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Review

Modeling the cultural evolution of language

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Abstract

The paper surveys recent research on language evolution, focusing in particular on models of cultural evolution and how they are being developed and tested using agent-based computational simulations and robotic experiments. The key challenges for evolutionary theories of language are outlined and some example results are discussed, highlighting models explaining how linguistic conventions get shared, how conceptual frameworks get coordinated through language, and how hierarchical structure could emerge. The main conclusion of the paper is that cultural evolution is a much more powerful process that usually assumed, implying that less innate structures or biases are required and consequently that human language evolution has to rely less on genetic evolution.

Keywords: Language evolution; Cultural evolution; Evolutionary linguistics; Biolinguistics; Semiotic dynamics

1. Introduction

In 1986, David Premack stated famously that "Human language is an embarrassment for evolutionary theory", and indeed, 25 years later we still seem to be struggling for proper answers to explain the origins of one of the most important features that sets humans apart from other species, despite the fact that over the past decade the fascinating question of the origins and evolution of language has received a growing amount of interest from many disciplines. We are indeed seeing contributions from anthropology, archeology, historical linguistics, neurobiology, cognitive psychology, evolutionary biology, genetics, artificial intelligence, and complex systems research. From 1996, there have been regular 'Evolution of Language' conferences that bring these diverse fields together in an interdisciplinary dialog [1], and there is a rapidly growing literature with monographs, collections of articles, and publications in a wide range of journals [2–7]. Out of all these activities, a new field of research is beginning to crystallize that does not approach the study of language evolution from the perspective of an existing discipline, but sees this research topic as its central core.

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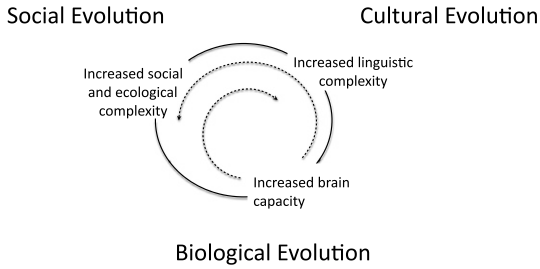

Fig. 1. The origins and evolution of language is the outcome of three evolutionary processes: Social and ecological evolution establishes the needs for language. Biological evolution establishes the necessary neurobiological apparatus and embodiment for language, and cultural evolution shapes which language systems arise and propagate in populations.

Even though there is certainly no consensus yet, not even about what an adequate theory of language evolution should look like, there is at least widespread agreement about one thing: The origins and evolution of language is based on a congruence of three different evolutionary processes, influencing and re-inforcing each other: socio-ecological evolution, biological evolution, and cultural evolution. Socio-ecological evolution is our best source for explaining the reasons why humans speak. The ecological pressures at the dawn of our species must have encouraged symbolic communication and the complexity of social structures must have grown to cope with these pressures [8–10]. Biological evolution is our best source for explaining how the embodiment and neural architecture necessary for language have originated and how they get reconstructed in development [7]. And cultural evolution is our best source for explaining how specific language subsystems, for example a tense–aspect system, may emerge and culturally propagate in a population [11]. Each evolutionary process pushes the other forward and gets pushed in turn. Increased social and ecological complexity promotes brain complexity and is enabled by increased linguistic capabilities. Linguistic complexity pushes biological complexity upwards and thrives on social and ecological complexity. So we get a self re-enforcing spiral process (see Fig. 1) in which different levels of evolution interact [12].

1.1. Biolinguistics and evolutionary linguistics

Everybody agrees that socio-ecological evolution must be acting as the background against which language origins and current language evolution takes place. But there is no consensus about the respective role of the other evolutionary processes. Some researchers emphasize the role of biological evolution, whereby they usually mean genetic evolution by natural selection [13–17]. Others emphasize the role of cultural evolution [18–21,6]. Those who hypothesize that there is a strong biological determination of the structure of language use the term *Biolinguistics* to refer to their work [22], whereas those who hypothesize that language is primarily shaped by cultural forces, use the term *Evolutionary Linguistics* [6].

For example, the biolinguist would argue that certain trends in the constituent ordering of affirmative sentences (for example, Subject–Verb–Objects as in English versus Subject–Objects–Verb as in Japanese) are biologically engrained as part of the innate language acquisition device, whereas the evolutionary linguist would argue that these choices (and even the more basic choice whether to use word order for expressing argument structure at all) are culturally constructed, agreed upon and shared [23].

The main challenge for the biolinguist is to show that (i) specific language features are genetically or epigenetically transmitted and (ii) are directly or indirectly subject to natural selection. It is the latter point that Premack puts into question, as the following more complete quotation shows:

> "Human language is an embarrassment for evolutionary theory because it is vastly more powerful than one can account for in terms of selective fitness. A semantic language with simple mapping rules, of a kind one might suppose that the chimpanzee would have, appears to confer all the advantages one normally associates with discussions of mastodon hunting or the like . . . syntactic classes, structure-dependent rules, recursion and the rest, are overly powerful devices, absurdly so" [24], pp. 281–282.

For evolutionary linguists, language features do not originate through genetic evolution and they are therefore not linked to biological fitness. So Premack's objection disappears. They argue that the features we find in human languages have a functional relevance in making symbolic communication more successful, and once such a functional viewpoint is taken, these features no longer appear as absurdly complex but make sense as adequate solutions to the very difficult problem of collectively building and culturally transmitting a symbolic communication system.

Evolutionary linguists do not deny of course that there is a neurobiological foundation for language and that human embodiment, such as the vocal apparatus on the properties of visual sensors in the retina, plays a significant role in constraining properties of human languages. But they hypothesize that the biology, even for such basic capacities as recognizing or producing hierarchical structure, is shared by many cognitive subsystems and hence not unique for language. They argue that the critical role of genetic or epigenetic evolution was to support broad changes to neuronal structure, for example for regulating synaptic growth [25], synaptic repairing [26], or brain expansion [27]. These changes have been important to improve human intelligence in general and so there has been plenty of selective advantage for them. Cognitive capacities which are relevant for other cognitive tasks such as visual perception or spatial cognition, get recruited for language and perhaps it is the capacity for recruitment and plasticity that is the key neurobiological innovation that made language possible.

1.2. Approaches to biolinguistics

Many different sources of evidence are being used to explore the role of biology in language. A first set of investigations looks at *language disorders*, such as Specific Language Impairments (SLI), and their genetic causes. The best known example of this approach are the investigations of the FOXP2-gene, which started with the identification of a linguistic impairment in the KE-family for morphology, such as for past-tense formation [28]. A genetic impairment could be isolated in the form of the FOXP2-gene [29] and the evolutionary history of this gene could be traced [30]. However, despite original enthusiasm, this gene is no longer considered to be "the" or "a" language gene [31] partly because the KE-family impairments are certainly not restricted to language but to many other cognitive capacities including facial motor control, and partly because FOXP2 is a regulatory gene that impacts a wide range of phenotypic features allover the body. The general lesson from these and other case studies is that there are probably no specific 'language genes'. Instead, the genetic influence on language is very indirect and we need to look at networks of gene interactions rather than single genes [32].

A second set of *comparative investigations* looks at human capacities relevant for language and compares them with those of other species (see the review in [33]). This can be the basis for reconstructing phylogenetic trees and for finding neurobiological homologues of possible precursors of the language faculty. For example, much research has focused on the mirror system discovered in motor areas as a possible precursor for the ability to recognize and reproduce speech gestures [34]. Another example is ongoing research into the acquisition and recognition of hierarchical structure. Experiments with cotton-top Tamarin monkeys [35] have shown that in contrast to human infants, these monkeys are not able to acquire context-free recursive phrase structure even though they can learn finite-state grammars. It is interesting to note also that non-human animals may occasionally show the capacity to deal with hierarchical structure in other domains (e.g. kinship) but cannot transfer this readily to other domains, suggesting limitations to recruitment.

A third set of investigations, pioneered by Cavalli-Sforza [36], tries to establish *correlations* between human populations, as identified by their genetic characteristics, features of their languages, and anthropological and archaeological markers (see a recent overview and examples in [37]). These investigations are useful from a population dynamics point of view because they allow a multi-faceted reconstruction of migration patterns and population mixing that is more reliable than if only one source of data is taken into account. Some researchers have taken these correlations as a way to investigate the genetic basis of specialized features of language, and argued, for example, for a genetic bias for the use of tones by speakers of Asian languages [38]. But these claims have been challenged on the basis that every human infant can learn every known human language and new phonetic, semantic or syntactic features have appeared or disappeared in languages.

There are still many other approaches currently being explored within the general perspective of biolinguistics, based on twin studies [15], on comparisons of neural systems needed for prehistoric tool building with those needed for language [39], on neuro-imaging studies to identify brain areas involved in language [40], and so on. There is also a large amount of work by linguists within the generative tradition to identify operations that are deemed necessary for language but difficult to learn on the basis of pure induction [41,22].

Finally, the biolinguistics paradigm has been explored by game-theoretic models [42] and by agent-based computer simulations [43]. One class of simulation models follows the same framework as that used widely in genetic algorithms and evolutionary programming research: There is a population of agents which have a genome that codes for certain aspects of language structure, for example a lexicon or a biased preference for a particular word order. These agents are made to interact and those that are more 'successful', where success is determined in terms of their ability to communicate in an artificial environment with other agents, play a bigger role in breeding the next generation of agents [44,16].

A second class of agent-based models is known as *iterated-learning models* [45]. They focus on showing that if a population has an innate bias for learning certain structure, this bias becomes expressed in their language after a number of generations [46]. Iterated learning models set up a chain of tutor-learner agents. The tutor produces utterances that the learner needs to acquire and after sufficient exposure, the learner becomes tutor for the next generation. Because the learning method imposes structure on data, even if that structure is not intentionally produced by the tutor, the learner ends up with a lexicon and grammar that is more complex or more structured than that of the tutor and this grammar is reflected in the data that he produces for the next learner in the chain. One of the major results of iterated-learning models is that a compositional structure indeed emerges in teacher–learner chains, if the learning method is biased towards such structure [47]. Recently the iterated-learning model has also been explored with human subjects [48]. It has turned out to be a very effective way to discover the learning biases that humans bring to bear on language-related tasks.

1.3. Approaches to evolutionary linguistics

Research within the Evolutionary Linguistics paradigm uses complementary sources of evidence. A first set of investigations focuses on *typological surveys* of the languages of the world. Recently large-scale efforts for describing languages have yielded vastly more data than available from earlier typological work. Examples of these efforts are the WALS database [49] or the corpora that are collected through on-line Internet usage. These data and the use of statistically more sophisticated techniques [50] have given a new impetus to the comparative and historical study of language structure [51], and have now lead to rather radical revisions of opinion from the side of typologists in favor of a cultural origins and evolution of language.

Earlier typological studies simply assumed that the categories used to describe languages (for example subject/object, nominative/dative, active/passive, etc.) were universal so that only the details on their usage and their surface realization (e.g. through morphology or syntax) differed across languages. However, it is now realized that these categories are not universal [52,53]. For example, there is no abstract category dative that is valid across all languages. Instead, each language has their own version of a dative, and for many languages the category dative does not make sense at all. This implies that formulating universals in terms of these categories is problematic as well and puts the notion of a highly specific innate Universal Grammar into question.

The typological data have also allowed the construction of cladistic trees that reflect family relations among languages with common origins, using similar techniques as utilized in biological typology studies. Tracking features across lineages has now shown that linguistic features are lineage-specific rather than universal, supporting the view that "cultural evolution is the primary factor that determines linguistic structure, with the current state of a linguistic system shaping and constraining future states" [54].

A second set of investigations from an Evolutionary Linguistics perspective has its roots in historical linguistics, which has a strong tradition going back to the 19th century. Intensive research has been conducted on how phonetic systems change, including the rise or disappearance of vowels and consonants, how new words get into languages or how meanings of words are shifting, and how new grammatical categories and constructions have emerged in the historical development of specific languages [55]. Particularly fascinating from the viewpoint of language evolution are the deep studies in grammaticalization phenomena that show for example how determiners have emerged, or how future becomes a grammatical category [56,57]. Explaining these historical data should be among the ultimate goals of any theory of language evolution, just as evolutionary biology is able to explain any phenotypic trait deemed to be of interest and completely deconstruct its origins, its ecological significance, and its selective advantage, thus explaining why the trait is there.

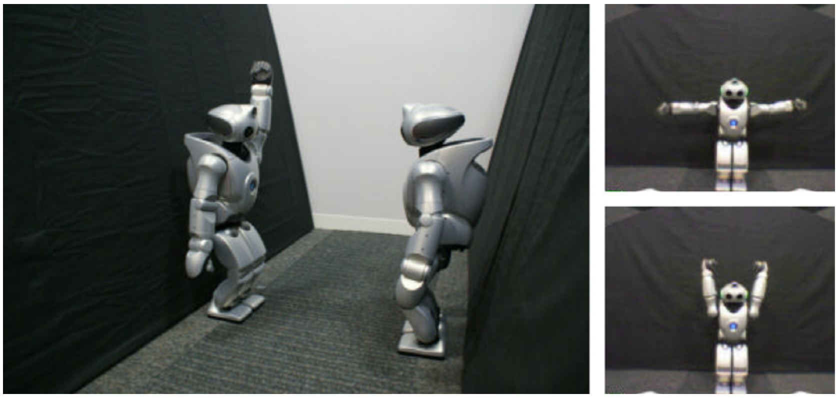

Fig. 2. Example experimental set up to study the cultural emergence of a vocabulary of action terms in a population of robots. The robot chosen as speaker asks the other robot to carry out a certain action and the game is a success if the other robot executes the action intended by the speaker. Robots start without a prior vocabulary of actions and without an inventory of action primitives, nevertheless they have been shown to relatively quickly develop a shared vocabulary using cultural evolution. The left image shows two robots facing each other during the language game. The images on the right show typical example postures as seen by the other robot.

Macroscopic and agent-based models exploring the evolutionary linguistics point of view have flourished as well. Agent-based models of cultural evolution always involve a population of (artificial) agents which can either be software agents operating in a virtual world [58] or physical robotic agents which interact with each other in a real world as experienced through a sensory-motor system [59]. The agents engage in interactions which are called *language games*. A language game is a routinized turn-taking interaction. Agents can play both the role of speaker and hearer. There is a shared cooperative goal, a shared restricted real world context, and the possibility of non-verbal communication, for example through gestures or joint action. The speaker has a specific communicative goal, conceptualizes the world for language, and transforms this conceptualization into an utterance. The hearer must parse the utterance, reconstruct its meaning and map it into his own perceptual experience of the world. Games may fail in which case diagnostics and repair strategies are used by speaker and hearer to expand, adjust and align their language systems so that they may have more success in the future.

The artificial agents in these experiments start with a set of functions that are hypothesized to be necessary and sufficient for seeing the emergence of possible language strategies to be successful in the language game. The agents then play a series of games where they configure possible strategies and try them out. What is *not* put in these agents are concrete choices, neither for the conceptual building blocks that they can use to formulate meanings, nor for the linguistic choices that they should use to express those meanings, because the goal is obviously to show how these may emerge through collective invention and negotiation.

Agent-based models are necessarily complicated and they significantly exercise and push the state-of-the-art in computer science, particularly Artificial Intelligence, computational linguistics, and robotics. Nevertheless, there has been steady progress over the past decade, co-occurring with significant advances in hardware and software engineering. Progress has first of all occurred in terms of the complexity of the embodiments and sensory-motor systems used. The earliest experiments employed simple cybernetic Lego vehicles and therefore hardly went beyond simple animal-like signaling [60]. They were followed by more systematic and larger-scale experiments with pan-tilt cameras that were particularly useful for studying the emergence of visually grounded lexicons [61]. Later the first experiments with fully autonomous 4-legged robots such as the Sony AIBO robot became possible, so that the evolution of action-oriented vocabularies could be studied [62]. More recently the state-of-the-art in humanoid robotics has become sufficiently advanced so that now two-legged humanoid robots can be used as platforms for systematic language evolution experiments. This has lead to a new series of simulations in which grammar has begun to play a significant role (see Fig. 2 from [63]).

Steady progress can also been seen in modeling the intentional–conceptual system that the speaker requires in order to conceptualize the meanings expressed in utterances and that the hearer requires to map reconstructed meanings back into action patterns and world models. In the earliest simulations, the intentional–conceptual system did not go beyond perceptually grounded categories, such as colors, which were acquired and aligned in co-evolution with emergent lexicons [64]. The complexity of meanings then moved up to predicates with arguments, for example in order to evolve ontologies and lexicons for spatial relations [65]. Most recently, the full complexity of human language semantics is being tackled by using a procedural approach to meaning and by operationalizing basic insights from cognitive semantics [66,67].

Finally significant progress can be seen in the complexity of the languages that emerge in these agent-based simulations. The earliest experiments focused on the emergence of lexicons for basic perceptually grounded categories in groups of agents and the main goal was to find efficient mechanisms for the origins and spreading of conventions. Once this was achieved researchers started to focus on predicate-argument structure, which made grammar become necessary in order to dampen combinatorial explosions in search [68] or to avoid ambiguity [69], and on more complex representations with the power of second order logic [70].

Just as research in innate biases is carried out in experiments with human subjects using iterated-learning chains, we see fascinating work similar to language games but now played by humans. It is carried out under the name of *experimental semiotics*. Pioneering work in this direction has been conducted by Bruno Galantucci [71], who uses a maze-like set-up and an odd interface medium to force players to develop some communication system from scratch. Some pairs remarkably succeed whereas others do not, and many different variations can be seen in the resulting communication systems. Other interesting examples emphasizing graphical symbol systems are discussed in [72] and [73].

The rest of the paper reviews in more depth work within the Evolutionary Linguistics paradigm from the viewpoint of agent-based modeling. Due to space limitations, I focus on issues related to lexicon and grammar even though there has been fascinating work on the origins of speech as well. The next section discusses the challenges that a theory of language evolution should address. Then some examples of research results are presented. The present survey is not exhaustive but intended to illustrate what could already be achieved.

2. Challenges for evolutionary linguistics

What are the fundamental problems that a theory of cultural language evolution is trying to solve? Before we can address this question, it is helpful to review some background notions in linguistics.

2.1. Language systems and language strategies

When studying the historical evolution as it occurred in human languages, there is clearly change at two different levels: that of language systems and that of language strategies. *Language systems* (sometimes called paradigms) capture the systematicity observed in some part of the vocabulary or grammar of a language, for example, a system of basic color terms, tense–aspect distinctions, movement verbs, cases or articles. Language systems group a set of paradigmatic choices both on the side of meaning (the conceptual system) and on the side of form (the linguistic system). The *conceptual system* includes pragmatic and semantic distinctions that are expressable in this language system and can therefore be used as building blocks for conceptualization. The *linguistic system* includes all the syntactic, morphological and phonological categories and structures to turn a conceptualization into a concrete utterance.

A given language comprises thousands of language systems, which are tightly integrated. Here are some examples:

1. German features a case marking system based on four paradigmatic cases: nominative, accusative, dative, and genitive, which semantically relate to the role of participants in the event introduced by the verb (such as agent, beneficiary, location and instrument). German requires agreement for case, number and gender between nominals and determiners and marks these features morphologically. This is illustrated in the sentence “Der Hund beisst den Mann”, where “der” and “Hund” is nominative, masculine, singular, and “den” and “Mann” are accusative, masculine, singular.
2. Spanish features a system of basic color terms including “blanco” (white), “negro” (black), “rojo” (red), “verde” (green), “amarillo” (yellow), “azul” (blue), and “marron” (brown). These colors carve out distinctive regions in the three-dimensional color space formed by the two color opponent channel dimensions (yellow–blue and red–green) and the lightness dimension (dark-light).
3. Russian features a refined aspect system based on ‘Aktionsarten’. Semantically, Aktionsarten highlight segments of the internal structure of the action or event denoted by the verb. For example, *delimitative* emphasizes the

beginning and the end, *ingressive* the beginning, *terminative* a definite ending to the action. Aktionsarten are expressed as morphological markers attached to the verb.

Many different language systems are called upon in the production of a single sentence. For example, the sentence “Mario saw a big elephant appearing left of his car” uses a system of lexicalized event types (“see”, “appear”) and object classes (“elephant”, “car”), a system of argument structure to introduce the roles of the two participants (the subject and the direct object), a system of proper names (“Mario”) to refer to a specific individual, a system of pronominal reference to refer back to individuals introduced earlier in discourse (“his”), a system of spatial relations (“left of”) and sizes (“big”) and a tense–aspect system to convey that the seeing event happened completely in the past (“saw”) and to highlight the beginning of the appear-event (“appearing”).

The distinction between different language systems does not imply that vocabulary or grammar is stored in terms of separate language systems. This is unlikely. It is now widely accepted that language users store knowledge about the vocabulary and grammar of their language in terms of *constructions*, which associate aspects of meaning with aspects of form [74]. A single construction typically packages a lot of constraints together for efficient parsing or production, and this implies that a single construction may incorporate elements of several different language systems. For example, a determiner-nominal construction, as illustrated with the phrase “the mouse”, not only concerns hierarchical structure and word order, signaling how the meanings of the constituents are to be linked to form the meaning of the whole, but also determination (definite vs. indefinite) and agreement (in number and countability between the article and the noun).

Typologists call the approach underlying a language system a *language strategy*. For example, they talk about color term strategies, relative-clause formation strategies, case strategies, coordination strategies (for combining nominals), negation strategies (for expressing negation), and so on. Knowledge about a language strategy requires both a meaning component for handling the formation, learning and adaptation of the relevant conceptual system and a linguistic component doing the same for the related linguistic system.

There is clear variation across languages in terms of which language systems, and hence which language strategies, they use. For example, Japanese does not have a case system; English does not have a grammatical Aktionsart system; Russian does not have a system of articles; French does not have a system of classifiers (as found in Bantu languages). And even if two languages employ the same strategy, the details of the language systems built with this strategy may still significantly differ. For example, Polish uses a genitive in situations where German uses a dative or accusative; Russian has an instrumental case absent from Spanish; Hungarian features cases expressing place or direction, such as inessive (in/inside), adessive (at), or illative (movement towards the inside), whereas Indo-European languages typically express the same relations with prepositions. Languages typically combine different strategies for the same function. For example, although English now uses constituent order and prepositions as the main vehicle for expressing the role of participants in events, there are still some remnants of an older case system which shows up in the declension of pronouns (as in “I” versus “me”).

2.2. Language change and language evolution

We know from the historical record that there is ongoing change in the paradigmatic choices of language systems, both at the conceptual and the linguistic level. The change takes the following forms:

1. There can be an increase in complexity of which choices have been adopted. For example, the basic color term “orange” entered the English language only in the beginning of the 16th century. Before that period, the same hue was referred to as yellow–red. But there can also be a decrease in complexity. For example, Dutch has lost the distinction between dative and accusative case.
2. The semantic territory that a particular paradigmatic choice covers can shrink or grow at the expense of other choices. For example, when the word “orange” came into vogue, it pushed aside the regions in the color space covered by red and yellow. Currently, the German dative is overtaking many of the uses that the genitive still has, and the genitive may disappear from German except for possessives, as it has in Dutch.
3. The way a semantic or grammatical feature gets marked can change and a morpheme may further erode until it gets too weak or even disappears and needs to be replaced by another expression of the same information. This is for example how the negation particle “pas” in French became obligatory (as in “je ne veux pas” (I do not want)),

after the Latin source "non" had eroded to "ne". "Ne" is occasionally left out entirely in contemporary spoken French and its reinforcer "pas" (originally coming from "un pas" (a step)) has become established as a negation particle.

All these changes are well known and have been reported extensively in the diachronic literature [55]. They are significant but do not destroy the logic underlying a particular language system, in other words, the underlying language strategy stays the same. But we also see in the historical record, particularly in creole formation, that there are occasionally more profound innovations, in the sense that new language strategies may become adopted by the population and others may disappear [20]. Here are a few examples:

1. Words like "yellow" or "blue" used to be brightness terms in old English and have now become hue terms. Speakers of old English predominantly used a color system based on brightness distinctions (now expressed with words like bright, shiny, dull, etc.) which was overtaken at the time of Middle English by predominant use of a system based on hue (with yellow, blue, red, green, etc.). A similar strategy shift took place in many languages [75].
2. Latin did not feature a system of articles for determination (i.e. for expressing how the referent of a nominal phrase must be accessed given a class of objects delineated by the nominal) but all languages derived from Latin (French, Catalan, etc.) developed such a system, usually out of demonstratives [76].
3. English used to have a case system for expressing the role of participants in events which was comparable in complexity to the case system of Latin or Greek, but this system eroded by the time of Middle English and got replaced by a system primarily based on constituent ordering and prepositions [77].

Thousands of such paradigmatic competitions are going on in languages at any given point in time, and often the fact that one variant becomes dominant may impact choices for other variants.

There is occasional debate about whether we should speak in the case of language about change only (as in geology) or whether it is appropriate to talk about true evolution (as in biology). Clearly, when a new strategy originates in a language community and gives rise to a newly emergent language system, it is appropriate to talk about language evolution. The level of novelty and innovation is certainly comparable to true innovation in biology. Even changes in a language system can be very significant and may lead to a ripple effect destabilizing other language systems and eventually requiring the introduction of new strategies.

2.3. Semiotic dynamics

The data about language change collected by historical linguists and sociolinguists have also brought up some important facts about how variants, both for language strategies and for paradigmatic choices of a language system, propagate in a population. Language change clearly does not happen instantaneously but is gradual. There is typically a period where novel strategies, meanings, and forms appear as small-scale micro trends, before they start to propagate very rapidly as they are being picked up by the majority of the population. This phase is usually followed by a slowed down propagation rate. Data collected about the frequency by which a population adopts a novel form therefore shows a so-called S-shaped curve [78]. This curve is very familiar from population biology, for example in the spreading of genes or diseases, suggesting that the cultural propagation of novel language meanings or forms follows the same universal laws as found in all complex adaptive systems [79].

A new norm can itself be overthrown again when yet another new linguistic innovation appears, similar to the way that new technological inventions may disrupt existing products, even if they have complete dominance of a market [80]. Moreover, older forms may still stick around and often strategies cooperate. For example, when a hue-based color system became dominant in Middle English, it did not entirely annihilate the existing brightness-based system (even though it was able to "steal" a lot of brightness words to become hue words), rather, the two strategies now co-exist side by side and can be combined, as in "shiny yellow" which makes use of both brightness and hue terms.

Language evolution, including grammatical evolution, is certainly not something that happened in the past, it is ongoing today and we can therefore apply Lyell's uniformitarianism principle, in the sense that the evolutionary processes we observe today are most plausibly the ones that have given rise to the very first languages. A good example of ongoing semiotic dynamics is the current evolution within the Spanish pronoun case system [81]. Accusative and dative cases are collapsing and persistent variation is found for three competing variants for expressing the surviving case: *leismo* with *le* instead of *lo*, *laísmo* with *la* instead of *le* when there is a feminine referent, and *loísmo* with *lo* instead of *le* for masculine or neuter referents. Each of these competing forms is surviving and speakers are familiar with the different variants and can even imitate them. The variants are associated with specific regions in Spain and speakers can identify from which region a speaker comes based on which variant he or she is using.

2.4. Challenges for theories of cultural language evolution

Given these observations, we can now define more clearly the fundamental questions that a theory of cultural language evolution should address.

First of all, it should explain *how a language system may emerge and continue to change*, assuming that all individuals of the language community share the same strategy. For example, the theory should be able to explain how a basic color term system, or a case system, or an agreement system can arise and continue to evolve, supposing that all language users know and use the same relevant language strategy. The paradigmatic choices both on the conceptual and on the linguistic side are open to change but the basic systemic principles are fixed and shared across all individuals in the community.

The assumption that everybody in a language community shares *a priori* the same language strategies is of course unwarranted, given all the cross-linguistic variation and change that we see at the level of language strategies as well, and so a theory of cultural language evolution should also attack a second, more difficult goal, namely to explain *how a new language strategy can emerge and propagate in a population*, how it can enter and possibly win a competition against other strategies, or on the contrary develop a symbiotic relationship.

What form should answers to both questions take? On the one hand, we will need to posit some general principles on how structure may culturally arise in language. The best candidates appear theories of cultural selection, as proposed for example in [20,6,82]: Individual language users invent and adopt variants that solve communicative problems, and those variants survive in the population which lead to increased communicative success, diminished cognitive effort, and social conformity. But then we need to instantiate these principles by identifying what kind of cognitive functions, embodiments and interaction patterns are needed to put them into action. The cognitive functions have to be specified at a sufficiently concrete level so that the theory's adequacy for explaining empirically observed linguistic phenomena can be objectively tested, just like the theory of evolution by natural selection needs to be instantiated with concrete facts about ecology, genetics and development in order to explain a particular trait such as lungs or butterfly wings.

Third, a theory of language evolution should explain the *semiotic dynamics* we see in cultural language evolution, such as the S-shaped curve. By semiotic dynamics, we mean the evolution over time of various macroscopic properties of a language or its use in a community, such as, how widespread a particular linguistic convention has been adopted, the average size of the vocabulary of all individuals, the average number of distinctive basic color concepts, the similarity in grammatical constructions for expressing argument structure, how dominant a particular strategy is, etc.

Semiotic dynamics explanations should follow from proposed answers to the previous questions, in other words from the cognitive functions proposed as necessary and sufficient for inventing and coordinating language systems and language strategies. It is certainly possible to model the S-shaped curve with an equation (namely the logistic or Vanderhulst equation) using aggregate quantities, such as the frequency of a particular form in the population at a particular point in time, but such models do not have any explanatory force from the viewpoint of a theory of language evolution. They merely describe the mathematical structure of the phenomena we observe. Just as the use of a logistic equation for describing the propagation of a disease does not explain what the disease is, how it is caused, how it originated, how it transits from one individual to another, or what counteraction could be taken.

3. Example studies

The past decade we have seen increasingly more sophisticated studies that address the issues outlined in the previous section through agent-based computer simulations that model empirically the phenomena observed in the evolution of human languages. These simulations are only possible if they capture the functional pressures that give

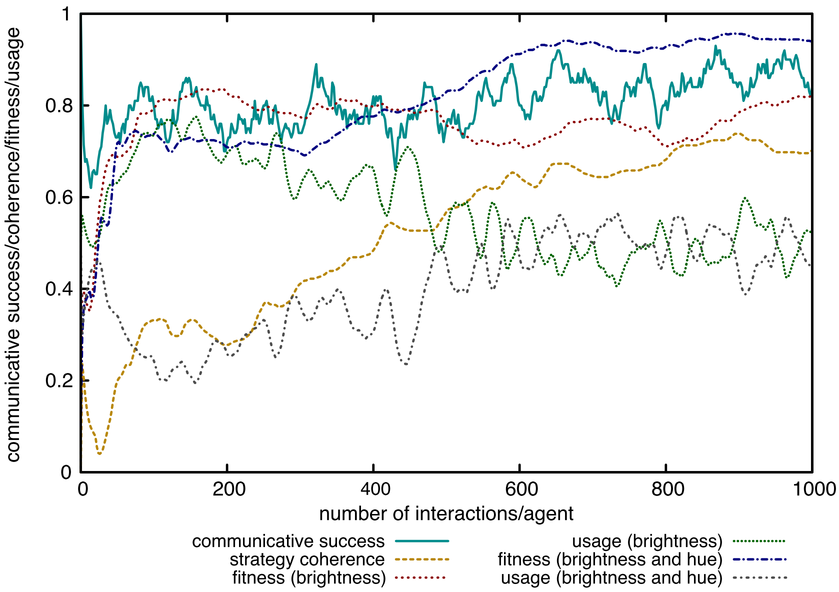

Fig. 3. Multi-agent experiment in which two strategies for color, a brightness + hue-based and a uniquely brightness-based strategy, compete with each other. In an initial phase agents develop words and color categories for each of strategies and the brightness-based strategy is dominant but around 400 games/agent it is overtaken by the brightness + hue strategy, even though both strategies remain in use. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

rise to linguistic structure, adequately model the needed cognitive functions, and are based on an effective theory of cultural evolution. Here are some examples:

1. Case systems express the role of participants in events. These roles are categorized into agent, patient, beneficiary, etc. and then mapped to surface categories like nominative, accusative or dative. How case systems may emerge in a cultural evolutionary dynamics has been intensively studied through agent-based computer simulations [83] and recently empirically observed grammaticalization phenomena could be adequately modeled [84]. The ongoing evolution in the Spanish case system (leismo, loísmo, laísmo) discussed earlier, could be successfully simulated starting from standard Spanish [85], showing that the agent-based simulations are reaching a degree of sophistication that makes them empirically relevant. Thus the simulations correctly predicted the different options that are currently developing within Spanish populations.
2. The origins of vague context-dependent quantifiers (such as many and some) could be shown to evolve in agent-based simulations based on real world scenes derived from robotic interactions [86]. Vague quantifiers yield more communicative success when the precise number of objects cannot always be determined based on differences between the speaker's and hearer's perception of the scene.
3. Agreement means that one constituent, for example the article in a nominal phrase, obtains some of the features of the nominal, such as gender or number. Many human languages use agreement as a way to signal hierarchical structure. There are now agent-based simulations that begin to explore how such agreement systems may emerge [87].
4. Much work has been going on simulating the emergence of color vocabularies in co-evolution with color categories [64]. Modeling the historically attested shift in color naming strategy from a brightness based to a hue-based strategy could also be achieved (see Fig. 3 from [88]).

Each of these experiments recreates the environmental conditions where the functionality of specific linguistic structures is beneficial or necessary for achieving communicative success while minimizing cognitive effort and includes an operationalization of the cognitive functions that agents need to exercise, invent, adopt and align their linguistic and conceptual inventories. Self-organization based on alignment and cultural selection within the context of collective language games then does the rest.

In the remainder of this section, three generic aspects that reoccur in all experiments are highlighted: How linguistic conventions become shared, how the conceptual systems underlying languages get shared, and how hierarchy emerges.

3.1. Sharing linguistic conventions

The first basic issue that comes up in every experiment is how a population can efficiently reach agreement on a linguistic convention, for example which word to use to express a certain meaning. The problem is difficult because (i) there is no central authority that imposes how everybody should speak, (ii) there is no telepathy with which one language user can inspect or directly influence the language system of another language user, and (iii) language users have mostly only local interactions (typically one-on-one) without a global overview. Nevertheless, a group can quickly reach a consensus on new conventions without generation change and certainly without genetically coding lexicons. How can we explain from the perspective of cultural evolution that nevertheless a population can reach a shared inventory?

There is now a consensus of a solution and it involves two aspects. First of all, let us assume that each language user stores in his own memory the set of conventions he is familiar with. When a speaker is missing a convention (e.g. he wants to express a particular meaning but has no word for it), we assume that he has the ability to *invent* a new one. This will seldom be entirely from scratch, but is often by analogy with already existing words. For example, the word “mouse” is adopted for the pointing device of a computer because early versions of such a device looked like a mouse with a tail. When a hearer is missing a convention in his inventory (e.g. he hears a new word or a word being used with a rather different meaning), we assume next that he is able to *acquire* the new convention by guessing the possible meaning of the unknown form, and then store this hypothesis in his own memory. The dual process of invention and acquisition causes conventions to spread in a population similar to viruses and it will already lead to a successful communication system but not to an efficient one. After some time language users will have stored all conventions present in the population and are therefore able to understand each other. But there is going to be a lot of variation because different individuals might have invented different conventions.

The second aspect of the solution is *alignment*. Alignment means that during parsing or production language users select from their inventory the linguistic conventions that they believe to give the highest chance of communicative success based on past evidence. To make this decision, we assume that each convention has an associated score in a language user’s inventory and that language users monitor the outcome of each communication they are involved in to determine this score. If the communication is successful they increase the chance that they will use the same convention in the future by increasing the score, while at the same time decreasing the score of any competing conventions (e.g. a synonym with the same meaning). This update strategy is known as the *lateral inhibition* strategy [89]. If the communication is not successful they decrease the score so that it is less likely that the convention is used again. Alignment introduces self-organization in the system because there is a positive feedback loop between use and success. The more a convention is successful, the more it gets used and the more it will become successful. We thus get at a critical point at which a phase transition occurs towards a shared system (see Fig. 4).

Alignment leads to faster convergence from scratch, smaller inventories, and faster learning by new members of a population of the existing inventory. The process is similar to self-organizing phenomena observed in physico-chemical systems, such as magnets, lasers or Belousov–Zhabotinsky style reactions [90]. It is also found in biological systems, such as ant path formation, termite nest building, or Turing-style morphogenesis [91]. Consequently the tools that have been developed for studying self-organizing systems in statistical physics and dynamical systems theory become applicable for studying the emergence of linguistic conventions and this has lead to a rapidly expanding area within complex systems science known as *semiotic dynamics* [92], which itself is part of a broader field that investigates social phenomena, such as opinion formation or crowd behavior, using the methods of statistical physics [93].

Alignment is not only justified because it is shown to work in computer simulations. There is a wealth of psychological evidence that partners in natural dialog continuously and rapidly align their inventories at all levels of language [94,95]. They start pronouncing phonemes in similar ways, use similar intonation patterns, tend to prefer similar words, align their use of grammatical constructions, even their conceptualizations and pragmatic cues. This kind of alignment happens very rapidly within the boundaries of a dialog but then has a longer lasting effect when the same individual engages in dialogs with others. Alignment also appears in experiments in which human subjects construct a shared communication system from scratch [96]. It is only when dialog partners have the capacity to align and are able to guess possible meaning in order to acquire conventions used by others that a new communication

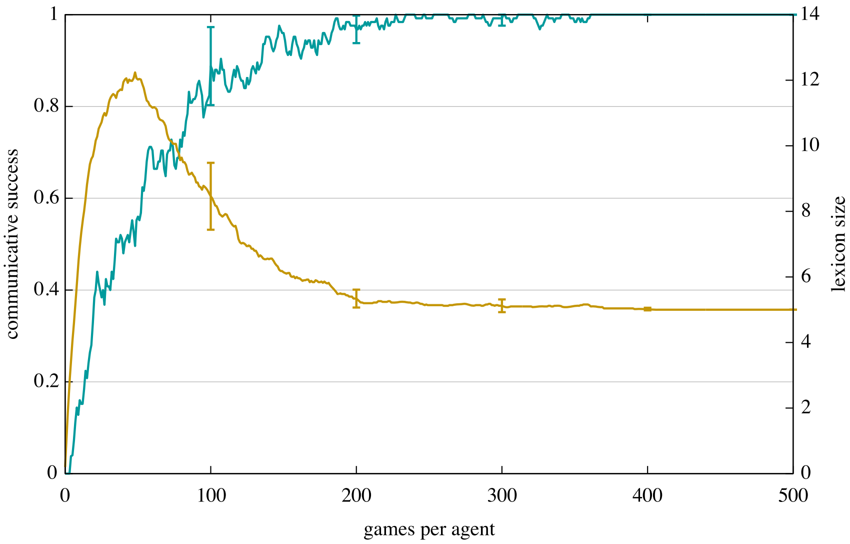

Fig. 4. Semiotic Dynamics of the Naming Game with 10 agents self-organizing a vocabulary to name 5 unique objects using proper names. The number of games per agent is shown on the x-axis. Both the running average of communicative success (left y-axis) and of the average vocabulary size (right y-axis) are shown. The agents reach 100% communicative success and lexical variation gets damped until an optimal vocabulary of 5 names, one for each individual object, emerges.

system can emerge. So the adoption of alignment as a central piece in a theory of cultural language evolution appears entirely justified.

The importance of alignment for reaching conventional agreement within a population was discovered in the mid-nineties through agent-based computer simulations [97]. Many different alignment strategies have since been proposed. They vary in terms of the amount of information they keep in the inventory, how they decide which convention to prefer, and how the update is done. For example, in the so-called Minimal Naming Game [98] agents throw away all competing variants as soon as they have encountered success with one variant, whereas in frequency based Naming Game systems [99] agents keep statistics of use and success. Simple Naming Games assume that there can be synonyms (one meaning multiple forms) which get progressively damped, but no homonyms (one form multiple meanings). The latter is unavoidable when meaning cannot be accurately guessed by the learner or when the speaker reuses existing words for new meanings leading to polysemy. The presence of homonymy requires more sophisticated alignment mechanisms but these have been demonstrate as well [100,101].

In addition to the study of the alignment mechanisms themselves, a significant body of research has developed during the past decade that explores the behavior of alignment from a complex systems point of view:

1. A number of scaling laws could be established. They capture how different macroscopic quantities such as population size or time to convergence or maximum lexicon size are related [98].
2. There is in addition a body of analytic results showing which properties are critical for effectively reaching agreement [102].
3. The impact of agent network structure on the time course of the system has been studied as well. These studies show for example that hubs can have a locally positive effect for coordinating convention choices but may impede global sharing [103,104].

In conclusion, we can say that the question how a set of conventions can become shared in a distributed population of autonomous individuals through a cultural process has been solved. The solutions are now used routinely in more complex simulation experiments.

3.2. *Explaining sharing of conceptual systems*

Successful communication requires in addition that language users share sufficiently the conceptualizations expressed by language. For example, the phrase “can you give me the olive green T-shirt” will only be understood properly if speaker and hearer share the color category ‘olive-green’. The rich set of aspectual distinctions in Russian can only be properly used when the relevant semantic distinctions have been mastered. The question how concepts become shared has been debated for centuries in terms of an opposition between a nature and a culture camp. Those arguing for a predominance of nature in concept formation argue that biological constraints (the structure of the human sensory apparatus, embodiment, innate biases) as well as statistical properties of the real world, are sufficient to explain how the members of a language community share concepts. This is also the point of view usually taken by those working within the biolinguistic paradigm. On the other hand, those arguing for an important role of culture argue that these biological and real world constraints still leave a lot of leeway. They are not enough to explain why we find a particular conceptual system. This is the viewpoint typically adopted by evolutionary linguists and is motivated by the overwhelming variation that we find across the languages of the world [105,53].

Research on agent-based simulations have yielded an answer to a crucial question for cultural approaches to concept formation, namely, if biological and real world constraints are not enough then how is it nevertheless possible for a group to arrive at a sufficiently shared set of conceptual distinctions to make language possible? The problem is even more difficult than reaching a linguistic consensus because language users have no direct feedback and no telepathic access to how others are conceptualizing reality.

Structural coupling is now accepted as being the solution to this problem. Structural coupling means that language users not only invent, adopt and align their use of linguistic conventions, but also invent, adopt and align the concepts expressed by these linguistic conventions *based on the outcome of their communicative interactions*. Each language user stores in his private memory an inventory of conceptual building blocks, for example a set of prototypical colors, spatial relations, types of actions, classes of objects, etc. These building blocks have scores indicating how far the language user believes these concepts may lead to successful communication. When the speaker requires a concept, for example to distinguish two objects from each other, he draws on his private inventory. When no concept is available, the speaker expands this inventory with a new concept that solves the problem at hand. For example, he might introduce a new color prototype (thus distinguishing blue and green) or introduce a new spatial relation (distinguishing between left and right). The speaker must then seek a way to express this novel concept which could be by the invention of a new word or the re-use of an existing word by analogy. When a listener is confronted with a word with unknown or expanded meaning, there will be a communicative failure but the listener can reconstruct the relevant concepts, based on the communicative goals, shared context, linguistic constraints coming from the rest of the utterance and additional dialog, and associate them with the new word use. These operations guarantee that not only new words but also their meanings spread in populations.

As in the case of linguistic conventions we also need alignment. When two individuals use certain concepts in a successful communication they will not only increase the score of the conventions they use but also of the concepts expressed by these conventions. Moreover they should fine-tune the concepts in a way that they are better suited for the present case. For example, the prototype representing the concept in memory might be shifted to fit better with the situation at hand, or some of the decision weights and thresholds might be adjusted to make a clearer categorical decision. In the case of a failed game, the score of the concepts involved goes down. A similar self-organizing effect now occurs as in lexicon formation. Those concepts that lead to successful games will be used more and they will better and better reflect the consensus. Note that concepts are automatically adapted to the communicative challenges posed by the environment because if a concept is not relevant in enough situations it will not become prominent and survive in the language of the group. If the concept is irrelevant for a particular language user he may not even construct it in the first place.

The domain of color categories has traditionally been used in the nature/culture debate. Although for decades it was thought that the color categories named in human languages are universal, and therefore could potentially be genetically coded as innate biases in concept acquisition, there is now a consensus that we can speak at best of trends in color categorization with language playing a clear role in determining which categories are adopted [106]. Agent-based computer simulations of color concept formation structurally coupled to lexicon formation have now convincingly shown that a shared color category system can arise *without* prior innate biases [64,107] (see Fig. 5 from [66]). The color categories that emerge in these simulations get closer to the universal trends we find in human languages when more ‘biological’ constraints are put in, for example when the perceptual system of the agents is similar to the opponent channels found in human color vision. Moreover the emergent color systems adapt to the environment in the sense that when only colors in specific ranges are presented, the language system will shrink and become more refined in these ranges [107].

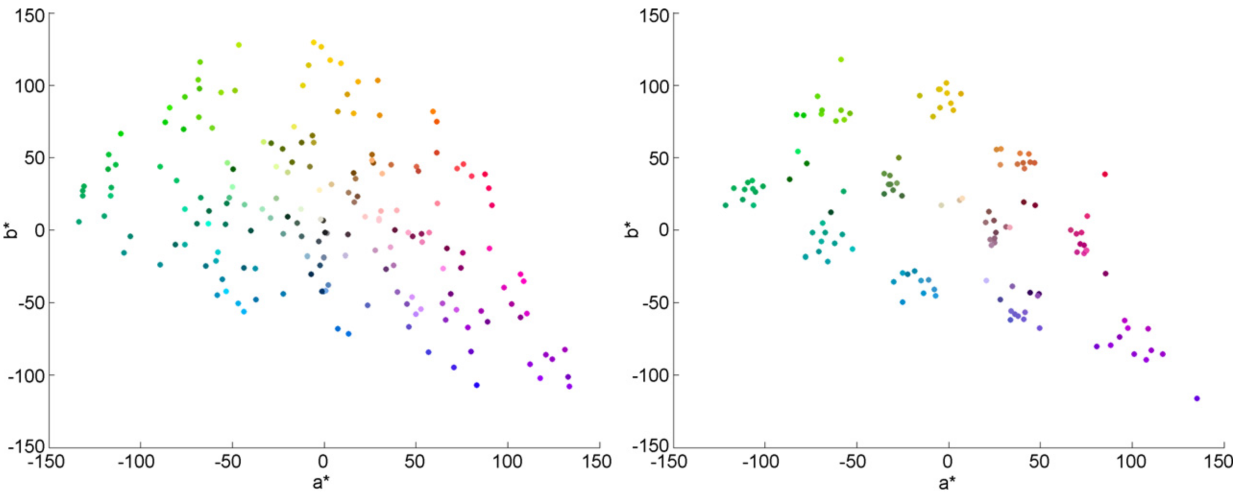

Fig. 5. Example experiment in the emergence of color categories through language games within a population of 10 agents. The left shows the prototypes of all agents not using structural coupling and the right when they use structural coupling including alignment. Without structural coupling, the categories are scattered more or less randomly over the color space. With structural coupling, the color categories cluster around certain regions of the color space. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

The principle of structural coupling has now been demonstrated in a wide range of domains and has become a standard component in more complex language game experiments. For example, spatial concepts, such as left-right, front-back or near-far could be shown to emerge if agents recruit general concept formation mechanisms and structurally couple them to an emergent spatial lexicon [108]. Similarly a shared set of action categories could be shown to emerge in a population which was playing action games (as in Fig. 2) [109]. The embodiment of the agents (namely humanoid shapes with a front and back, arms and legs, etc.) plays in each case an important role to shape which categories arise. Also the nature of the environments the agents encounter strongly influences what categories are needed and will be retained. Structural coupling is also effective for explaining how the semantic categories playing a role in grammar may emerge and get coordinated in the population. For example, agent-based models of the origins of case systems have shown that semantic roles (such as agent, patient, beneficiary, etc.), which typologists have observed to be to a large extend language-specific, can also get coordinated when they are structural coupled to the forms that express these semantic roles in terms of surface cases [110].

All these experiments substantiate the basic hypothesis of cultural language evolution, namely that although biological and real world constraints provide the basic framework, the actual choices for what language systems and strategies are adopted in a language community depend crucially on cultural processes, including earlier states of the language systems which constraint what new innovations are possible. These experiments show that it is not necessary to introduce strong innate biases. Indeed such biases would make language systems less adapted to the environments and ecological goals that language users might have.

3.3. Hierarchy formation

A third generic area concerns the origins of hierarchical structure. It is well known that human languages are compositional in the sense that words can be put together into phrases and phrases can be combined to form larger phrases. Syntactic composition goes hand in hand with the semantic composition of meanings of each building block. From a biolinguistic perspective, compositionality and hierarchy is a direct consequence of the innate language-specific biases implied by Universal Grammar. From an evolutionary linguistics perspective, handling hierarchical structure is a generic cognitive capacity, also needed in action planning and action sequence recognition, structured object recognition, social organization and many other tasks. The question is rather why would human languages use hierarchy and what is the cultural process through which hierarchy emerges.

The first step towards hierarchy is compositionality, meaning that utterances are composed of multiple words which individually can be reused in other contexts. Although there have been some proposals that holistic utterances came first [111] and then (by chance) some recurring sections of utterances became associated with recurring meanings [112], a more efficient and cognitively more plausible mechanism is based on re-use. Speakers utilize all available words to cover the meaning they try to convey and if some parts are missing, new words are invented for those parts. Listeners can reconstruct partial meaning based on their own inventory and will thus have an easier time to guess the meaning of newly invented words. Alignment, as discussed in the previous sections, then does the necessary work in coordinating which words survive in the population and how much meaning they cover. Agent-based computer simulations have shown that this straightforward mechanism leads indeed to the emergence of a compositional language [113,114].

But compositionality in itself does not yet mean hierarchical structure. The question of the origins of hierarchy has been approached from two directions: syntax-directed and semantics-directed. Syntax-directed approaches are in line with theories of language processing that favor exemplar-based inventories [115] and with so-called usage-based models of language learning [116]. Recurrent combinations of words (so-called collocations or, in the case of structures, collostructions [50]) are assumed to be stored as such in memory and thus become available as patterns that can immediately be re-used. These patterns can then undergo processes of generalization that can be used as templates for subsequent patterning, as shown for example in the agent-based simulations reported in [117,114,23]. Interestingly, deep issues arise to maintain systematicity (in the sense of the same form for the same meaning) because the evolutionary dynamics of building blocks may go counter to the evolutionary dynamics of usage patterns. However this can be solved by applying alignment at multiple levels, and not only in a bottom-up but also in a top-down fashion [118].

Semantics-directed approaches hypothesize that the main source of hierarchical structure in language comes from the fact that semantics is compositional. For example, the words in the nominal phrase “the big red block” form a hierarchical structure because the meanings of the individual words each contribute towards the communicative goal of the phrase as a whole, namely to identify an object in the present context. Another example is seen in a sentence like “The woman threw flowers at the bride” which describes an action. The reason why the different phrases form a sentence structure is because the nominal phrases each introduce a participant of the action, and their ordering signals who is doing what to whom. Experiments in semantics-directed grammar formation are ongoing and they go hand in hand with experiments on the emergence of complex compositional semantics [119]. A recent example concerns agent-based simulations in the domain of spatial language [120]. Complex conceptualization strategies (e.g. that require perspective taking, selection of a landmark, etc.) are developed and coordinated by the agents and grammatical structures are used to express the internal structure of conceptualizations and how the spatial concepts are to be used. There is undoubtedly enormous room for further progress in this area and given the growing sophistication of tools for agent-based models of cultural language evolution we can expect to see many new experiments in the very near future.

4. Conclusions

This paper provided a survey of recent research in language evolution, structuring the field into two alternative approaches: the biolinguistic approach, which puts a strong emphasis on innate structure and hence on biology as the driving factor in the origins of linguistic structure, and the evolutionary linguistic approach, which emphasize the role of cultural evolution within constraints provided by the biology and the ecological niches in which human populations operate. The final sections of the paper focused more concretely on the evolutionary linguistics approach by defining more clearly the key challenges and by highlighting some of the major results achieved so far. Of course, many researchers take a middle position exploring both biological and cultural aspects. Indeed, there is no doubt that language evolution is the consequence of socio-ecological, biological *and* cultural evolutionary processes and much remains to be discovered about each of these processes and their interaction.

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