The Law of Brevity in Macaque Vocal Communication is not an Artefact of Analysing Mean Call Durations*

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ABSTRACT

Words follow the law of brevity, i.e. more frequent words tend to be shorter. From a statistical point of view, this qualitative definition of the law states that word length and word frequency are negatively correlated. Here the recent finding of patterning consistent with the law of brevity in Formosan macaque vocal communication (Semple, Hsu, & Agoramoorthy, 2010) is revisited. It is shown that the negative correlation between mean duration and frequency of use in the vocalizations of Formosan macaques is not an artefact of the use of a mean duration for each call type instead of the customary ‘word’ length of studies of the law in human language. The key point demonstrated is that the total duration of calls of a particular type increases with the number of calls of that type. The finding of the law of brevity in the vocalizations of these macaques therefore defies a trivial explanation.

INTRODUCTION

In his pioneering work, Zipf observed that more frequent words tend to be shorter, and attributed this phenomenom to a general principle of least effort (Zipf, 1949). At the level of the dependency between length and frequency,
this principle can be considered an informal precursor of a compression principle, i.e. assigning smaller lengths to more frequently used words, that has been studied with mathematical rigor in information theory (Cover & Thomas, 2006). Indeed, the law of brevity is a requirement for optimal coding. Consider that the mean code length of a vocabulary of \( n \) words is (Cover & Thomas, 2006)

\[
E_{CL} = \sum_{i=1}^{n} p_i d_i, \tag{1}
\]

where \( p_i \) is probability of use of the \( i \)th most probable word and \( d_i \) is its length. It has been proven that the minimization of \( E_{CL} \) needs that (Ferrer-i-Cancho et al., in press)

\[
d_1 \leq d_2 \leq d_3 \leq \ldots d_n, \tag{2}
\]

which constitutes the core of our notion of the law of brevity. As \( p_1 \geq p_2 \geq p_3 \geq \ldots \geq p_n \) by definition, Equation (2) means that the length of a word cannot increase as its probability increases. In the absence of ties in probabilities or lengths, Equation (2) simply means that word length must be a strictly monotonically decreasing function of word probability under optimal coding (Ferrer-i-Cancho et al., in press). From such ideal dependency one expects a perfect negative correlation between word frequency and word length in a text. Accordingly, we define a generalized law of brevity as a tendency of the size or length of a unit to decrease as its frequency increases (Ferrer-i-Cancho & Hernández-Fernández, 2013), which is justified from an information theory perspective, and has the advantage of being neutral with regard to the functional dependency between \( p_i \) and \( d_i \).

The law of brevity has been reported for many languages (e.g. Zipf, 1949; Straus et al., 2007; Jayaram & Vidya, 2009). Recently, parallels of the law of brevity have been investigated in the behaviour of other species. A negative correlation between frequency and size (in behavioural units) of surface behavioural patterns has been reported for dolphins (Ferrer-i-Cancho & Lusseau, 2009), and a negative correlation has been found between frequency of use and duration of vocalizations of Formosan macaques (Semple et al., 2010). However, support for this law has not been found in analyses of the vocalizations of two New World primates, common marmosets and golden-backed uakaris (Bezerra et al. 2011). The universality of the law in the behaviour of other species is a matter of current discussion (Ferrer-i-Cancho & Hernández-Fernández, 2013; Bezerra et al., 2011).
In the study by Semple et al. (2010), the law of brevity was studied by means of a correlation analysis of the relationship between mean call duration and frequency of use (the latter being quantified as the number of calls of each type recorded). It has been argued that a negative correlation between two variables, X and another Z = Y/X (e.g. Z is the mean duration, X is the frequency of use and Y is the total duration) is an unavoidable consequence of the definition of Z as quotient involving X because then Z \sim 1/X (Solé, 2010). The argument is mathematically flawed, because Z \sim 1/X requires that X and Y are uncorrelated (Hernández-Fernández, Baixeries, Forns, & Ferrer-i-Cancho, 2011; Li, 2012). However, the important message for quantitative linguistics researchers is that a negative correlation between Z = Y/X and X could potentially be a trivial consequence of the independence between X and Y.

With respect to the data analyzed by Semple et al. (2010), let \( D \) be the total duration of all calls of a particular type (\( D \) is the sum of all the durations of the calls of a given type). The main objective of this article is to demonstrate that the negative correlation between frequency of use \( f \) and mean call duration \( d = D/f \) in Formosan macaques is not a straightforward consequence of the definition of \( d \) as a mean. More formally, we want to reject \( d = c/f \) (where \( c \) is a constant) by showing that \( D \) and \( f \) are correlated. This potential problem in the study of the law of brevity by Semple et al. (2010) does not concern the analysis performed by Ferrer-i-Cancho and Lusseau (2009), where the correlation analysis focused on the dependency between size of a behavioural pattern in elementary behavioural units (not a mean size) and frequency. For some quantitative linguistics researchers, another important problem, namely the fit of a particular function, e.g. \( d \sim f^b \) where \( b \) is a constant, would need to be addressed as is customary in quantitative linguistics research (e.g. Jayaram & Vidya, 2009). It should be noted firstly that we wish to stay neutral on the issue of the most appropriate function for human language or animal behaviour in general in the present article. For instance, standard information theory suggests that \( d \sim \log f \) could be a more appropriate function based upon optimal coding considerations (Cover & Thomas, 2006) but as far as we know, this alternative functional dependency has not been considered. Secondly, it is our aim here to contribute to defining a statistically rigorous methodology for studying via correlation analysis the law of brevity as a tendency for more frequent elements to be shorter.
METHODS

The same dataset used in Semple et al. (2010) was re-analysed here. This dataset was originally extracted from Hsu, Chen, and Agormaoorthy (2005), who described the vocal repertoire of wild Formosan macaques, based on 375 hours of field recordings from a well habituated long-term study population in Taiwan. Recordings were made from animals of all age classes: infant (<14 months), juvenile (14 months to 3 years), subadult (male: 4 to 5 years; female: 4 years) and adult (male: 6 years and above; females: 5 years and above). From these recordings, the vocal repertoire was classified by the authors on the basis of calls’ acoustic structure, as determined from spectrographic analyses. Thirty five distinct call types were described, though not all of these were given by animals of all age classes. For each call type in the repertoire, Hsu et al. (2005) reported the number of calls of each call type that were analysed in the study, which provides our value of \( f \); this definition of \( f \) is therefore analogous to that of the frequency of a word in a text. In addition they reported the mean duration (measured in milliseconds from spectrograms) of all exemplars of the call type, which provides our value for \( d \). Full details of the call types, their frequency (\( f \)), mean duration (\( d \)) and total duration (\( D \)) are given in Table 1.

Pearson’s and Spearman’s correlations, carried out in SPSS v. 17.0, were used to explore the relationship between \( D \) and \( f \). As in Semple et al. (2010), two levels of analysis were considered, i.e. the whole repertoire of vocalizations (\( n = 35 \) call types) and also just those vocalizations produced by all age classes (\( n = 17 \) call types), as some vocalization are not produced by all age groups (Hsu et al., 2005; see Table 1).

RESULTS

Figure 1 shows the dependency between \( D \) and \( f \) in the vocalizations of Formosan macaques at the two levels of analysis. \( D \) and \( f \) are highly correlated in the whole data set (Pearson’s correlation test: \( n = 35, r = 0.597, p < 0.001 \); Spearman’s correlation test: \( n = 35, r_s = 0.727, p < 0.001 \)), and in the reduced data set of calls given by all age classes (Pearson’s correlation test: \( n = 17, r = 0.671, p = 0.003 \); Spearman’s correlation test: \( n = 17, r_s = 0.758, p < 0.001 \)).
Table 1. Call types in the vocal repertoire of Formosan macaques as classified by Hsu et al. (2005), number of each call type recorded, and mean duration as measured from spectrograms (all data from Hsu et al., 2005), and the total duration calculated for this study.

| Call type                          | Given by all age classes? | Number recorded (f) | Mean duration in ms (d) | Total duration in ms (D = d × f) |
|------------------------------------|--------------------------|---------------------|------------------------|---------------------------------|
| Contact coo                        | Yes                      | 249                 | 260                    | 64740                           |
| Isolation coo                      | No                       | 73                  | 320                    | 23360                           |
| Long distance coo                  | No                       | 204                 | 430                    | 87720                           |
| Cohesion coo                       | No                       | 56                  | 330                    | 18480                           |
| Atonal greeting                    | No                       | 65                  | 100                    | 6500                            |
| Tonal greeting                     | No                       | 29                  | 280                    | 8120                            |
| Girney                             | Yes                      | 84                  | 220                    | 18480                           |
| Female copulation call             | No                       | 556                 | 60                     | 33360                           |
| Male copulation call               | No                       | 42                  | 140                    | 5880                            |
| Mounting grunt                     | No                       | 14                  | 280                    | 3920                            |
| Alarm call                         | Yes                      | 77                  | 210                    | 16170                           |
| Grunt                              | Yes                      | 430                 | 130                    | 55900                           |
| Threat rattle                      | No                       | 148                 | 160                    | 23680                           |
| Growl                              | No                       | 169                 | 190                    | 32110                           |
| Vibrato growl                      | Yes                      | 56                  | 130                    | 7280                            |
| Roar                               | No                       | 29                  | 210                    | 6090                            |
| Bark                               | No                       | 20                  | 210                    | 4200                            |
| Squeal                             | Yes                      | 103                 | 440                    | 45320                           |
| Noise scream                       | Yes                      | 129                 | 380                    | 49020                           |
| Undulated scream                   | Yes                      | 61                  | 600                    | 36600                           |
| Tonal scream                       | Yes                      | 20                  | 390                    | 7800                            |
| Tonal squeak                       | Yes                      | 151                 | 140                    | 21140                           |
| Compound squeak                    | Yes                      | 194                 | 160                    | 31040                           |
| Chuckle                            | Yes                      | 20                  | 220                    | 4400                            |
| Food yell                          | Yes                      | 13                  | 310                    | 4030                            |
| Oui                                | Yes                      | 12                  | 430                    | 5160                            |
| Harmonic arch                      | Yes                      | 7                   | 330                    | 2310                            |
| Tonal hack                         | Yes                      | 197                 | 30                     | 5910                            |
| Compound hack                      | Yes                      | 288                 | 90                     | 25920                           |
| Squawk                             | No                       | 96                  | 90                     | 8640                            |
| Cluck                              | No                       | 83                  | 40                     | 3320                            |
| Gecker                             | No                       | 116                 | 30                     | 3480                            |
| Whine                              | No                       | 24                  | 340                    | 8160                            |
| Weeping                            | No                       | 15                  | 70                     | 1050                            |
DISCUSSION

It has been shown that the law of brevity documented in the vocal communication of Formosan macaques defies a trivial explanation. *A priori*, a lack of correlation between $D$ and $f$ would have been surprising from a mathematical perspective. Notice that $D$ is defined as a sum of the durations of each vocalization type that is bounded below by a number greater than zero. To see this, introducing some notation is necessary. $\delta_i$ is defined as the duration of the $i$th occurrence of vocalization type of frequency $f_i$ and $\delta_{\text{min}}$ is defined as the minimum duration of a vocalization type. Then it follows that

![Figure 1. The dependency between total duration $D$ (in milliseconds) and number of calls recorded $f$, for each call type in the Formosan macaque vocal repertoire. Each point represents one call type. Black circles indicate calls given by members of all four age classes (adult, sub-adult, juvenile and infant); open circles are all other calls in the repertoire.](image-url)
Notice that $\delta_{\text{min}} > 0$ for a vocalization to be perceived. Equation (3) and the fact that $\delta_{\text{min}} > 0$ indicate that the knowledge about the exact value of $f$ constrains the set of possible values of $D$, i.e. there is a bias for the growth of $D$ as $f$ increases. The point is whether $\delta_{\text{min}}$ is large enough so that this bias really matters from a practical point of view. However, there might be other factors that determine dependency between $D$ and $f$ beyond Equation (3) and, as has been shown, a simple correlation test can help us to show that $D$ varies with regard to $f$.

The correlation results presented here indicate that the relationship between $D$ and $f$ is not purely linear, i.e. the relationship does not obey

$$D = af + b,$$  \hspace{1cm} (4) 

where $a$ and $b$ are constants. Notice that $b = 0$ is needed by the definition of $D$ (Equation (3)) so that $D = 0$ when $f = 0$. Thus, if $D$ followed Equation (4) then $d = D/f = a$, but $d$ and $f$ are significantly correlated (Semple et al., 2010). Here a very important problem for quantitative linguistics research and linguistic theory has been addressed: the statistical significance of statistical regularities of language. Contrary to what many researchers have claimed (e.g. Miller & Chomsky, 1963; Suzuki, Tyack, & Buck, 2005; Solé, 2010), various statistical patterns of language are hard to explain in terms of artefacts or simplistic random processes such as the famous random typing experiment (Miller & Chomsky, 1963); this applies not only to Zipf’s law of brevity but also Zipf’s law for word frequencies in both human language (Zipf, 1949) and dolphin whistles (McCowan, Hanser, & Doyle, 1999) and Menzerath-Altman’s law in genomes (Ferrer-i-Cancho & Forns, 2009). Statistical patterns of language are accompanied by other statistical properties that invalidate the trivial explanations proposed so far, e.g. dependency between total duration and frequency in Formosan macaques (shown here), dependencies between behavioural context and whistle type or dependencies in whistle type sequences in dolphins (Ferrer-i-Cancho & McCowan, 2009; Ferrer-i-Cancho & McCowan, 2012), and dependencies between chromosome number and total genome size (Hernández-Fernández et al., 2011).

Thus, it is clearly possible to distinguish between a simplistic explanation and a deeper explanation for a given statistical law of language. Not
looking at other properties of the system for further checking, and the lack of statistically rigorous methods to evaluate the fit of a trivial explanation to actual data (see Ferrer-i-Cancho & Elvevåg, 2010 for the case of Zipf’s law) has led, in our opinion, to wrong conclusions about the importance and the enormous potential of statistical patterns not only of human language, but also of vocal communication and other behaviour in non-human animals.

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