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How children explore the phonological network in child-directed speech: A survival analysis of children's first word productions

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ABSTRACT

We explored how phonological network structure influences the age of words' first appearance in children's (14–50 months) speech, using a large, longitudinal corpus of spontaneous child–caregiver interactions. We represent the caregiver lexicon as a network in which each word is connected to all of its phonological neighbors, and consider both words' local neighborhood density (*degree*), and also their embeddedness among interconnected neighborhoods (*clustering coefficient* and *coreness*). The larger-scale structure reflected in the latter two measures is implicated in current theories of lexical development and processing, but its role in lexical development has not yet been explored. Multilevel discrete-time survival analysis revealed that children are more likely to produce new words whose network properties support lexical access for production: high degree, but low clustering coefficient and coreness. These effects appear to be strongest at earlier ages and largely absent from 30 months on. These results suggest that both a word's local connectivity in the lexicon and its position in the lexicon as a whole influences when it is learned, and they underscore how general lexical processing mechanisms contribute to productive vocabulary development.

Introduction

Why do children systematically produce some words at an earlier age than other words? What biases guide word learning, and how might these biases change as the child develops? Researchers have identified a variety of word properties that influence acquisition, including semantic, morphosyntactic, and formal properties (e.g. Gentner & Boroditsky, 2001; Gleitman, Cassidy, Nappa, Papafragou, & Trueswell, 2005; Hills, Maouene, Maouene, Sheya, & Smith, 2009; Hills, Maouene, Riordan, & Smith, 2010; Stevens, Yang, Trueswell, & Gleitman, 2012; Steyvers & Tenenbaum, 2005; Stoel-Gammon, 2011; Vihman & Velleman, 2000). Some of these are properties of the word itself, and others concern relationships among words on semantic or formal dimensions. In the latter group, much attention has focused on how the phonological similarity of single words to other words in the rest of the lexicon influences ease of acquisition. The most common and long-standing operational definition of phonological similarity involves *phonological neighbors*, words that differ by

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the addition, deletion, or substitution of one phoneme (Landauer & Streeter, 1973). The number of neighbors that a target word has, based on this definition, is known as the target's (*phonological*) *neighborhood density*.

The focus on neighborhood density has yielded important insight into the role of phonological similarity in language development as well as lexical processing (Bernstein Ratner, Newman, & Strekas, 2009; Charles-Luce & Luce, 1990; Coady & Aslin, 2003; Garlock, Walley, & Metsala, 2001; Luce & Large, 2001; Metsala, 1997; Newman & German, 2002; Stoel-Gammon, 2011; Storkel, 2004; Swingley & Aslin, 2002; Vitevitch, 2002; Vitevitch & Luce, 1998, 1999; Vitevitch, Luce, Pisoni, & Auer, 1999), and neighborhood density is a central concept in prominent theories in these domains (Dell & Gordon, 2003; Luce & Pisoni, 1998; Metsala & Walley, 1998; Walley, 1993). However, the results of neighborhood density research are complex, and researchers have long grappled with a sense that neighborhood density does not capture important aspects of phonological similarity between words in the lexicon (e.g. Bailey & Hahn, 2005; Mathey, Robert, & Zagar, 2004; Mathey & Zagar, 2000; Yarkoni, Balota, & Yap, 2008; Zamuner, 2009).

Some of these problems stem from a formal consequence of the traditional definition of phonological neighbor: a word's neighbors usually have neighbors of their own, which in turn have other neighbors, and so on. The definition of phonological neighbors thus implicitly defines a representation of an entire lexicon in which each word is connected to all of its neighbors, a *phonological network* (Arbesman, Strogatz, & Vitevitch, 2010a, 2010b; Vitevitch, 2008). In the present study, we apply this definition over a large corpus of child-directed speech to construct a phonological network that approximates the lexical exposure of American English speaking preschoolers.

The structure of complex networks such as this may be quantified both at and beyond the scale of local neighborhoods (Newman, 2003), potentially shedding light on the relationship between when children learn a word and how the word is embedded in the phonological network. We focus on three common network-theoretic measures, all defined at the level of individual words: traditional neighborhood density (henceforth referred to using the equivalent network-theoretic term *degree*), *clustering coefficient* and *coreness* (all defined below). The impact of a word's degree on when it is learned has been extensively studied in previous work, and clustering coefficient and coreness are particularly well-suited to measuring the kind of larger-scale network structure implicit in current theories of lexical and phonological development (cf. recent attention to clustering coefficient in research on adult lexical processing Chan & Vitevitch, 2009, 2010; Yates, 2013). We will use the term *phonological network properties* to denote degree, clustering coefficient, and coreness, which together provide a richer description of each word's phonological relationship to the rest of the lexicon than is available from degree alone.

We assess the power of these phonological network properties for predicting when new words enter children's productive lexicons, using a large longitudinal corpus of spontaneous child–caregiver interaction spanning child ages 14–50 months (Rowe & Goldin-Meadow, 2009; Rowe, Raudenbush, & Goldin-Meadow, 2012). Using longitudinal data allows us to examine both how phonological network structure affects word learning, and how its role changes as children develop. We do so using *survival analysis*, a statistical technique for modeling the time elapsed prior to some event, here the first time a target word is observed in the spontaneous speech of a given child (Barber, Murphy, Axinn, & Maples, 2000; Reardon, Brennan, & Buka, 2002; Singer & Willett, 1991, 2003). Survival analysis also allows us to control for a set of covariates known to impact word learning: frequency, length, syntactic category, phonotactic probability, child gender, and quantity of caregiver speech input.

Our study thus focuses on two main questions about children's productive vocabulary growth:

1. Do children produce some words earlier than others based on both local and larger-scale phonological network properties in child-directed speech? If so, what are the directions of the effects of degree, clustering coefficient, and coreness?
2. Does children's sensitivity to these properties change over time, and if so, how?

We begin with an overview of aspects of network science which are relevant for our investigation, then contextualize the network-theoretic approach within the literature on neighborhood density and review recent efforts to apply it to lexical organization, processing, and acquisition. We then describe our data, analytic strategy, and results.

Background

The lexicon as phonological network

A complex network consists of a set of *nodes* and a set of *edges* linking pairs of nodes based on some *edge condition* (Newman, 2003). In a phonological network of the kind examined here (see the network fragment in Fig. 1), the nodes are the words in the lexicon, and the most common edge condition is the traditional definition of a phonological neighbor (Landauer & Streeter, 1973): two words are linked if they differ by the addition, subtraction, or substitution of a single phoneme (Arbesman et al., 2010a, 2010b; Vitevitch, 2008), based on words' adult-like segmental composition. While this definition neglects the role of features, suprasegmentals, the position of the edit, and so on (e.g. Bailey & Hahn, 2005; Mathey & Zagar, 2000; Mathey et al., 2004; Yarkoni et al., 2008; Zamuner, 2009), considering an entire network substantially enriches the concept of phonological neighborhoods with the capacity to quantify larger-scale structure.

The most local property of nodes in a network is their *degree*, which in the present case corresponds to neighborhood density: the number of edges connected to the word. *Clustering coefficient* expands the focus to take in properties of a target word's neighbors, and is defined as the proportion of all pairs of a target's neighbors that are neighbors of each other. For example, in Fig. 1, *sat* has four neighbors,