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Signal dimensionality and the emergence of combinatorial structure

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ABSTRACT

In language, a small number of meaningless building blocks can be combined into an unlimited set of meaningful utterances. This is known as combinatorial structure. One hypothesis for the initial emergence of combinatorial structure in language is that recombining elements of signals solves the problem of overcrowding in a signal space. Another hypothesis is that iconicity may impede the emergence of combinatorial structure. However, how these two hypotheses relate to each other is not often discussed. In this paper, we explore how signal space dimensionality relates to both overcrowding in the signal space and iconicity. We use an artificial signalling experiment to test whether a signal space and a meaning space having similar topologies will generate an iconic system and whether, when the topologies differ, the emergence of combinatorially structured signals is facilitated. In our experiments, signals are created from participants' hand movements, which are measured using an infrared sensor. We found that participants take advantage of iconic signal-meaning mappings where possible. Further, we use trajectory predictability, measures of variance, and Hidden Markov Models to measure the use of structure within the signals produced and found that when topologies do not match, then there is more evidence of combinatorial structure. The results from these experiments are interpreted in the context of the differences between the emergence of combinatorial structure in different linguistic modalities (speech and sign).

1. Introduction

Language is structured on at least two levels (Hockett, 1960). On one level, a small number of meaningless building blocks (phonemes, or parts of syllables for instance) are combined into an unlimited set of utterances (words and morphemes). This is known as *combinatorial structure*. On the other level, meaningful building blocks (words and morphemes) are combined into larger meaningful utterances (phrases and sentences). This is known as *compositional structure*. In this paper, we focus on *combinatorial structure*.

This paper investigates the emergence of structure on the combinatorial level. Specifically, we are interested in how the topology of a signalling space affects the emergence of combinatorial structure. We hypothesise that combinatorial structure will be facilitated when a meaning space has more dimensions (ways meanings can be differentiated) than the signal space has dimensions (ways signals can be differentiated). We are also interested in the emergence of iconicity. Iconicity is the property of language that allows meanings to be predicted from their signals. We posit that iconicity can also be facilitated by the topology of a signalling space, but when a meaning space and a signal space have similar numbers of dimensions, rather than differing ones. Taken together, these hypotheses will have different predictions for systems with different topologies. We posit that it is dimensionality that is at the root of why different signal structures may be facilitated by different linguistic modalities in the real world (speech and sign).

Previously, linguists have hypothesised that combinatorial structure is present in all human languages, spoken and signed (Hockett, 1960). Further, evidence suggests that at least in the hominid lineage, the ability to use combinatorial structure is a uniquely human trait (Scott-Phillips & Blythe, 2013). It therefore needs to be explained why human language has combinatorial structure. Hockett (1960) proposed that combinatorial structure emerges when the number of meanings, and therefore signals, grows, while the signal space stays the same. If all signals are unique (i.e. they do not overlap in the signal space), this means that the signal space becomes more and more crowded and that signals become more easily confused. Combining elements from a smaller set of essentially holistic signals into a larger set of longer signals makes it possible to increase the number of signals beyond what

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can be achieved by purely holistic signals. Others have hypothesised that combinatorial structure may be adopted as an efficient way to transmit signals when more iconic strategies are not available. Goldin-Meadow and McNeill (1999) propose that there is a relation between the emergence of combinatorial structure and the (in)ability for mimetic (≈iconic) signal-meaning mappings; spoken language needs to rely on combinatorial structure exactly because it cannot express meanings mimetically (iconically). Roberts, Lewandowski, and Galantucci (2015) argue that early in a language's emergence, if iconicity is available, this will be adopted over methods that are more efficient for transmission (such as combinatorial structure). This happens because iconicity is high in referential efficiency, which is more useful when languages are in their infancy, i.e. when linguistic conventions have not yet been firmly established in the language community.

An important source of evidence regarding the emergence of combinatorial structure comes from newly emerging sign languages, such as Al-Sayyid Bedouin Sign Language and Central Taurus Sign Language (Caselli, Ergin, Jackendoff, & Cohen-Goldberg, 2014; Sandler, Aronoff, Meir, & Padden, 2011). While these languages do combine words into sentences, the words they use do not appear to be constructed from combinations of a limited set of meaningless building blocks (e.g. handshapes). In other words: these languages do have compositional structure, but lack combinatorial structure (at least in the initial stages of their emergence). Conversely, it is not easy to imagine a spoken language without a level of combinatorial structure. Nothing similar has ever been reported for emerging spoken languages such as contact languages, pidgins and creoles. Taken together, these observations suggest that different linguistic modalities cause differences in how structure emerges. Here we ask whether this is due to the availability of more iconicity in signed languages, or a constraint in the amount of distinctions possible in spoken languages.

2. Signal-space crowding and the emergence of combinatorial structure

Mathematical models (Nowak, Krakauer, & Dress, 1999) and computational models (Zuidema & de Boer, 2009) show that combinatorial signals can indeed theoretically emerge from holistic signals as a result of overcrowding in the signal space. However, in reality, the process of transition from holistic to combinatorial signals involves more factors. The evidence from emerging sign languages mentioned above shows that apparently fully functional languages can get by without combinatorial structure. These emerging languages slowly transition from a state without combinatorial structure to a state with combinatorial structure, without a marked increase in vocabulary size (Sandler et al., 2011). Apparently, the size and flexibility of the sign modality allows for a fully holistic language (on the word level) in an initial stage.

Backing up the naturalistic results, and in contrast with the models, experimental investigations have failed to show a strong correlation between the crowdedness of the signal space and the emergence of combinatorial structure. Verhoef, Kirby, and de Boer (2014) investigated the emergence of structure in sets of signals that were produced with slide whistles. Participants learnt a set of 12 whistled signals, and after a short period of training, their reproductions were recorded and used as learning input for the next "generation" of learners. This process of transmission from generation to generation was modelled in an iterated learning chain of 10 generations (Kirby, Cornish, & Smith, 2008). They found that even in this small set of signals, combinatorial structure emerged rapidly and in a much more systematic way than through gradual shifts as predicted by Nowak et al. (1999) and Zuidema and de Boer (2009). This indicates that processes of reanalysis and generalisation of structure play a more important role than just crowding of the signal space.

Roberts and Galantucci (2012) also investigated whether crowding in the signal space affected the emergence of combinatorial structure. Participants developed a set of signals to communicate about different animal silhouettes. The instrument used to generate graphical signals (designed by Galantucci, 2005) prevented them from either drawing the silhouettes, writing the name of the animals, or using other pre-existing symbols. They found that there was no strong relation between the number of animals communicated by participants and the level of structure found in signals.

Little and de Boer (2014) adapted Verhoef et al.'s (2014) slide whistle experiment to investigate how the size of the signal space would affect the emergence of structure. By limiting the movement of the slider of the slide whistle with a stopper, the possible signals were restricted to a third of the original pitch range. There was no significant difference in the emergence of structure between the reduced condition and the original condition, indicating that there was no strong effect of reducing the available signal space on the emergence of combinatorial structure. However, although the stopper prevented a certain portion of the pitch range from being used, it did not affect participants' ability to replicate essential features of the trajectories that could be produced without a stopper (for example, a rising pitch repeated). With the specific example of slide whistle signals, it is not the size of the signal space that would cause overcrowding, but the way in which signals in the space can be modified and varied. This idea is at the core of the present work and will be discussed more thoroughly below.

The current experimental evidence, then, seems to suggest that crowding in the signal space does not play such a primary role in the emergence of structure as predicted by Hockett. However, it is clear that the nature of the signal space must influence the emergence of combinatorial structure, otherwise, we could not explain that the sign languages can exist (at least briefly) without combinatorial structure, whereas spoken languages apparently cannot. One reason for this difference between modalities could be the extent to which a given signalling medium allows for the use of iconicity.

3. Iconicity and combinatorial structure

Hockett (1960) proposed that an arbitrary mapping between signal and meaning is a design feature of language. However, it is now well-accepted that there is a non-trivial amount of iconicity in human language. In spoken language, the most salient example is true onomatopoeia, the property that a word sounds like what it depicts (e.g. cuckoo, peewit, chiffchaff and certain other bird names), though this is quite rare. A more common form of iconicity is sound symbolism, which has now been demonstrated to be much more widespread than previously thought (Blasi, Wichmann, Hammarström, Stadler, & Christiansen, 2016). In sound symbolism, there is a less direct relation between the signal of a word and its meaning than in onomatopoeia. One example is that of the relation between the size of an object that a word indicates and the second formant of the vowel(s) it contains. Vowels with a high second formant tend to indicate smallness, as in words like "teeny" (Blasi et al., 2016). Another very different example is that words that start with sn- often have something to do with the nose: sneeze, sniff, snot, snout etc. (possibly because "sn" is onomatopoeic for the sound one makes when one has a cold). Here sn- almost functions like a morpheme, but its meaning is not sufficiently well-defined to be a true morpheme, and there are many words starting with sn that have nothing to do with the nose. In sign languages, there is a lot of visual iconic structure. For instance, the sign for tree in British Sign Language has the arm representing