What's in a Name?

Luciano da Fontoura Costa
Institute of Physics at São Carlos. University of São Paulo,
São Carlos, SP, PO Box 369, 13560-970, phone +55 162 73 9858,
FAX +55 162 71 3616, Brazil, luciano@if.sc.usp.br
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Among the several findings deriving from the application of complex network formalism to the investigation of natural phenomena, the fact that linguistic constructions follow power laws presents special interest for its potential implications for psychology and brain science. By corresponding to one of the most essentially human manifestations, such language-related properties suggest that similar dynamics may also be inherent to the brain areas related to language and associative memory, and perhaps even consciousness. The present work reports a preliminary experimental investigation aimed at characterizing and modeling the flow of sequentially induced associations between words from the English language in terms of complex networks. The data is produced through a psychophysical experiment where a word is presented to the subject, who is requested to associate another word. Complex network and graph theory formalism and measurements are applied in order to characterize the experimental data. Several interesting results are identified, including the characterization of attraction basins, association asymmetries, context biasing, as well as a possible power-law underlying word associations, which could be explained by the appearance of strange loops along the hierarchical structure underlying word categories.

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'... that which we call a rose
By any other name would smell as sweet'
(Romeo and Juliet, ACT II)

I. INTRODUCTION

Despite its long tradition in mathematics and computer science, graph theory [1] has reached great popularity only recently through innovative research in the novel area which became known as complex networks [2]. By integrating theoretical principles, especially from statistical mechanics, with experimental and simulated data, recent investigations have shown that several important natural phenomena such as infectious diseases, ecological systems, protein folding, society and the internet, are characterized by scale-free and/or small-world behavior as far as their connectivity is concerned [2]. In particular, studies modeling linguistics in terms of complex networks have indicated that several aspects of human language, such as word proximity [3] and synonyms [2, 4], are at least partially characterized by power law behavior. As language corresponds to one of the most essential manifestations of the human brain, such findings can be taken as an indication that that complex structure, or at least its portions more closely related to language and associations, may also be intrinsically organized according to power laws and scale free behavior [4]. As the conscious and predominantly sequential flow of ideas in humans, James's *fringe of consciousness* [5], is closely related to the externalization of ideas through language, it is also possible that the scale free properties found in linguistic structures can also be an intrinsic property of consciousness.

The current work aims at investigating such possibilities through a psychophysical experiment involving human subjects to associate words from the English language. By understanding the presented words and associations as graph nodes and edges, respectively, it is possible to perform a quantitative analysis of the digraph connections by considering statistics (average and standard deviation) of network measurements such as the node degree, the average length, and the clustering coefficient.

The current article starts by describing the experimental approach and proceeds by analysing and discussing the respectively obtained data.

II. THE PSYCHOPHYSICAL EXPERIMENT

Along the last decades, psychophysics has establishing itself as an important area in psychology and neuroscience, providing invaluable means for quantifying perception. Provided the experiments are carefully devised and conducted, objective and relatively precise information can be obtained about the dynamics of perception. As in physics, the experiments have to be planned and performed while most factors likely to influence the investigated phenomena are kept constant. The popularization of personal computers has motivated the use of such machines for automating of psychophysical experiments, accounting for enhance repeatability and standardization.

In this work, a program was developed in SCILAB with the specific finality of investigating associations between words from the English language. Starting with the word 'sun', the subject is prompted to associate a subsequent word. No specific instructions are given regarding the type of association, except that special characters, plurals and verb conjugations are to be completely avoided.

There is no time limit for providing the new word, and the experiment can be broken into several sections, while collecting all the obtained data stored into files. An illustration of the first steps of the experiment is provided below, where the words supplied by the subject are represented in italic:

sun $\mapsto$ *desert*

desert $\mapsto$ *pyramid*

sun $\mapsto$ *gold*

pyramid $\mapsto$ *triangle*

pyramid $\mapsto$ *desert*

triangle$\mapsto$ *square*

...

Observe that the only predefined word is that presented first, all the others being subsequently defined by the subject. The presented and suggested words are henceforth referred to as *presented word* and *input word*, respectively. After each new word is input, its presence in the current list of words is verified, the word being included otherwise. Each word is treated as a graph node, and each pair of words is understood as a graph edge (presented word, input word). The therefore obtained direct graph (i.e. a digraph), with the frequency of each association treated as the weight of the respective edge, provides an interesting formal representation of the word associations. The whole sequence of presented and input words is recorded for further analysis. In order to guarantee the words to be presented in a uniform fashion, in the sense that each word is presented about as many times as the others, a density probability function $p(w)$ describing the number of times each word is presented is kept all times. The presented words are drawn from the complemented density function, i.e. $max\{p(w)\} - p(w)$, so that the less frequently presented words have higher likelihood to be chosen, leading to a levelling effect. The experiment terminates after a pre-defined number of words are presented, and the more recent input words, which have consequently been presented only a few times, are excluded from the data and respective network.

III. RESULTS

The above experiment was performed with a single subject along a whole week, totaling 305 different words from which 250 words were chosen (the remainder, more recently input words, were discarded for the sake of enhanced uniformity). A total of 1930 associations were recorded. The types of the input words is given in Table I, and Table II shows the frequency of types of associations. Figure 1 presents the population of each input word, and Figure 2 depicts the occurrence of new words along the presentation stages identified by i. Figure 3 gives the histogram of repeated associations. The average and standard deviation of the node degree k, clustering coefficient C and average length ℓ are presented in Table III. Figure 4 shows the histogram of equal words apart by specific lags along the presentation sequence. For instance, the ordinate value at lag 100 indicates the number of equal words distant of lag along the sequence. For the sake of enhanced uniformity, the sequence is considered up to its total length minus the maximum lag value. The loglog curves of the cumulative output and input node degree (recall that we are dealing with a digraph) are presented in Figures 5 and 6.

noun	161
adjective	62
verb	15
proper noun	6
other	6
TOTAL	250

TABLE I: Total of words by category.

	noun	adjective	verb	proper noun	other
noun	595	233	62	26	16
adjective	612	222	48	9	0
verb	37	20	7	1	1
proper noun	9	6	0	7	0
other	7	0	1	0	11

TABLE II: Number of associations by category.

IV. DISCUSSION

The several interesting trends and phenomena identified by analysis of the experimental data are characterized and briefly discussed in the following:

A. Attractor formation: As shown in Figure 2, the number of new words input by the user tended to diminish, reaching a near equilibrium state where very few new words are likely to be added. This suggests an attraction basin defined by the initial word.

B. Word density asymetry: As illustrated in Figure 1,

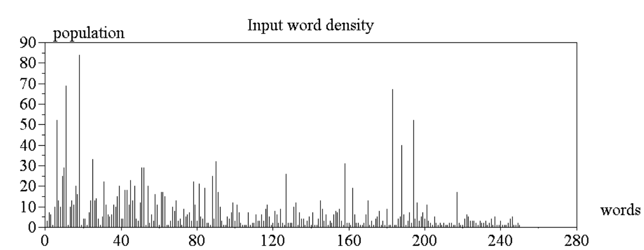

FIG. 1: The histogram of input words.

FIG. 2: The occurrence of new words along the presentation sequence, indexed by i.

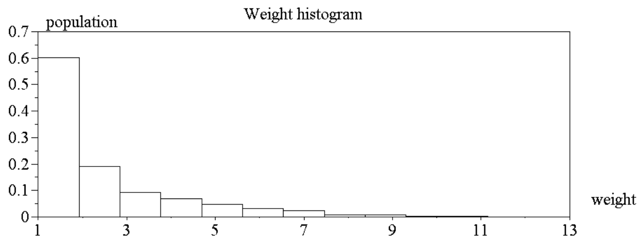

FIG. 3: Histogram of weights, i.e. the number of times specific associated pairs of words were produced during the experiment.

k	7.72 ± 10.93
C	0.075 ± 0.17
ℓ	3.32 ± 0.95

TABLE III: The node degree k, clustering coefficient C and average length ℓ for the network obtained in the psychophysical experiment.

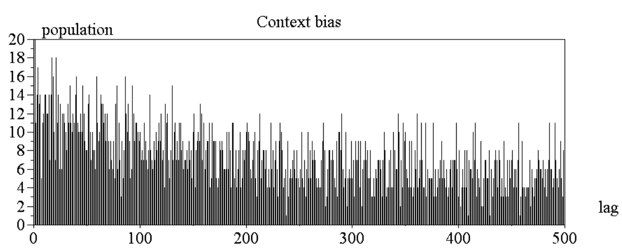

FIG. 4: The population of equal input words distant one another by specific lag values.

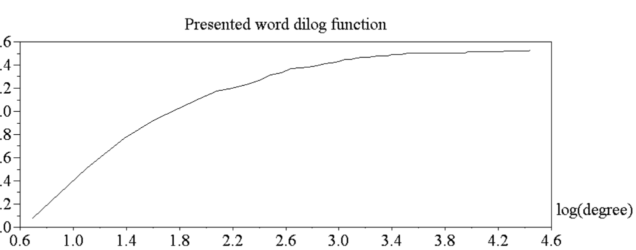

FIG. 5: Loglog representation of the cumulative output node degree.

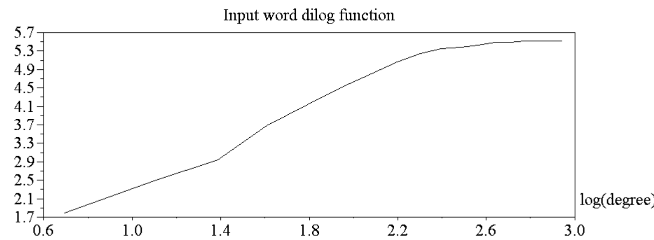

FIG. 6: Loglog representation of the cumulative input node degree. An approximatedly straight region is observed along the lefthand side of the graph.

the subject tended to enter some words more often than others. Particularly, there was a generalized preference for adjectives such as *good* and *long*, among others. This is hardly surprising, as adjectives are more immediately applicable to several words.

C. Edges asymmetry: As clearly seem from Table II, not every association is reciprocal, i.e. the existence of an edge (i, j) does not necessarily implies the presence of (j, i). Examples of such asymmetric cases obtained in the considered experiment include $(sky, blue)$ and $(blue, sky)$. To some extent, such asymmetries are observed in cases involving a more common word followed by a less common one, such as a general adjective and a specific noun. Another characteristic that has been verified from the experiment is the tendency of the associations to correspond to synonyms and antonyms, especially regarding pairs of adjectives.

D. Wide variation of node degree: The high standard deviation obtained for the node degree indicates that the number of associations induced by each presented word varies considerably. It is possible that more common words which usually appear connected to several other words, such as adjectives, tend to favor higher number of associations.

E. Associations asymmetry: One of the clearest results deriving from the reported experiment was the fact that some associations tended to be much more stable than others, in the sense that they were more systematically repeated and yielded a smaller number of variations. Examples of such cases include $(bread, butter)$ and $(pecker, wood)$. This property seems to be connected to the node degree wide dispersion, in the sense that association pairs involving at least one word characterized by higher node degree tended to favor a higher number of different associations.

F. Context biasing: As is clear from Figure 4, the choice of a word by the subject tended to be influenced by those more recently input. The memory effect seems to disappear for lags higher than 250 presentations.

G. Small-world features The relatively low average length shown in Table III suggests that the obtained association follows the small-world paradigm. This is an immediate consequence of the fact that the experiment inherently targets word associations.

H. Power-law features: As could be expected, the output and input degree distributions shown in Figures 5 and 6 resulted markedly different, with the latter being more compatible with power-law scaling, especially at the initial portion of the curve.

As the limited power-law trend corresponds to the possibly more complex and interesting identified features, it is further discussed in the following, including a possible explanation. Although difficult to be defined, the conscious portion of thinking is a predominantly sequential process. While solving a problem, or just relaxing, the flow of ideas and concepts takes place as a sequence of ideas associated in some way which is highly dependent on the context defined by the more recent thoughts. To a large extent, the successive ideas are characterized by some strong or weak association. For instance, after thinking about the sky, next possible ideas are likely to be blue, air, sun or clouds. Therefore, at least part of the flow of thoughts can be thought in terms of a Markovian system. At the same time, memories are often related to associations [6]. From the computational point of view, it is possible to enhance the storage potential by organizing the stored concepts in a hierarchical fashion, so that the description of new concepts at lower hierarchical levels can include only the features not covered by the upper levels. For instance, the description of a cat can be derived from that of mammals, including only those characteristics that are intrinsic to cats (see Figure 7). This concept of inheritance leads naturally to associations between concepts and ideas, even between two non-adjacent hierarchical levels, a phenomenon that can be related to Hofstadter 'strange loops' [7]. Though additional features are certainly incorporated into the brain dynamics, such hierarchical and associative schemes lead to the interesting situation where several concepts end up associated, even if indirectly, to those in the upper hierarchies. Consequently, the concepts tend to become more and more associated as one moves from the lower to the upper hierarchical levels, possibly leading to a rich gets richer scheme, and hence to scale free organization.

Given that the adjacency matrix of the obtained graph can be immediately understood as the transition matrix of a Markovian systems, it is possible to use Monte Carlo simulation in order to produce sequences of associated words, such as that illustrated below. As the context is limited to one association level, such sequences are characterized by subsequent repetitions of words.

> horse, brown, bear, brown, sugar, sweet, good, earth, land, good, well, good, time, out, sun, hot, water, cold, water, cold, wool, sheep, four, clock, six, tea, leaf, thin, sheet, wide, field

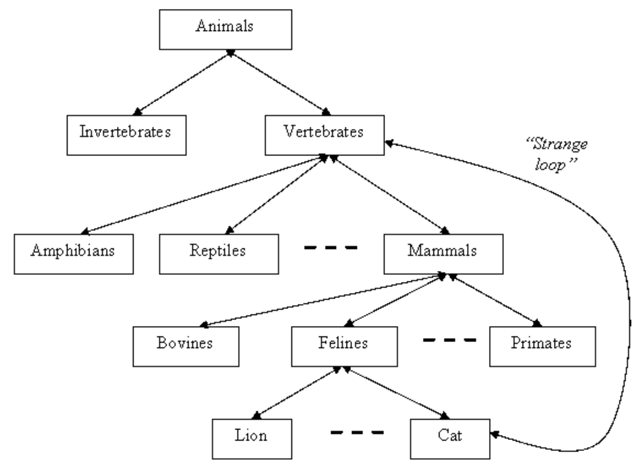

FIG. 7: Hierarchical organization of words and formation of strange loops imply that words in higher hierarchical levels acquire higher number of associations.

V. CONCLUDING REMARKS

The present work has illustrated how complex network and graph theory concepts and formalisms can be applied to characterize human cognitive activities, namely the association of words. While previous related works such as Motter et al.[4] investigated word associations through the use of static databases, the current approach considered psychophysical experiments. The main differences implied by such an approach are the fact that the importance of associations can be inferred from the respective frequencies. In addition, a random element is implied by the fact that the user is likely to vary the chosen associations while affected by the context established by the presentation sequence.

Although limited to a single subject, the obtained experimental results led to a series of interesting findings, including the identification of attraction basins, context biasing, association asymmetries, small-world features, and near power-law scaling of the node degree. A putative model possibly underlying the latter phenomenon, involving the appearance of strange loops in the hierarchical categorization of words, has also been proposed. While extensive additional investigations are required in order to confirm such preliminary results, it is felt that the identified phenomena are likely to provide a reasonably formal scaffolding for further investigating and understanding word associations by humans and even more sophisticated brain dynamics [4].

Several are the possibilities implied by the reported developments. First, it is important to note that the specific measurements extracted from digraphs obtained from different subjects can be possibly correlated to individual features or even for diagnosis. At the same time, it is likely that the obtained graphs will present a core shared by several subjects, corresponding to those more established and invariant collective concepts, while the graph difference residuals could provide interesting information about intrinsic individual features and preferences. Another interesting task would be to extend the reported approach in order to investigate associations in visual language, for instance by using eye-tracking systems. Several possibilities for further investigation can be defined by considering modified versions of the adopted psychophysical experiment. For instance, it would be interesting to study situations where the subject is allowed to enter a continuous flow of associated words, without any interference from the computer, except the presentation of the first word. Although more complex, given the additional degrees of freedom, such investigations could provide additional insights about long time memory effects, which are poised to reduce the number of word repetitions in respective Monte Carlo simulations. It would be interesting to compare how such extended context modifies the properties of the respectively obtained networks.

Acknowledgments

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