. Some of these also occur in other (animal) communication systems, but others possibly do not. This list is particularly useful when comparing animal communication systems with human language, an approach that has been more recently advocated by, e.g., Fitch (2000, 2005). Another useful frame of reference is Jackendoff's (2002, chapter 8) evolutionary scenario (see also, Jackendoff, 1999). This scenario is a potential pathway through which language could have evolved to become more complex, and is especially useful for linguists, as it gives an indication of what protolanguage like communication systems (of which Bickerton's, 1984, protolanguage is only one stage) would look like. The ideas of a faculty of language in the broad sense (all adaptations for language, including those shared with animals) and a faculty of language in a narrow sense (those adaptations for language that are unique to humans) as proposed by Hauser, Chomsky, and Fitch (2002) could also serve as a frame of reference for linguists and biologists. Finally, attempts have also been made to define a number of traits in the fossil record that could be indicative of language. Foley (2006) gives an example of a list of such traits.

Such frames of reference are especially useful for comparing and interpreting data. However, the problem of the complexity of the process of language evolution remains. Computer models have no difficulties in handling complexity, and can therefore be used as another means to make the study of language evolution less speculative. We therefore propose in this paper and in this special issue, different ways in which computer models can and have been used to investigate language evolution. In order to prevent computer modeling from becoming a fact free science as John Maynard Smith (1995) has famously called it, we argue that there should be a constant interaction between real data and modeling. We will not attempt to give a checklist or a list of best practices, however, but hope to illustrate the different ways of interaction between experiment and computer modeling with a number of concrete examples in this special issue.

3 Methodology of research

A general scientific method will proceed through the following four stages:

1. Observe a particular phenomenon that has not yet been explained successfully.

2. Generate a hypothesis that would explain this phenomenon.
3. Deduce a prediction from this hypothesis through logical thinking.
4. Test through experimentation or observation whether these predictions can be verified or falsified.

If the predictions are verified positively, there is suggestive evidence that the hypothesis is correct, when they are falsified, the hypothesis should be discarded and one should go back to step 2. This is general philosophy of science in line with C.S. Peirce's notions of *abduction* (step 2), *deduction* (step 3) and *induction* (step 4) (Peirce, 1931–1958).

This process of doing science is quite common and applies to all disciplines in science, from physics and economy to linguistics and psychology. Crucial in this scientific process is the abstracting away from the observation of a natural phenomenon and describe this into a formalism using tools, such as mathematics or logic, which can then be used to generate predictions that can be tested using experiments or observations. Although these methods are applied in all disciplines, we believe that some disciplines, such as physics, economy and chemistry, have a stronger tradition in applying formal tools for theorizing than other disciplines, such as linguistics, psychology, archaeology, sociology and even biology. This is roughly the distinction between exact sciences and humanities.

We do not say that the disciplines from humanities do not use formal tools; Chomsky's (1965) generative grammar is an example of a formal model. However, many formalisms in the humanities are descriptive rather than predictive, i.e. the theories tend to lack logical axioms from which hard and measurable predictions can be deduced. We do not claim that this is bad practice, but it is very hard to make testable predictions on the basis of descriptive formalisms. So, in a sense, theories that are formulated in descriptive formalisms are *underdetermined* by the empirical data available (Noble, de Ruiter, & Arnold, 2009). We believe that mathematical and computer modeling provide a more predictive formalism. First of all, theories have to be specified completely before they can be formalized computationally or mathematically. Secondly, within a computational or mathematical framework predictions follow automatically from the formalism. These predictions can then be falsified through empirical observation or experimentation and – in certain cases – even through computer simulations.

Such modeling is quite common in the 'hard' sciences. Especially in physics, chemistry and biology, computational and mathematical models are often used to study complex phenomena, ranging from galaxies through weather systems to micro-organisms. In order to test those theories that cannot be manipulated experimentally, such as the Big Bang theory, or the Earth's atmosphere, scientists carry out computer simulations and then need to assess whether the yielded predictions are in line with the empirical observations. For instance, simulations of the Big Bang should generally lead to a distribution of galaxies and stars that is statistically highly similar to the one observed in reality. So, physicists have to rely on a continuous interaction between theoretical methods (mathematics and

computer modeling) and empirical methods (observation and experimentation). This may involve breaking up theories into smaller (verifiable) pieces, modifying (parts of) a formalism, as well as gathering new empirical data through experimentation and/or observation.

Since the process of language evolution is also very complex and not very well amenable to experimental manipulation, we believe that computer simulations and mathematical modeling are crucial tools to test theories concerning the origins and evolution of language. In order to use these tools properly, the approach taken by the physicists needs to be adopted: computer modelers of language evolution have to idealize and abstract away from the observed phenomena regarding language evolution (e.g. the cognitive and dynamic processes of learning, linguistic structures, speech, social interactions and semiotics). By running computer simulations (or robotic experiments) of these models, we can produce predictions that can be compared to empirical data. In order to improve the quality of the predictions, it is important to initialize the model's parameters as close as possible to reality based on empirical data. Otherwise, any correlation may be an artifact or bias of the parameter settings, rather than verifying the correctness of the model.

It is possible to distinguish three types of formal modeling (Vogt, 2009): analytical models (AM), agent-based analytical models (ABAM) and agent-based cognitive models (ABCM). AM (e.g., Nowak, Plotkin, & Jansen, 2000; Abrams & Strogatz, 2003) are mathematical models that typically describe an evolving system using a limited set of mathematical equations, so that the evolution can only be described at a meta-level. ABAM (e.g., Baxter, Blythe, Croft, & McKane, 2009; Minett & Wang, 2008) are models that define the dynamics and interactions within one or more populations of individuals (or agents) who are themselves defined by a mathematical equation. ABCM (e.g., Batali, 2002; de Boer, 2000; Noble, 2000; Steels & Belpaeme, 2005; Kirby, Smith, & Brighton, 2004; Zuidema, 2003) are models that also describe the dynamic processes of a population, but where each individual is designed by a computer program that implements the production, interpretation and learning of linguistic elements. It is clear that the level of detail in ABCM is much higher than in AM. The level of detail regarding the empirical data that should be involved is likewise more complex for ABCM than for AM. For AM macroscopic observations (e.g. the distribution of languages in a region) are sufficient, but for ABCM it is also necessary to understand behavior on an individual level. For instance, to improve the quality of the predictions regarding the emergence of word-meaning mappings, agents should use various socio-cognitive mechanisms (e.g., joint attention, mutual exclusivity, the whole object bias etc.) with a similar frequency distribution as human children do. Also, for ABCM, as well as for ABAM, it would be important to know the type of social networks in a population, the frequency with which individuals speak, etc. Only when the level of detail increases, can a model yield predictions that correlate more closely to macroscopic empirical data, such as the distribution of languages.

It can be fruitful to use different kinds of models in different stages of investigating aspects of language evolution (or for that matter, any complex system). If one does not really know what factors are relevant, it might be useful to construct a relatively detailed ABCM. Through manipulation of this model it might then become clear what factors are crucial for reproducing the phenomena one finds in the real system. In order to gain more analytic understanding, it might then be useful to construct a much simpler abstract model, that takes into account only these factors, but that might be solvable mathematically. One could subsequently update the ABCM on the basis of this analytical insight, or construct experiments with human subjects to test predictions of the model. In this way different types of modeling as well as experiments can interact.

We have argued that many aspects of language evolution research involve such complex dynamics that it is hard to form descriptive theories that are powerful enough to produce verifiable predictions, and that in those cases formal modeling (i.e. from analytical models to agent-based cognitive models) is crucial, because this allows one to generate hard predictions that can be empirically verified. In some cases, computer models can help with verification of predictions as well. When the formal models become more and more complex, it is increasingly necessary that, prior to or as part of generating predictions, the model is constructed reliably based on empirical data, including statistical distributions regarding the occurrence of the behaviors that are modeled.

4 The special issue

With this special issue, we aim to encourage an increased interaction between the computer modeler and the empiricist to try and bridge the gap between the empirical data and the abstractions of the model. The reason why we believe this approach is crucial to advance scientific knowledge concerning language evolution is that the human brain, languages, societies and their interactions are all too complex for traditional pen-and-paper analysis, and that the only way to investigate theories and hypotheses on language evolution is to model them computationally. However, such computer models only make sense when they are closely tied to empirical data. Due to the gap between what contemporary computer models can achieve and the complexity of human languages, establishing such links is extremely difficult, it is necessary to organize, construct and test computer models and empirical data in smaller manageable chunks.

To achieve this, and thereby improve the acceptance of results achieved with the computer models of language evolution, it is essential that there is a deep interaction between computer modelers and scientists doing experimental work. We believe that this should lead to a better construction of formal theories, thus ensuring that the computer models are empirically realistic and testable. In certain cases, it might be possible to falsify a theory through computational modeling, but normally one should use empirical data during the process of producing and verifying predictions. The interdisciplinary interactions should help to obtain such empirical data through locating it in the literature, obtaining

it from language corpora or other databases, or – when such data is absent – even by collecting new data through observation and experimentation.

We acknowledge that interdisciplinary interactions are often hard because computer modelers do not know the jargon of, for instance, linguists or biologists. Experimental scientist, on the other hand, are often not used to appreciating the abstractions typical for computer models. Nevertheless, we feel such interactions can be highly fruitful as long as all partners remain focused, interested and patient. The contribution by Blythe and Croft (2009) to this special issue is a personal account on the experiences in the collaboration between physicist Blythe and linguist Croft in their prior collaboration in the study presented in (Baxter et al., 2009). This essay is quite unconventional for *Adaptive Behavior*, as it does not describe, nor review a scientific study, but relates on personal experiences and frustrations caused by the interaction between disciplines and on strategies to deal with the problems they faced.

Other papers in this special issue illustrate different ways in which modeling and experimental research can interact. The contribution by Lieven and Vogt (2009) focuses on a usage-based approach to language acquisition. It illustrates how computer simulations of language evolution that implement the usage-based approach can be used to generate predictions, which can be used to verify the model using data from recent dense database studies (Lieven et al., 2003).

The paper by Fitch and de Boer (2009) illustrates how in the case of the investigation of (the evolution of) speech, computer models that were often constructed for purely practical reasons – speech synthesis, recognition and compression – have influenced our theoretical understanding of speech. It also illustrates how models that have been constructed (on the basis of empirical data) for one particular purpose cannot always be used safely for investigating different questions.

Kirby and Smith (2009) describe recent experiments that have been designed on the basis of earlier computational models. These experiments test whether the results of the (much simplified and abstract) computer models, are also found when humans face a situation that is the same as that faced by the artificial agents. This work is part of an ongoing effort to give an experimental foundation to the work on the iterated learning paradigm (Kirby, Cornish, & Smith, 2008).

Zuidema and Verhagen (2009) give a contribution in which they survey the formalisms that have been proposed in the study of linguistics, and how well these could be used to explain the evolution of language. Linguistic formalisms are grounded in empirical description of language and have therefore generally been of a more descriptive than predictive (as defined above) nature. It turns out that they are not always suitable for use in an evolutionary framework. Zuidema and Verhagen therefore suggest a number of ways in which the formalisms can be extended to be better suited for evolutionary modeling.

Finally, Noble et al. (2009) discuss how to model the evolution of monkey alarm calls by taking empirical findings as a starting point. Through careful argumentation, they propose to use a carefully argued methodology inspired from (mostly) 20th century trends in evolutionary biology, ethology and cogni-

tive science. This contribution thus clearly illustrates the direction of research methodology that we aim for in this special issue.

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