Int. J. Nonlinear Anal. Appl. 12 (2012) No. 2, 1563-1566
ISSN: 2008-6822 (electronic)
http://dx.doi.org/10.22075/ijnaa.2021.22221.2339

Resilience in semantic networks: A new approach for studying language impairment in Alzheimer's disease

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(Communicated by Madjid Eshaghi Gordji)

Abstract

Language impairment in Alzheimer's disease can occur because of deficits in semantic levels of language processing. It can be studied using computational models of language such as complex semantic networks which are strongly related to semantic memory. We hypothesize that the concept of resilience in scale-free semantic networks can truly model and predict semantic language deficit in Alzheimer's disease. We suggest that increasing the variety of words in the lexicon of patients with Alzheimer's disease, improves the resilience of their semantic networks through breakdowns. Moreover, enlarging the size of the semantic networks of patients with Alzheimer's disease can make these networks more resilient.

Keywords: Alzheimer's disease, Language Impairment, Semantic Networks, Resilience.
2010 MSC: 26D15, 26D10.

1. Alzheimer's disease and semantic language impairment

Alzheimer's disease is characterized by progressively worsening deficits in several cognitive domains, including language. Language impairment in Alzheimer's disease primarily occurs because of a decrease in semantic and pragmatic levels of language processing. Semantic processing involves language content, such as words and their meaning. The associated impairments include difficulties with word-finding, naming, and word comprehension. These difficulties include empty speech (using ambiguous referents), semantic paraphasia (choosing incorrect words), word inventing, and loss of verbal fluency. Pragmatic processing goes beyond words and their meaning and involves language adaptation to the context and social situation. Examples of pragmatic problems are repeating ideas, digressing from the topic, speaking too much at inappropriate times, and talking too loudly [6].

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Received: December 2020 *Accepted:* January 2021

2. Semantic network model and language deficit in Alzheimer's disease

To study semantic language deficit in Alzheimer's disease with a computational approach, we should firstly model the language and then examine its impairment. In literature, language has been studied through various methods from probabilistic models to dynamic and network representations [8, 9, 7]. In between, language networks specifically, semantic networks can be used to model language and analyze it by network science tools. Semantic networks are made of some "words" as the "nodes" and their relations as the "links". For instance, in the sentence "birds can fly", the words "bird" and "fly" are the nodes; they are connected by the proposition "can", as the link [7]. Moreover, semantic networks are strongly related to semantic memory. Semantic memory typically refers to memory for word meanings, facts, concepts, and general world knowledge. It is well known that semantic memory is vastly damaged in Alzheimer's disease. As a consequence, the semantic level of language processing is also impaired in this disease. The key question is how this impairment can be modelled, analyzed, and predicted.

During semantic language impairment in Alzheimer's disease, some words and their relations can't be remembered. In other words, a kind of node and/or link loss happens in the semantic network of the patients' language. The nodes and the links become aged so that they have less participation in the network. The degrees of the nodes decreases and the links become less weighted. As the disease progresses, the number of forgotten words increases and their retrieval becomes harder and harder. The researcher in the field of neurodegerative diseases, want to know how much the semantic network of a patient with Alzheimer's disease can resist against the node and link losses. To answer this question, we propose to model this language deficit in Alzheimer's disease, by the help of a concept in network science, namely the "resilience".

3. Resilience of semantic network in patient with Alzheimer's disease

Resilience is defined as the ability of a system to preserve its functionality while a failure happens [5]. In other words, a resilient system can adjust its activity to retain its basic functionality when errors, failures, and environmental changes occur [2]. In complex networks, such as semantic networks, failure can be a node and/or link loss. When such networks are subjected to random breakdown, a fraction f of the nodes (words) and their connections are randomly removed. As a result, their integrity might be lost. When f exceeds a certain threshold, $> f_c$, the network is divided into smaller disconnected sections. Below this critical threshold, there still exists a connected sub-network that spans the whole system whose size is proportional to the size of the main system. Random breakdown in a network can be studied as a case of infinite-dimensional percolation. The percolation theory helps us to identify the global connectivity of complex networks with a critical threshold $> f_c$ that distinguishes between the connectivity phase and the fragmented phase of networks. Apart from finding the percolation threshold, percolation theory yields quantitative information on the critical properties near the critical threshold, showing how fast or slow the system's collapse is [5, 3].

The usual percolation model in grids and other lattices (graphs whose drawing forms a regular tiling), assumes that the sites (nodes) or bonds (links) in the lattice are occupied with some probability (or density), p, and unoccupied with probability $q = 1 - p$. The system is considered percolating if there is a path from one side of the lattice to the other, passing only through occupied links and nodes. When such a path exists, the component or cluster of sites that span the network from side to side is called the spanning cluster or the infinite cluster. The percolation phase transition occurs at some critical density p_c that depends on the type and dimensionality of the lattice. In networks (e.g., language networks), the notion of "side" is not applicable. However, the ideas of percolation theory can still be applied to obtain useful results. The main difference compared to lattices is that the condition for percolation is no longer the spanning property, but rather the property of having a giant component. This component (cluster) defines as a cluster containing $O(N)$ nodes, where N is the total original number of nodes in the network. The condition of the existence of a giant component above the percolation threshold and its absence below the threshold also applies to lattices and therefore can be considered as more general than the spanning property [4].

To examine the existence of a giant component, we should first know the degree distribution ($P(k)$) in the network. According to literature, semantic networks constructed based on WordNet, Roget's thesaurus and, free-association databases show the best fitting power-law distribution [10]. This means all these semantic networks are categorized as scale-free networks [10]. They are inhomogeneous networks, for which $P(k)$ decays as a power-law, i.e. $P(k) \sim k^{-\gamma}$, free of a characteristic scale. As shown in [2], γ, the power-law exponent for the $P(k)$ distribution in Associative, Roget and WordNet networks is respectively 3.01, 3.19 and 3.11. After finding the degree distribution of the network, we should determine the type of failure in the network that can be a random failure or an intentional attack. As we have no specific pattern for node and/or link losses in the semantic network of patients with Alzheimer's disease, we rightly assume it as a random failure.

Previous researches about scale-free networks show that these networks are much more resilient to random failures in comparison with a random network such as Erd"os–R'enyi(ER) [1]. However, the resilience of scale-free networks depends on some parameters like the size of the network (N) and the amount of γ. As Cohen and Havlin [4] have shown that scale-free networks with $2 < \gamma < 3$ are very robust to the random breakdown of almost all of the nodes, especially the networks with larger sizes (Figure 1). In these networks, the transition happens in infinite sizes. For $\gamma > 3$, the scale-free networks are vulnerable to random breakdowns; the spanning cluster disintegrates after the breakdown of half of the nodes, and the network becomes fragmented [4].

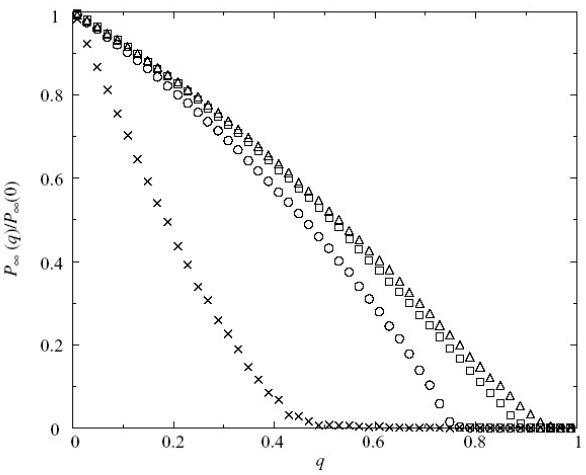

Figure 1: Percolation transition for networks with power-law degree distribution. The vertical Axis shows the fraction of nodes that remain in the spanning cluster after the breakdown of a fraction q of all nodes, $P_\infty(q)/P_\infty(0)$, for $\gamma = 3.5$ (crosses) and $\gamma = 2.5$ (other symbols), as obtained from computer simulations of up to $N = 10^6$. In the $\gamma = 3.5$ case, it can be seen that for $p < p_c \approx 0.5$ the spanning cluster no longer exists and the network becomes fragmented.However, for $\gamma = 2.5$(such as the Internet), the spanning cluster resist up to nearly fully breakdown. The different curves for N=100 (circles), $N = 10^3$ (squares), and $N = 10^4$ (triangles) illustrate the finite size effect: the transition exists only for finite networks, whereas the critical threshold q_c approaches 1 as the networks grow in size [4].

4. Concluding remarks and future perspectives

We hypothesize that scale-free semantic networks with power-law degree distribution for $3 < \gamma < 3.2$, are not robust to random breakdowns such as node and/or link loss, which happens in Alzheimer's disease. After the breakdown of a fraction q_c of all nodes, the giant component of these semantic networks does not exist anymore. However, we suppose that some suggestions may improve the resilience of these networks:

1-Decreasing the amount of γ; by designing rehabilitation packages for increasing the variety of words in the lexicon of patients with Alzheimer's disease.

2-Increasing N, the size of the semantic network; by designing rehabilitation packages for increasing the number of words in the lexicon of patients with Alzheimer's disease.

By determining the resilience of semantic networks against failures, language impairment in Alzheimer's disease can be modelled. In conclusion, we believe that applying the resilience concept in language impairment in Alzheimer's disease may lead to proposing some new methods for designing disease-modifying interventions and managing the abnormalities. Consequently, these new computational methods can be applied in health services to improve people's quality of life.

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