The evolution of language

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Communicated by Robert May, University of Oxford, Oxford, United Kingdom, May 7, 1999 (received for review March 12, 1999)

ABSTRACT The emergence of language was a defining moment in the evolution of modern humans. It was an innovation that changed radically the character of human society. Here, we provide an approach to language evolution based on evolutionary game theory. We explore the ways in which protolanguages can evolve in a nonlinguistic society and how specific signals can become associated with specific objects. We assume that early in the evolution of language, errors in signaling and perception would be common. We model the probability of misunderstanding a signal and show that this limits the number of objects that can be described by a protolanguage. This “error limit” is not overcome by employing more sounds but by combining a small set of more easily distinguishable sounds into words. The process of “word formation” enables a language to encode an essentially unlimited number of objects. Next, we analyze how words can be combined into sentences and specify the conditions for the evolution of very simple grammatical rules. We argue that grammar originated as a simplified rule system that evolved by natural selection to reduce mistakes in communication. Our theory provides a systematic approach for thinking about the origin and evolution of human language.

Language remains in the minds of many philosophers, linguists, and biologists a quintessentially human trait (1–3). Attempts to shed light on the evolution of human language have come from many areas including studies of primate social behavior (4–6), the diversity of existing human languages (7, 8), the development of language in children (9–11), and the genetic and anatomical correlates of language competence (12–16), as well as theoretical studies of cultural evolution (17–21) and of learning and lexicon formation (22). Studies of bees, birds, and mammals have shown that complex communication can evolve without the need for a human grammar or for large vocabularies of symbols (23, 24). All human languages are thought to possess the same general structure and permit an almost limitless production of information for communication (25). This limitlessness has been described as “making infinite use of finite means” (45). The lack of obvious formal similarities between human language and animal communication has led some to propose that human language is not a product of evolution but a side-effect of a large and complex brain evolved for nonlinguistic purposes (1, 26). Others suggest that language represents a mix of organic and cultural factors and, as such, can only be understood fully by investigating its cultural history (16, 27). One problem in the study of language evolution has been the tendency to identify contemporary features of human language and suggest scenarios in which these would be selectively advantageous. This approach ignores the fact that if language has evolved, it must have done so from a relatively simple precursor (28, 29). We are therefore required to provide an explanation that proposes an advantage for a very simple language in a population that is prelinguistic (30–32). This work can be seen as part of a recent program to understand language evolution based on mathematical and computational modeling (33–37).

The Evolution of Signal–Object Associations. We assume that language evolved as a means of communicating information between individuals. In the basic “evolutionary language game,” we imagine a group of individuals (early hominids) that can produce a variety of sounds. Information shall be transferred about a number of “objects.” Suppose there are $m$ sounds and $n$ objects. The matrix $P$ contains the entries $p_{ij}$, denoting the probability that for a speaker object $i$ is associated with sound $j$. The matrix $Q$ contains the entries $q_{ij}$, which denote the probability that for a listener sound $j$ is associated with object $i$. $P$ is called “active matrix,” whereas $Q$ is called “passive matrix.” A similar formalism was used by Hurford (22).

Imagine two individuals, $A$ and $B$, that use slightly different languages $L$ (given by $P$ and $Q$) and $L'$ (given by $P'$ and $Q'$). For individual $A$, $p_{ij}$ denotes the probability of making sound $j$ when seeing object $i$, whereas $q_{ij}$ denotes the probability of inferring object $i$ when hearing sound $j$. For individual $B$, these probabilities are given by $p'_{ij}$ and $q'_{ij}$. Suppose $A$ sees object $i$ and signals, then $B$ will infer object $i$ with probability $\sum_j q_{ij}$. A measure of $A$’s ability to convey information to $B$ is given by summing this probability over all objects ($n$). The overall payoff for communication between $A$ and $B$ is taken as the average of $A$’s ability to convey information to $B$, and $B$’s ability to convey information to $A$. Thus,

$$F(L, L') = \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{m} (p_{ij} q'_{ij} + p'_{ij} q_{ij}).$$ [1]$$

In this equation, both $L$ and $L'$ are treated once as listener and once as speaker, leading to the intrinsic symmetry of the language game: $F(L, L') = F(L', L)$. Language $L$ obtains from $L'$ the same payoff as $L'$ obtains from $L$. If two individuals use the same language, $L$, the payoff is $F(L, L) = \sum_{i=1}^{n} \sum_{j=1}^{m} p_{ij} q_{ij}$.

Hence, we assume that both speaker and listener receive a reward for mutual understanding. If for example only the listener receives a benefit, then the evolution of language requires cooperation.

In each round of the game, every individual communicates with every other individual, and the accumulated payoffs are summed up. The total payoff for each player represents the ability of this player to communicate information with other individuals of the community. Following the central assumption of evolutionary game theory (38), the payoff from the game is interpreted as fitness: individuals with a higher payoff have a higher survival chance and leave more offspring who learn the language of their parents by sampling their responses to individual objects.

Fig. 1 shows a computer simulation of a group of 100 individuals. Initially, all individuals have different random entries in both active and passive matrices. After some rounds, specific sounds begin to associate with specific objects. Even-

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the similarity between sounds, \( i \) and \( j \), is given by

\[
S_{ij} = \frac{1}{5} \sum_{k=1}^{m} \frac{u_{jk} q_{ik}}{1 + d_{kj}},
\]

where \( u_{jk} \) is the similarity between sounds \( j \) and \( k \), and \( q_{ik} \) is the similarity between objects \( i \) and \( k \). The probability of interpreting sound \( i \) as sound \( j \) by \( u_{ij} \). The payoff for \( L \) communicating with \( L' \) is now given by

\[
F(L; L') = \frac{1}{2} \sum_{i=1}^{n} \sum_{j=1}^{n} p_{ij} \left( \sum_{k=1}^{m} u_{jk} q_{ik} \right) + p'_{ij} \left( \sum_{k=1}^{m} u_{jk} q_{ik} \right).
\]

The probabilities, \( u_{ij} \), can be expressed in terms of similarities between sounds. We denote the similarity between sounds \( i \) and \( j \) by \( s_{ij} \). We obtain \( u_{ij} = s_{ij} / \sum_{k=1}^{m} s_{ik} \). As a simple example, we assume the similarity between two different sounds is constant and given by \( s_{ij} = s \), whereas \( s_{ij} = 0 \). In this case, the probability of correct understanding is \( u_{ij} = 1 / (1 + (m - 1)e) \). The maximum payoff for a language with \( m \) sounds (when communicating with another individual who is using the same language) is given by \( F(m) = \sum_{i=1}^{n} \mu_{i} q_{i} \), and therefore \( F(m) = m / (1 + (m - 1)e) \). The fitness, \( F \), is an increasing function of \( m \) converging to a maximum value of \( 1/e \) for large values of \( m \). Without error, we would have \( F(m) = m \). Thus, in the presence of error, the maximum capacity of information transfer is limited and equivalent to what could be achieved by \( 1/e \) sounds without error.

Next, we assume that objects can have different values, \( a_{i} \). (For example when a leopard represents a higher risk than a python, the word ”leopard” may be more valuable than ”python.”) We have \( F(m) = [1 + (m - 1)e]^{-1} \sum_{i=1}^{m} a_{i} \), where the objects are ranked according to their value, \( a_{1} > a_{2} > \ldots \). This fitness function can adopt a maximum value for a certain number \( m \) and decline if the value of \( m \) becomes too big. In this case, natural selection will limit the number of sounds used in the language and consequently also limit the number of objects described. Fig. 2 shows a computer simulation of this extended evolutionary language game. The final outcome is a language that uses only a subset of all available sounds to describe the most valuable objects.

The principal result of the extended model, including misunderstanding, is that of a ”linguistic error limit”: the number of distinguishable sounds in a protolanguage, and therefore the number of objects that can be accurately described by this language, is limited. The simulation shows how a protolanguage can emerge in an originally prelinguistic society.

For \( m = n \), the evolutionary optimum is reached if each object is associated with one specific sound and vice versa. Evolution does not always lead to the optimum solution, but certain suboptimum solutions, in which the same signal is used for two (or more) objects, can be evolutionarily stable. Interestingly, errors during language acquisition increase the likelihood of reaching the optimum solution (M.A.N., J. Plotkin, and D.C.K., unpublished work).

A Linguistic Error Limit. Below, we discuss two essential extensions of the basic model. First, we include the possibility of errors in perception: early in the evolution of communication, signals are likely to have been noisy and can therefore be mistaken for each other. We denote the probability of interpreting sound \( i \) as sound \( j \) by \( u_{ij} \). The payoff for \( L \) communicating with \( L' \) is now given by

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language, is limited. Adding new sounds increases the number of objects that can be described but at the cost of an increased probability of making mistakes; the overall ability to transfer information does not improve. This obstacle in the evolution of language is interesting parallels with the error-threshold concept of molecular evolution (40). The origin of life has been described as a passage from limited to unlimited hereditary replicators, whereas the origin of language as a transition from limited to unlimited semantic representation (41).

Word Formation. The way to overcome the error limit is by combining sounds into words. Words are strings of sounds. As before, we define the fitness of a language as the total amount of successful information transfer. The maximum fitness is obtained by summing over all probabilities of correct understanding of words. For a language with \( m \) sounds (phonemes) and a word-length \( l \), the maximum payoff is given by \( F(m, l) = m^l(1 + (m - 1)e)^{-1} \), which converges to \( 1/e^l \) for large values of \( m \), thus allowing a much greater potential for communication. This equation assumes that understanding of a word is based on the correct understanding of each individual sound.

More realistically, we may assume that correct understanding of a word is based (to some extent) on matching the perceived string of phonemes to known words of the language. Consider a language with \( N \) words, \( w_i \), which are strings of phonemes: \( w_i = (x_{i1}, x_{i2}, \ldots, x_{in}) \). For \( m \) different phonemes there are \( m^l \) possible words. A particular language will contain a subset of these words, \( N \leq m^l \). We define the similarity between two words as the product of the similarities between individual phonemes in corresponding positions. The similarity between word \( w_i \) and \( w_j \) is \( S_{ij} = \prod_{k=1}^{l} s_{ik} \), where \( s_{ik} \) denotes the similarity between the \( k \)-th phonemes of words \( w_i \) and \( w_j \). The probability of correctly understanding word \( w_i \) is \( P_i = 1/S_{i} \), where \( P_i = 1 \) if word \( w_i \) is part of the language, and \( P_i = \sigma \) if word \( w_i \) is not part of the language. The parameter \( \sigma \) is a number between 0 and 1 and specifies the degree to which word recognition is based on correct understanding of every phoneme versus understanding of the whole word. If \( \sigma = 0 \), then each word is only compared with every other word that is a part of the language; correct understanding of a word consists in comparing the perceived word with all other words that are part of the lexicon. An implicit assumption here is that individuals have perfect knowledge of the whole lexicon. If \( \sigma = 1 \), then every word is compared with every other possible word that can be formed by combining the phonemes. Correct understanding of a word requires a correct identification of each individual phoneme. The listener does not need to have a list of the lexicon. A value of \( \sigma \) between 0 and 1 blends these two possibilities. In this case, recognition of a word is to some extent based on identification of each individual phoneme and to some extent on identification of the word selected from the list of all words that are contained in the language. The maximum payoff for such a language is given by \( F = \sum_{i=1}^{N} P_i \) (Fig. 3).

Combining sounds into words leads to an essentially unlimited potential for different words. This step in language evolution can be seen as a transition from an analogue to a digital system. The repertoire is not increased by adding more sounds, but by combining a set of easily distinguishable sounds into words. In all existing human languages, only a small subset of the sounds producible by the vocal apparatus are employed to generate a large number of words. These words are then used to construct an unlimited number of sentences. The crucial difference between word and sentence formation is that the first consists essentially of memorizing all (relevant) words of a language, whereas the second is based on grammatical rules. We do not memorize a list of all possible sentences.

The Evolution of Basic Grammatical Rules. The next step in language evolution is the emergence of a basic syntax or grammar. Recall that by combining sounds into words, the protolanguage achieves an almost limitless potential for generating words with the power of describing a large number of objects or actions. Grammar emerges in the attempt to convey more information by combining these words into phrases or sentences. Simply naming an object will be less valuable than naming it and describing its action. (A leopard can be stalking, in which case it is a serious risk, or merely sleeping and thereby posing a lesser risk.) There is an obvious advantage to describing both objects and actions. Suppose there are \( n \) objects and \( h \) actions; there are \( nh \) possible combinations, but only a fraction, \( \phi \), of them may be relevant (for example: leopard runs; monkey runs; but not banana runs). A “nongrammatical” approach would be to conceive \( N = \phi nh \) different words for all combinations. A “grammatical” approach would be to have \( n \) words for objects (i.e., nouns) and \( h \) words for actions (i.e.,...
sent an important prerequisite for the evolution of language. (ii) In the presence of errors, only a very limited communication system describing a small number of objects can evolve by natural selection (Fig. 2). We believe that this error limit is where most animal communication came to a stop. The obvious means to overcome this limit would be to use a larger variety of sounds, but this approach leads into a cul-de-sac. A completely different approach is to restrict the system to a subset of all possible sounds and to combine them into “words” (Fig. 3). (iii) Finally, although grammar can be an advantage for small systems (Fig. 4), it may become necessary only if the language refers to many events. Thus, the need for grammar arises only if communication about many different events is required: a language must have more relevant sentences than words. It is likely that for most animal communication systems, the inequality (4) is not fulfilled.

We view this paper as a contribution toward formalizing the laws that governed the evolution of the primordial human languages. There are, of course, many important and more complex properties of human language that we have not considered here and that should ultimately be part of an evolutionary theory of language. We argue, however, that any such theory has to address the basic questions of signal–object association, word formation, and the emergence of a simple syntax or grammar, for these are the atomic units that make up the edifice of human language.

**APPENDIX**

Consider two objects, $O_1$ and $O_2$, that can cooccur with two actions, $A_1$ and $A_2$. Thus, there are four events, $O_1A_1, O_1A_2, O_2A_1$, and $O_2A_2$. The nongrammatical approach is to describe each event with a separate word, $W_1$, $W_2$, $W_3$, $W_4$, $N_1V_1$, $N_2V_1$, $N_1V_2$, and $N_2V_2$. The grammatical approach is to have separate words for objects, $N_1$ and $N_2$, and actions, $A_1$ and $A_2$. Consider mixed strategies that use the grammatical system with probability $x$. The active matrix, $P$, is given by

$$P = \begin{pmatrix}
1 - x & 0 & 0 & 0 & x & 0 & 0 & 0 \\
0 & 1 - x & 0 & 0 & 0 & x & 0 & 0 \\
0 & 0 & 1 - x & 0 & 0 & 0 & x & 0 \\
0 & 0 & 0 & 1 - x & 0 & 0 & 0 & x
\end{pmatrix}.$$ 

The rows correspond to the four events: $O_1A_1, O_2A_1, O_1A_2$, and $O_2A_2$. The columns correspond to the eight signals: $W_1$, $W_2$, $W_3$, $W_4$, $N_1V_1$, $N_2V_1$, $N_1V_2$, and $N_2V_2$. The pure strategies, $x = 0$ and $x = 1$, describe nongrammar and grammar, respectively. The passive matrix, $Q$, is obtained by replacing all nonzero entries in $P$ by 1 (and transforming this matrix). Note that mixed strategies, $0 < x < 1$, have eight nonzero entries, whereas pure strategies have only four nonzero entries in both $P$ and $Q$. Thus, mixed strategies have the possibility to understand both grammar and nongrammar, whereas the two pure strategies do not understand each other. Finally, we include the possibility of errors, either in implementation or comprehension. The error matrix is given by

$$D = \begin{pmatrix}
\eta_1 & \eta_1 \xi & \eta_1 \xi & \eta_1 \xi & 0 & 0 & 0 & 0 \\
\eta_1 \xi & \eta_1 & \eta_1 \xi & \eta_1 \xi & 0 & 0 & 0 & 0 \\
\eta_1 \xi & \eta_1 \xi & \eta_1 & \eta_1 \xi & 0 & 0 & 0 & 0 \\
\eta_1 \xi & \eta_1 \xi & \eta_1 \xi & \eta_1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \eta_2 & \eta_2 \xi & \eta_2 \xi & \eta_2 \xi & 0 \\
0 & 0 & 0 & \eta_2 \xi & \eta_2 & \eta_2 \xi & \eta_2 \xi & \eta_2 \\
0 & 0 & 0 & \eta_2 \xi & \eta_2 \xi & \eta_2 & \eta_2 \xi & 0 \\
0 & 0 & 0 & \eta_2 \xi & \eta_2 \xi & \eta_2 \xi & \eta_2 & \eta_2
\end{pmatrix}.$$
Here, $\xi$ is the similarity between words or the fraction of times a word is mistaken or misimplemented for another. We used $\eta_1 = 1/(1 + 3\xi)$ and $\eta_2 = 1/(1 + \xi)^2$. We assume that the nongrammatical one-word sentences are not confused with the grammatical two-word sentences. The error matrix specifies the crucial difference between grammar and nongrammar.

The system can be completely understood in analytic terms. The payoff for language $x$ communicating with language $y$ is given (with Eq. 2) by: $F(x, y) = (2 - x - y)f_1 + (x + y)f_2$, where $f_1 = 4/(1 + 3\xi)$ and $f_2 = 4/(1 + \xi)^2$. These equations hold for $x$ and $y$ between 0 and 1. Otherwise, we have $F(x, 0) = F(0, x) = (2 - x)f_1$ and $F(x, 1) = F(1, x) = (1 + x)f_2$. The payoffs for nongrammar and grammar are, respectively, $F(0, 0) = 2f_1$ and $F(1, 1) = 2f_2$. Because $f_1 < f_2$ and $f_2 < 2f_1$, we have the following interesting dynamics: both $x = 0$ and $x = 1$ are evolutionarily stable strategies that cannot invade any other strategy, but every mixed strategy, $x$, is invaded and replaced by every other strategy, $y$, if $x < y < 1$. Thus, the adaptive dynamics flow toward grammar. Alternatively, one can also assume that the pure strategies can understand each other, that is, the passive matrices of all strategies are the same; in this case, grammar ($x = 1$) is the only evolutionarily stable strategy and can beat every other strategy.
