Building a linguistic corpus from bee dance data

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Abstract

This paper discusses the problems and possibility of collecting bee dance data in a linguistic corpus and use linguistic instruments such as Zipf's law and entropy statistics to decide on the question whether the dance carries information of any kind. We describe this against the historical background of attempts to analyse nonhuman communication systems.

1 Introduction

The idea for this paper originated from a small paper that my daughter wrote for her bachelor study biology at the University of Wageningen, Netherlands. In this paper she discussed the views on the function of the so-called 'honey bee dance', more in particular the opposition of A. Wenner and others against the established theory first put forward by K. von Frisch that the shape and direction of a dance performed by a bee communicate to other bees the direction and distance of a food source (for a recent discussion of the established views see [2]).

As a computerlinguist I am not qualified to judge between the two views. Of course the 'bee dance' is often referred to in linguistic textbooks as an example of non-human communication, although not many linguists would go so far as to call it 'speech' or even 'language'.

However, I wondered if the techniques that are used in the field of corpus linguistics could be applied to the data that were collected by the entymologists in studying the bee dance. More in particular: if it could be demonstrated that the data in this corpus had certain features in common with linguistic corpora, this could indicate that the bees communicated something. Whether this 'something' concerned the location of a particular succulent brand of honey or just local hive gossip was (to me) a matter of no concern.

It rapidly became clear that there already existed ample literature on the subject of animal communication. Indeed the first attempt to statistically analyse bee dance data in the light of Shannon's information theory is from Haldane and Spurway in 1954 [3], who used the original data of von Frisch. Also, the theories of Zipf, notably Zipf's laws and the principle of last effort played an important role in the analysis of both human language and animal communication systems and even in
the study of manuscripts of unknown origin such as the Voynich manuscript\(^1\)\(^2\).

Often the debate on whether to call a certain communication system a ‘language’ is based on different definitions of ‘language’ or even philosophical leanings of the participants in the debate. This is even true in the Wenner attacks on the theory of von Frisch. Als Kak \(^6\) remarks: “It appears that the controversy is partly of a semantic nature. What does language mean? (...) Operationally this means that a language must be associated with a vocabulary of basic signs and sounds and a grammar that allows the signs or sounds to be combined into an unlimited number of statements.”(my emphasis, P.). This key notion of language having an unlimited number of elements returns in many papers (e.g. Ujhelyi \(^{15}\)) and is also true for the words in human language, as was mathematically proven by Kornai \(^7\). Ujhelyi also points out that the main difference between human and animal communication is that animal communication only allows for a limited set of messages, which are in general genetically fixed. However, the work of McCowan and her collaborators \(^{12}\) \(^{11}\) at least proves that enough variation exists in the communication of humans, dolphins and squirrel monkeys to observe Zipf’s law at work.

I started this research in the hope that enough data could be obtained from bee dance data to also observe Zipf’s law in action, but it turned out that this kind of data was not at all suitable for this kind of analysis.

Before data can be analysed it must be collected and stored in a suitable format. After the explanation of the principles of the honey dance, and the mathematical principles underlying the Zipfian laws and entropy, we will proceed to the problems of collecting the data and the analysis or translation to a format that is suitable for comparing the patterns with those of other (human) languages.
2 Animal communication

2.1 The bee dance

In 1947 it was observed by K. von Frisch [16] that there was a certain pattern to the movements that a bee makes on the comb (see figure 1). This pattern described approximately a figure 8, and on the traverse the bee waggles its abdomen as if for emphasis. Von Frisch observed that the angle of this traverse with the vertical indicated the direction of a honey source (more precise: the angle with the vertical correlated with the angle vis-a-vis the sun of the honey source). The duration of the dance, then, would indicate the distance.

Von Frisch and his followers also noted that other bees indeed seemed to observe the dance closely, and afterwards acted upon it, therefore they assumed that the dance had a communicative function and the bee dance theory was born. Because of the exciting nature of this discovery, many authors followed up and meticulously analyzed every possible aspect of the dance. We already mentioned the controversy generated by Wenner and Wells and the seminal work of Halldane and Spurway, but we could add dozens of scientists. Haldane and Spurway computed the correct amount of information in a message for non-discrete values such as direction, coming to approx. 5 cybernetic units (sic!) as to direction, 4 to 5 as to distance and 2 to 3 as to the number of workers needed. This totals to about 12 bits, equivalent to a human language of 4000 phrases (signifiants with corresponding signifiés), needing less than a hundred words by human or English standards.

Put differently, a code of all possible combinations of only three characters would cover the communication system of the honey bee dance. Towne and Gould [14] were among the many scientists who continued research in the spatial precision of this communication, giving much attention to the mathematics of communication and survival in circumstances where the scatter and quantity of the flowers varied. I was mildly amazed that I could not find the observation radius of the recruit in flight as a factor in the discussion.

A typical database for the processing of bee dance data might look like table 1. Here, every observation includes three estimates of the angle with the vertical direction of the central line of the ‘8’. From this angle and the height of the sun at that moment, the direction is computed. For that reason, the azimuth and time-of-day are also included in the table. The distance of the honey source is deducted from the duration of the dance; for this purpose the number of dances, the total time and the average time are noted in the table. Finally the data are translated to an X and Y value for subsequent plotting.

2.2 Other examples

It is tempting to consider the human communication system as a descendant of evolutionary earlier systems such as, indeed, the bee language, but of course this is not necessarily true. On the contrary, it seems that the communication of humans and higher mammals are based on sound and ambiguity [12]. The direct predecessor of human language should be found in territoriality messages and monogamous duetting [15]. As we will see below, it conforms to Zipfian laws and is firmly rooted in mathematics. Other animals communicate over a variety of channels, including sound, but also in movement, smell such as our honey bees. Haldane and Spurway put forward the notion that the honey bee dance is a highly ritualized intention movement.

\(^1\) The Voynich manuscript is a 16th century manuscript written in an unknown language and alphabet, but probably a hoax.
Table 1: A series of observations of the bee dance (courtesy M. Beekman).

Phylogenetically quite near the honey bee we find other communication, e.g. of ants. Reznikova[13] notes that the duration of the contact between scout and recruits is linearly correlated to the number of the traverse where food was found, and suggests that this is a indication that ants can count. In our opinion this resembles more a playback-like report than an indication of counting discrete units.

Just the observation of an act of the scouting bee and the subsequent reaction of the recruits is not enough to call the behaviour 'language' or 'communication', even if the reaction of the recruits makes sense in the context. To give an example: imagine a student entering his dormitory, smelling of beer and staggering around in circles before collapsing in a chair. His friends would observe this behaviour, come to the conclusion that at least one pub in the vicinity had opened its doors and walk out to see if they can find a place where music and light indicate the presence of an open pub. I would hesitate to call the action of the first student 'communication', and certainly not that particular communication that is called language. If different pubs would sell different beers, that caused different reactions in the 'scout student' so that his friends would not only recognize the fact that a pub had opened, but also which pub had opened, this still would not be called 'language', because language presupposes intentionality[6]. But substituting one problem of the meaning of 'language' by that of the meaning of 'intentionality' does not really help; what we need is a model where 'language' is defined and inbedded within the broader term of communication. As we will see below, thanks to the work of Ferrer and Solé, this is possible within the general framework of Zipf’s laws and the principle of least effort.

3 Least effort and mathematics

Zipf’s law is the observation that frequency of occurrence of some event $P$ as a function of the rank $i$, where the rank is determined by the above frequency of occurrence, is a power-law function $P_i \approx \frac{1}{i^a}$ with the exponent $a$ close to unity. This is true for interesting phenomena such as the frequencies of words in human languages, and for the size of the population of cities or the division of wealth. Later other researchers such as Wentian Li[10] have proven that Zipf’s law also holds for less interesting phenomena, such as randomly generated sequences of characters. Research like that of Cohen, Mantegna and Havlin[11] tried to find the differences between such 'random languages' (my terminology 2) and

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2The original term in the paper is 'artificial', but this causes problems with the terms used for computer languages and such like.
real languages. In the paper mentioned here, it was found that the value of the Zipf-derivates and especially the entropy of the word frequencies differed after all between the natural language texts and the artificial texts. Landini [8] also used Zipf's law when he looked for meaning in the Voynich manuscript. The consensus of all researchers is that the emergence of a Zipf relation between phenomena in a language-like construct does not prove that the item under consideration is a language, but that a real language almost certainly displays Zipf behaviour.

Ferrer and Solé [4] describe a double law for Zipf, i.e. the fact that the Zipfian curve is best described by two or even more functions. This suggests the existence of two 'regimes' in English, one general lexicon (5000 for BNC) and a specialized lexicon.

In a later paper [5], Ferrer and Solé formulate an attractive model that establishes Zip's law as a necessary trajectory in the relation between signifiant and signifié that lies at the basis of all communication. They use modelling of signals and objects in a simple binary matrix $a_{ij}$ of $n$ signals and $m$ objects (Saussure's signifiant and signifié). If a signal refers to an object, the corresponding cell is one, else it is a zero.

In figure 2 there are two examples of such signal-object matrices. The English speaker invests no effort when he wants to refer to the furniture, money institute or river bank; the word 'bank' covers all three. The listener however has to work very hard to extract the true meaning from context. The Dutch situation is the opposite: the speaker has to select one from three words, whereas the listener knows immediately what is referred to.

Ferrer and Solé vary the zero’s and ones in the matrix using an evolutionary algorithm. They then use the signal entropy to compute the minimum cost of the combined effort for both parties in such matrices:

$$\Omega(\lambda) = \lambda H_m(R\mid S) + (1 - \lambda) H_n(S)$$

where the parameter $\lambda$ weighs the contribution of each party. The following equation describes the mutual information for different values of $\lambda$:

$$I_n(S, R) = H_n(S) - H_n(S\mid R)$$

and $L$ describes the effective lexicon size in relation to the number of signals

$$L = \frac{\left\{ i \mid \mu_i > 0 \right\}}{n}$$

where $\mu_i = \sum_j a_{ij}$ in matrix $a$.

If the $I_n(S\mid R)$ and $L$ are plotted against $\lambda$ we get the graphs as in figure 3. It is immediately clear that there is a catastrophic transition at $\lambda \approx 0.41$ both for $I_n = (S\mid R)$ and $L$. In a second experiment, Ferrer and Solé plotted the normalized frequencies of the signals in the matrices against their rank for different values of $\lambda$. It was found that Zipf's law emerged in a small window near $\lambda = 0.41$. Together it means that Zipf’s law is not just a trivial outcome of a simple process, as would...
be suggested by the fact that it is also valid for random languages, but that it is an intrinsic part of the mathematic model of communication.

Considering the graphs of figure 3, we see that animal communication is placed in the upper right, where one-to-one signal-object maps are situated. As we have already seen, this is not the case for the dolphins and squirrel monkeys of McCowan and possibly other animal systems.

4 Conclusions

Corpus Linguistics is the discipline that studies language(groups) from big samples of that language(group), with a strong emphasis on quantitative phenomena and methods. Traditionally, of course, such language samples were restricted to human languages, but with progressive research in biology and animal communication systems, corpora of non-human language-like phenomena are a distinct possibility. The sounds emitted by dolphins and collected by e.g. McCowan [12, 11] clearly constitute a corpus, and so may other registrations of animal behaviour constitute corpora.

Our survey so far of animal communication centered on the mathematical qualities of the data, such as Zipfian distribution and entropy, and we sought to find these qualities in the bee dance data. Our main problem was and is therefore whether the bee dance language data can be analysed and stored in such a way that a Zipfian distribution (if present) can be detected. Partly this depends on the quantity of the data-types. If the assumptions of Haldane and Spurway are correct, and if there really are 12 bits of information contained in the bee dance, this may well be the case. The second and as yet unsolved problem is the articulation of the data, i.e. the splitting into meaningful 'words', and we hope to tackle this problem in the next few months.

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The diagram shows a plot of \( P(i) \) against the word rank \( i \). The graph displays a power law relationship, with the exponent approximately -1.92, indicating a Zipf's law distribution. The y-axis is on a logarithmic scale, ranging from \( 10^{-7} \) to \( 10^0 \), and the x-axis represents the word rank \( i \) on a logarithmic scale from \( 10^0 \) to \( 10^6 \).