Language's place in nature

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Human language has enabled our species to exchange information and to formulate ideas; understanding how human linguistic faculties evolved is one of the great challenges in evolutionary theory. Studies of the evolution of human language can be broadly separated into two types of approaches: those that consider the (e.g. phylogenetic) relationships between existing languages and their common ancestors; and those that try to understand the evolution of the human language capacity itself. For the latter case, Martin Nowak and co-workers have now shown that evolutionary game theory provides a framework in which the evolution of linguistic elements, such as word formation and syntax, can be investigated. These recent studies show that natural selection will favour the evolution of such 'human' linguistic elements from simple animal communication if they enable more reliable exchange of relevant, that is fitness-enhancing, information.

All human populations communicate by means of language and all spoken languages appear to show similar complexity[1]. From this and the close connection between language and other cognitive facilities, it follows that the human language faculty must be seen as a part of human biology and not solely part of human culture[1–3]. Shortly after Darwin's *Origin of Species* was first published in 1859, the realm of evolutionary theory was extended to include human language. Charles Darwin and T.H. Huxley argued that pedigrees of languages would resemble human pedigrees, and, in 1865, F.W. Farrar published the perhaps first treatise on the evolution of language[4]. Although phylogenetic studies of languages are therefore surprisingly old, the stringent application of a framework that includes generation of diversity (mutation) and natural selection to the evolution of language is relatively recent. Because language is inseparable from other cognitive facilities, its evolution poses a unique problem.

Simple animal languages – for example, the dance of the bees, whale song, and signalling among birds – have received great attention from biologists, but the unique characteristics of human language, such as symbolic reference and syntactic structure, have so far been the domain of philosophers, linguists, anthropologists and psychologists – until recently at least[2,3,5], when biologists, including Martin Nowak and co-workers, began to consider aspects of the evolution of language, including evolution of lexical structures[6], syntax[7] and, most recently, universal grammar[8]. Their approach is solidly set in the framework of evolutionary game theory[9]: individuals (the players) that fare best in one generation will produce relatively more offspring in the next. The level of success, or lack thereof, is embodied in the relative fitness of an individual and Nowak *et al.* connect fitness to linguistic capacity[6–8].

All nonhuman animal languages are probably iconic or indexical, meaning that there is a one-to-one relationship between objects and lexical elements (words or sounds)[10]. Human language is the only language that is symbolic, allowing us to refer to absent and even abstract objects and situations. Grammar expedites this ability by providing the structure that underlies meaningful sentences. The way in which the correct grammar is learned by children is one of the classic conundrums of linguistics: from only a finite number of examples picked up from parents, children can reliably derive the rules of the grammar of their speech community. Their attempt to cope with irregular verbs (e.g. 'goed' instead of 'went') also indicates that humans are able to extrapolate from a set of rules to related situations. This 'poverty of stimulus' during language acquisition has led Chomsky to postulate the existence of a universal grammar, an innate human ability to derive the structure of language[11] from a small number of sample sentences. Universal grammar acts as a restriction of the grammatical search space and allows us to parse and create an infinite number of grammatically correct sentences; equally, it enables children to determine the correct grammar during language acquisition.

Playing the language game

Nowak and his co-workers base their approach[6–8] on the canonical quasi-species model[12]. The ability of an individual adopting language L to communicate with every other individual in that population determines the payoff, which is equivalent to the fitness[9] – this is the principal underlying assumption[5–8]. The number of individuals who adopt language L in the next generation is proportional to the fitness conferred by L, but, because acquisition is error-prone, some individuals will end up speaking a different language L'. Applying this methodology, Nowak and Krakauer[6] showed how the combination of sounds into meaningful words can evolve among communicators if a large number of messages needs to be conveyed, but would result in increasing ambiguity owing to constraints on vocalization and acoustic perception when adding new sounds. Stringing a limited number of sounds and/or letters together opens up the possibility of constructing an effectively infinite number of words.

Nowak and Krakauer also take the next step and investigate under what conditions a simple syntax or grammar can evolve that regulates the combination of words into sentences[6]. Nonsyntactic or iconic language has different words for a lion or a zebra sleeping and running; syntactic language, however, has nouns

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(lion, zebra) and verbs (run, sleep) and a set of rules that regulates communication. In the case of four events (lion runs, lion sleeps, zebra runs and zebra sleeps) grammar offers no advantage, because two nouns and two verbs are needed and it has the additional cost that the grammatical role of each word also has to be remembered. However, if the number of events exceeds the sum of nouns and verbs, then grammar can evolve.

This work was extended by Nowak *et al.*[7] who consider the average number, R, of communicators who learn a word from a speaker. In nonsyntactic language, $R > 1$ must hold for every symbol relating to an event (e.g. lion sleeps) for a word to persist in a population; in syntactic language, the basic reproductive ratios, R, of verbs and nouns must both exceed unity to allow persistence. Only when the number of relevant events exceeds the syntactic threshold will the fitness of syntactic communicators be higher than the fitness of nonsyntactic communicators; this threshold depends on the versatility of linguistic components (every animal can sleep, but few fly; therefore 'sleep' is more versatile than is 'fly') and the cost of memorizing the grammatical functions of words[7].

Evolving universal grammar

In a recent paper, Nowak *et al.*[8] consider how the evolution of universal grammar can be understood in a game-theoretical approach. They investigate the population dynamics of individual grammars (G) and the evolutionary demands on a universal grammar (U). Each grammar, G, is a set of rules that determines the structure of sentences; a universal grammar, U, is the search space over a set of n possible grammars. Pairwise relationships, a_{ij}, between these grammars are collected in the matrix $\boldsymbol{A} = (a_{ij})$ and the average probability of mutual understanding between two grammars G_i and G_j is given by $F(G_i,G_j) = (a_{ij} + a_{ji})/2$. Entries in $\boldsymbol{A}$ have values between zero (in the case of mutual incomprehensibility) and one (perfect mutual understanding), and grammars that are similar to the majority of present grammars are associated with higher fitness values and therefore more offspring. If the process of language acquisition from the parents is error-prone, a set of quasi-species equations can be derived that describes the population dynamics of grammatical systems.

In such a framework, Nowak *et al.* then examine when universal grammar, which provides the foundation for language acquisition, is able to induce a coherent grammatical structure among a population. In other words: given that a set of possible grammars G exists, when does U suffice to direct children effectively to finding the correct grammar? Two extreme types of learning behaviour are then investigated in some detail, from which boundaries for the maximum size of grammatical search spaces that are consistent with grammatical coherence can be derived. The coherence threshold relates the properties of the universal grammar, such as the size of the search space, to the performance of the learning process. In the evolution of universal grammars, those that have an effective learning mechanism combined with a sufficiently large search space (but smaller than the coherence threshold) will be favoured. The limited period over which we learn language might therefore be a result of natural selection acting on universal grammar[3,8].

Language and nature

These studies reveal a common theme underlying the evolution of language: the combinatorial structure of language that perhaps reflects a combinatorial structure in nature[6–8]. Starting from a limited number of constituents (sounds, words and sentences), Nowak *et al.* demonstrate that the evolution of composites (such as words and sentences) and rules is favoured when the number of relevant events that needs to be referred to exceeds a threshold. Syntactic communicators only have to remember components of events and can combine them into new forms for which the nonsyntactic communicator lacks words. The evolution of current human grammars has afforded us with the ability to express infinitely many sentences, including those which are not yet or not at all relevant.

In the absence of 'linguistic fossils'[10], which could guide us, these mathematical models provide a test for our intuition of how language could have evolved. The application of evolutionary game theory should prove to be a useful tool for linguists interested in the evolution of language. So should the application of ecological methods[1,13]: the dynamics of language creation, diversification and extinction complement human genetic data and offer an additional perspective into human history[1,14]. Real data is available and ought to be considered in theoretical studies[1,13–16]. But, perhaps most fundamentally, the combination of learning theory[17] and evolutionary game theory offers a new approach towards the understanding of the relationship between behaviour and cognitive abilities[8–11,17].

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