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# Editors' Introduction to Networks of the Mind: How Can Network Science Elucidate Our Understanding of Cognition?

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**Abstract**

Thinking is complex. Over the years, several types of methods and paradigms have developed across the psychological, cognitive, and neural sciences to study such complexity. A rapidly growing multidisciplinary quantitative field of network science offers quantitative methods to represent complex systems as networks, or graphs, and study the network properties of these systems. While the application of network science to study the brain has greatly advanced our understanding of the brains structure and function, the application of these tools to study cognition has been done to a much lesser account. This topic is a collection of papers that discuss the fruitfulness of applying network science to study cognition across a wide scope of research areas from generalist accounts of memory and encoding, to individual differences, to communities, and finally to cultural and individual change.

*Keywords:* Cognitive networks; Mind; Memory; Network science

## 1. Introduction

Thinking is complex. Anyone studying the mind and its underlying neural mechanisms would probably agree with such a statement. But how can we study such complexity? Over the

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course of the history of the psychological, cognitive, and neural sciences, multiple paradigms and tools have been developed to address various aspects of this complexity. In the past two decades, a rapidly developing quantitative and multidisciplinary field has emerged, known as network science (Barabási, 2012; Newman, 2018). Network science is based on mathematical graph theory and offers quantitative ways to represent complex systems as graphs, or networks, where nodes represent the basic components of the system and edges represent the relation between them. To date, network science has been applied across many areas of scientific investigation, such as studying transportation routes, electrical gridlines, social networks, organization structure and flow of information, protein structure, and the neuronal connectivity of the *Caenorhabditis elegans* (Barabási, 2016; Coscia, 2021; Newman, 2018).

One extremely well-known and complex biological system is the brain. The application of network science methodology to study the brain's structure and function has revolutionized how we now examine neural structure and function (Sporns, 2011). The impact of network science on studying the brain is evident by the establishment of a subfield known as network neuroscience (Bassett & Sporns, 2017; Bassett, Zurn, & Gold, 2018). But what about the mind? Can cognition be represented as graphs or networks to study the complexity of, for example, learning, memory, and language? This question is the focus of this topic.

Network science has so far been applied to cognitive science to a much lesser extent than one may expect. This is a surprise since classic cognitive theory (mainly related to language and memory) developed in the 20th century already used network terminology. One prominent example is the classic model proposed by Collins and Loftus (1975) who proposed a theory on semantic memory. According to this model, the authors argue that semantic memory—the cognitive system that stores knowledge—is organized as a network where nodes correspond to concepts and edges denote the conceptual similarity between these concepts (Collins & Loftus, 1975; Figure 1).

Early application of network science in cognitive research focused on various aspects of the language domain (e.g., Ferrer-i-Cancho & Solé, 2001). However, an important milestone is the work of Steyvers and Tenenbaum (2005) who analyzed different linguistic corpuses as semantic networks to study various models of language development. The work of Steyvers and Tenenbaum (2005) is considered by some to be the cornerstone of cognitive network science.

### *1.1. Cognitive network science: A quick overview*

Cognitive network science—the application of network science methods to study cognition—is still largely centered around research on language and memory (Baronchelli, Ferrer-i-Cancho, Pastor-Satorras, Chater, & Christiansen, 2013; Castro & Siew, 2020; Karuza, Kahn, Thompson-Schill, & Bassett, 2017; Siew, Wulff, Beckage, & Kenett, 2019).

To date, network science in cognitive science has provided novel quantitative insights on various linguistic phenomena (Siew, 2018; Steyvers & Tenenbaum, 2005; Vitevitch, 2008), enabled the direct examination of the theory that highly creative individuals have a more flexible semantic memory (Kenett, 2018; Kenett & Faust, 2019b), identified mechanisms of language development through models of network growth (Hills, Maouene, Maouene,

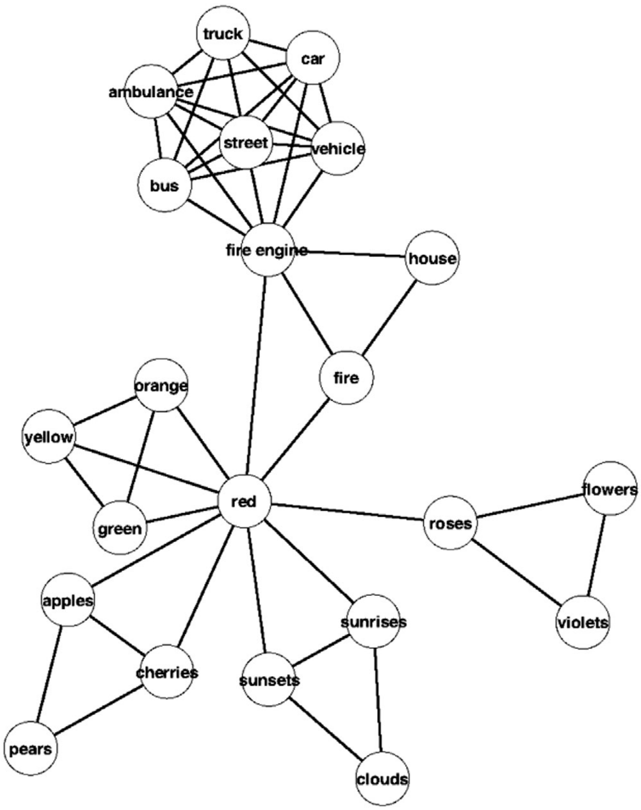


Fig 1. An illustration of the theoretical organization of concepts in semantic memory, based on the model proposed by Collins and Loftus (1975)

Sheya, & Smith, 2009; Steyvers & Tenenbaum, 2005), demonstrated how statistical learning is facilitated by regularities captured by conceptual network-based neighborhoods (Karuza, Kahn, & Bassett, 2019), shed novel light on how knowledge accumulation in typical aging leads to semantic memory network maturation (Cosgrove et al., 2021; Dubossarsky et al., 2017; Kenett, Ungar, & Chatterjee, 2021), shown how phonological networks predict lexical retrieval (Vitevitch, Chan, & Goldstein, 2014; Vitevitch, Chan, & Roodenrys, 2012), allowed examining different models of cognitive search (Abbott, Austerweil, & Griffiths, 2015; Hart et al., 2018; Hart et al., 2017; Jones, Hills, & Todd, 2015), examined the conceptual space of emotions and how they relate to each other (Dover & Moore, 2020), and provided new insight on second language structure, and its relation to first language structure, in bilinguals (Borodkin, Kenett, Faust, & Mashal, 2016; Lange, Hopman, Zemla, & Austerweil, 2020).

These studies highlight a growing interest of network science application across a wide breadth of research on cognitive science. Thus one may ask, what is the contribution of using such quantitative tools to study cognition? What is this approach bringing to the cognitive table that is not possible to be achieved with existing methods and paradigms? This issue is the focus of our topic.

### *1.2. Networks of the mind: How can network science elucidate our understanding of cognition?*

The aim of our topic is to illustrate the feasibility, strength, and potential of applying network science methodology to a wide range of cognitive research. Specifically, our topic was inspired by a symposium on this topic that took place at the 2019 annual meeting of the Cognitive Science Society (Kenett, Castro, Karuza, & Vitevitch, 2019). For this topic, we invited contributions that reflect a wide—but not exhaustive—range of applications of cognitive network research. We specifically required the authors to focus on the general contribution of network science in their own respective domains.

Importantly, the application of network science to study various aspects of human behavior not covered in this topic are also slowly increasing. Such areas include personality (Beck & Jackson, 2021), emotions (Dover & Moore, 2020), and psychometric research (Borsboom et al., 2021). Our aim in this topic is to illustrate the general potential of cognitive network science, in the hope that it will spark greater interest and application, in any cognitive and psychological domain that is theorized to have structure and processes that operate over such a structure.

The structure provided below shows how the articles in this topic scale from generalist accounts of memory and encoding, to individual differences, to communities, and finally to cultural and individual change. This scaling from individuals to groups to culture is another particular strength of cognitive network science, which is the ability to use the same methodological approach to quantify and produce theory from individuals to populations. In the final article of our topic, we discuss what challenges cognitive network science poses for itself, based on the constraints it might invoke in understanding the mind, and how we can potentially use these to drive the field forward. Overall, the papers in our topic can be organized according to the following themes:

*How the mind represents information?* In "A critical review of network-based and distributional approaches to semantic memory structure and processes" Kumar, Steyvers, and Balota (2021) conduct an in-depth review and assessment of the utility of studying semantic memory as a semantic network. The authors go back to the original model proposed by Collins and Loftus (1975) and then move quickly in time to the work of Steyvers and Tenenbaum (2005), ending up in current work conducted by the authors looking at semantic search and retrieval. Importantly, the authors discuss critical issues related to semantic memory—such as spreading of information or compositionality—and whether a network approach can account for these issues. Throughout this integrative review, the authors compare and consider text-based distributional semantic models as an alternative to the network-based approach.

*How the mind encodes information?* In "The value of statistical learning to cognitive network science," Karuza (2021) explores how statistical dependencies among the stimuli we experience in the world can be used to form edges in networks of experience. Karuza then shows how these in turn can be used to explore the foundations of learning to segment words in speech, identify grammatical patterns, and understand events through event segmentation. These form a foundation for what is called graph learning and can be applied to general learning strategies that fall under the rubric of statistical learning. By focusing on how networks can be used to predict learning, users of this network approach can evaluate what kinds of relationships in the world are most predictive of learning in various contexts.

*How the mind changes across the lifespan?* In "Understanding the aging lexicon by linking individuals' experience semantic networks, and cognitive performance", Wulff, De-Deyne, Aeschbach, and Mata (2021) highlight the role of semantic memory in typical aging. Specifically, the authors link experience dependent changes in semantic memory structure to individual differences in aging. Doing so, they demonstrate the strength of cognitive network science in studying aging, based on previous work by the authors (Wulff, De Deyne, Jones, Mata, & Consortium, 2019). Importantly, the authors argue for the importance of studying individual-based semantic memory network structure in relation to aging, and not typically estimated aggregated group-based networks. To do so, they present a proof of concept that is based on a multiday repeated free association task, an approach that they argue is better than other proposed methods to achieve that aim. The authors present the results of their proof-of-concept in relation to studying aging effects and discuss how cognitive network science can advance the research of typical aging.

*How the mind changes due to pathology?* In "Methodological considerations for incorporating clinical data into a network model of retrieval failures", Castro (2022) discusses how cognitive network science can be utilized to study clinical populations, focusing on retrieval failures in people with aphasia. This is one example of a number of studies that apply cognitive network methods to examine clinical populations suffering from thought disorders, such as Alzheimer's disease and Schizophrenia (for a review, see Kenett & Faust, 2019a). Specifically, Castro focuses on a cognitive multiplex network—a network structure that has two layers—a semantic layer and a phonological layer. Such a multiplex layer facilitates investigating how both sources of information, measured via a network representation, relates to aphasia. Finally, the author highlights key issues in clinical research that cognitive network science must be able to account for, namely heterogeneity of clinical conditions related to individual differences and change over time, calling for individual-based time-evolving network research.

*How the mind represents language?* In "What can network science tell us about phonology and language processing? ", Vitevitch (2021) addresses the application of cognitive network methodologies to studying psycholinguistic phenomena. The author describes his classic work on the structure of the phonological network (Vitevitch, 2008), and how consistent phonological network properties have been found across several languages (Arbesman, Strogatz, & Vitevitch, 2010). Finally, the author discusses how phonological network properties predict human performance in various phonological tasks, results that highlight the validity of such network measures. Finally, this article argues for more general significance of phonological network research, referring to clinical and social research. Overall, this paper argues for the significant advantages of using network science to study psycholinguistic phenomena.

*How communities represent language?* In "Cognitive network science for understanding online social cognitions: A brief review", Stella (2021) highlights how cognitive network science can be used to understand the psychological dispositions found in "big" social media data. For example, though frequency is one way to evaluate word salience, another potentially more valuable way is to look at how words are structured in networks by communicators. This is also consistent with the rising recognition that words in context (e.g., contextual diversity) are often more predictive than word frequency (Johns, 2021). These contextual relationships, captured by network science, allow investigators to see how concepts and beliefs are linked and framed by social media users. This has the advantage of allowing us to better understand users than we might using standard bag-of-words models that throw structure out the window. Thus, this paper raises important strengths and weaknesses of the network-based account of semantic memory.

*How does knowledge evolve?* In "An autocatalytic network model of conceptual change," Gabora, Beckage, and Steel (2021) focus on how networks can evolve through self-catalysis: New nodes are formed from interactions of existing nodes. These networks structures are reflexively autocatalytic, with nodes capable of interacting with one another to produce new nodes, which can then act on the network and in turn produce additional novel nodes. Initially proposed for molecular networks, Gabora and colleagues describe how these reflexively autocatalytic networks have been used to understand cultural evolution as a recombing of existing cultural schemas. For example, by combining a computational schema developed in artificial intelligence with a schema for encoding memory, we arrive at cognitive science such as model of the mind as a computer. Gabora, Beckage, and Steel go on to apply this approach to formalize an individuals' conceptual change, by discussing different learning strategies that facilitate understanding regarding Earth as a planetary body. This is achieved by exposing how preexisting knowledge can be used to construct novel insight and form resilient knowledge structures that are self-reinforcing.

*What's next for cognitive network science?* In "Is the mind a network? Maps, vehicles, and skyhooks in cognitive network science," Hills and Kenett (2021) undertake a theoretical exercise to re-examine the metaphor of the mind and its many potential alternatives or elaborations. To do so, the authors begin with a brief overview of different historic models of semantic memory, highlighting Tolman's (1948) notion of cognitive maps and processes that operate over it, which are in line with the prominent model proposed by Collins and Loftus on semantic memory as a semantic network (Collins & Loftus, 1975). Next, the authors consider alternatives to the mind as a network metaphor. Finally, the authors highlight key issues in cognitive network science that any interested user should be aware of. The authors conclude that cognitive network science is still in an active state of development, and this development reflects a continuing contribution of network science to our understanding of the complexity of the mind.

## 2. Conclusion

Network science is a rich domain that has been applied to understand a multitude of topics ranging from social networks, to species interactions, to robustness of energy grids. These applications stem from our growing understanding of complex systems as dependant on the way the systems are structured, how their interactions influence their behavior, and how this allows such systems to adapt and self-organize. The application of network science to the mind is another step in the evolution of our understanding of how cognition itself depends on similar properties of its interacting elements. This topic attempts to give readers a glimpse at the scope of cognitive network sciences applications, but it is admittedly the tip of a large and growing iceberg.

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