Cognition 141 (2015) 87–102

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Compression and communication in the cultural evolution of linguistic structure

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ARTICLE INFO

Article history:
Received 7 February 2014
Revised 9 February 2015
Accepted 29 March 2015
Available online 14 May 2015

Keywords:
Cultural transmission
Language evolution
Iterated learning

ABSTRACT

Language exhibits striking systematic structure. Words are composed of combinations of reusable sounds, and those words in turn are combined to form complex sentences. These properties make language unique among natural communication systems and enable our species to convey an open-ended set of messages. We provide a cultural evolutionary account of the origins of this structure. We show, using simulations of rational learners and laboratory experiments, that structure arises from a trade-off between pressures for compressibility (imposed during learning) and expressivity (imposed during communication). We further demonstrate that the relative strength of these two pressures can be varied in different social contexts, leading to novel predictions about the emergence of structured behaviour in the wild.

1. Introduction

Language is unique among the communication systems of the natural world in exhibiting rich combinatorial and compositional structure. Our species can productively construct novel signals on the fly by recombining reusable meaningless elements (speech sounds) to form meaning-bearing units (morphemes and words) which are further recursively combined. Furthermore, the meanings of these complex utterances are derivable in a predictable way from the composition of their subparts. The precise way in which this *combinatorial* and *compositional* structure is realised differs from language to language and is part of the knowledge that each language learner must acquire. Nevertheless, the existence of this kind of systematicity is both universal to all languages – it is one of the fundamental *design features* of human language (Hockett, 1960) – and largely absent in the communication of other species.[1]

Understanding the origins of this structure is a central goal of cognitive science. A recent productive approach treats it as a consequence of cultural evolution (Christiansen & Chater, 2008). Languages, in common with many other human behaviours, persist through a repeated cycle of learning and production: individuals learn a language by observing the linguistic behaviour of their speech community, and the linguistic behaviour they subsequently produce shapes learning in others. Languages potentially change and evolve as a result of their

[1] Some aspects of this universality remain controversial. For example, the evidence for recursion in some languages is limited (Everett, 2005), although such languages remain open-ended in their productivity. Equally, some aspects of the suite of structural design features can be found in a limited way in other species (Collier, Bickel, van Schaik, Manser, & Townsend, 2014). Bird song is combinatorial (Berwick, Okanoya, Beckers, & Bolhuis, 2011), and bee dance is compositional in a limited sense (von Frisch, 1975). However, bee dance is not culturally transmitted like human language, and neither birds nor bees can exploit these properties to communicate an open-ended set of meanings.

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http://dx.doi.org/10.1016/j.cognition.2015.03.016
0010-0277/

transmission, adapting to the biases inherent in the processes of language learning and language use.

In this paper we present computational and experimental models of the processes of language transmission which show that structure (specifically, compositionality) arises from cultural evolution when language is under pressure to be both learnable and expressive: language learning by naïve individuals introduces a pressure for simplicity arising from a domain-independent bias for compressibility in learning, and a pressure for expressivity arises from language use in communication. Crucially, both must be in play: neither pressure alone leads reliably to structure. The structural design features of language are a solution to the problem of being compressible and expressive, a solution delivered by the process of cultural evolution.

1.1. Compressibility and expressivity in language design

The idea that key features of language arise from the trade-off between competing pressures has a long history. Competing motivations of speaker and hearer, for instance, have been a rich explanatory tool for cognitive scientists (e.g. Zipf, 1949; Ferrer i Cancho & Solé, 2003; Piantadosi, Tily, & Gibson, 2012) and linguists seeking explanations for typological universals of language (e.g. Givón, 1979; DuBois, 1987; Kirby, 1997; Jäger, 2007): for example, utterances in a language will tend to minimise effort for the speaker as long as distinctiveness for the hearer is not compromised (Zipf, 1949). This kind of observation can be couched in terms of *compression*, i.e., optimisation of a repertoire of signals such that the energetic cost of unambiguously conveying any meaning is minimised. This leads naturally to the inverse relationship between frequency and length of words identified by Zipf (1936); more generally, it has been suggested that such optimally-compressible signal inventories are a universal feature of natural communication systems across all species (Ferrer i Cancho et al., 2013).

The fact that language is compositional and combinatorial – that it has system-wide structure – also means that languages as whole systems are compressible, i.e., allow the formation of compressed representations. We commonly refer to these representations as *grammars*, which are concise descriptions of the generative system underlying a language. These are compressed to the degree that they are more concise than a simple listing of all the possible utterances in a language. Note that this notion of compressibility is orthogonal to the compressibility of signals themselves.[2] For example, regular morphological paradigms are highly systematic and therefore highly compressible, but this potentially comes at the cost of less efficient signals, since exploiting unsystematic irregulars might allow shorter forms (e.g., "ran" is shorter than "runned" but leads to a more complex, less compressible morphological paradigm).

For our purposes, it will be useful to consider the compressibility of three classes of languages: *holistic* languages, lacking any of the system-level structure (e.g. compositionality) that characterises natural languages; *structured* languages, which exhibit system-level structure (e.g. where aspects of meaning reliably co-occur with sub-parts of signals); and *degenerate* languages, in which every meaning is associated with a single, shared, maximally ambiguous signal.[3] Holistic languages are incompressible: the most concise encoding of a holistic language would be a dictionary that simply listed every signal paired with its meaning, i.e., the 'grammar' of this language would simply recapitulate the language in its entirety. Structured languages, in contrast, permit some compression: a grammar which captured the systematic regularities of such a language would be considerably shorter than a dictionary of all the signals in the language. Finally, degenerate languages are maximally compressible, since the entire language can be captured by a single rule stating the identity of the ambiguous signal. Following, e.g., Chater and Vitanyi (2003) and Kemp and Regier (2012), we assume that learners are naturally biased towards simpler, compressible languages, in line with the notion that a preference for simplicity is a fundamental cognitive principle: languages which permit the formation of compressed mental representations are easier to learn than those which do not.

As highlighted by Kemp and Regier (2012), the most compressible languages are not necessarily useful for communication: in particular, a degenerate language is highly compressible but not *expressive*, since it does not allow a speaker to discriminate an intended referent from possible alternative referents in a context. In contrast, less compressible languages (e.g. holistic or structured languages) are expressive to the extent that they provide a unique and unambiguous signal for every meaning. As demonstrated by Regier and colleagues for a range of cases (kinship categories, colour terms, numeral systems: Kemp & Regier, 2012; Xu & Regier, 2014; Regier, Kemp, & Kay, 2015), natural language lexicons exhibit a near-optimal trade-off between these two pressures, being among the most expressive and yet compressible of all possible systems. However, showing that language is near-optimal with respect to these two pressures does not provide an explanatory mechanism for this striking fit between the design and the function of language – the problem of linkage (Kirby, 1999) remains. In this paper we show that cultural evolution, the process by which languages persist through a cycle of learning and use, solves the problem of linkage, and (under some conditions) leads to the emergence of languages which are both highly compressible and highly expressive. Furthermore, we show that this same trade-off between compressibility and expressivity, which has been used to explain the structure of lexicalised concepts in various domains, also explains the existence of structural design features like compositionality.

[2] A consideration of the possible competition between system-wide compressibility and the compressibility of signals is an obvious extension to the model we present in this paper, as are a range of other possible additional pressures on a language being transmitted (e.g., the structure of the world:Perfors & Navarro, 2014).

[3] In reality, languages may not lie cleanly in one or other of these classes. They may exhibit some partial compositionality, or they may be partially degenerate, for example.