EMPIRICAL MODELS OF PHONOLOGICAL NETWORKS AND THEIR GROWTH IN ENGLISH

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and their growth in English

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My appreciation goes out to my husband, Gerald, for patiently supporting me throughout the years-long odyssey that culminated in this book.

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PREFACE

Lexical knowledge is a crucial pillar of linguistic competence, upon which all other linguistic functions depend. Decades of psycholinguistic research have explored the cognitive representations of words in our minds and their internal organization, the so-called mental lexicon. Of particular interest have been the pathways of word acquisition and retrieval, the functional components of the mental vocabulary, and the interrelations between words encoded in the vocabulary. Research of the mental lexicon is voluminous and has significantly advanced our understanding of how the human mind processes words, both in first languages and those learned later in life.

To unravel the intricacies of the mental lexicon, researchers have primarily employed a "bottom-up approach" based on the reconstruction of linguistic processes, such as word recognition and lexical learning, by focusing on individual words and their formal and functional neighborhoods. This method has built a solid theoretical foundation to capture phenomena observed in experimental tests over decades. Recent advances in the mathematical domain of network sciences have opened up promising avenues for a "top-down" approach to studying the mental lexicon. This involves viewing words as parts of a vast, interconnected network. Novel insights into functional and developmental patterns can come from modeling the mental lexicon as a complex system, where the performance of one part relies on another, and the whole system is more than the sum of its parts. This bird's-eye view of the mental lexicon as a complex system facilitates the exploration of its grander structure, unveiling new patterns of hierarchical relationships and lexical access dynamics. Ultimately, it can lead to more predictive models of the factors that influence lexical processes.

The research field of lexical network science is relatively new, with studies primarily focused on a limited number of languages, mainly those involving first language users. Second languages have been underrepresented in this research. This book aims to address this gap by introducing readers to the methodology and utility of network science for second languages, specifically English as a second language[1]. To offer

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[1] The term "second language" will be used throughout this book in the psycholinguistic sense of any language learned after the first (native) language of a speaker, with the exception of bilingualism (see, e.g., Gass & Se-

a comprehensive perspective, the book will also present a lexical word form network of British English as a first language to allow for meaningful comparisons between the linguistic patterns of English as a first and second language. The focus of this book is on mathematical modeling of network-theoretical concepts within the phonological lexica of language users at various proficiency stages of English, their psycholinguistic implications, and the question of what network science can contribute to theories of word learning and lexical access. By approaching second language networks through the lens of evolving network theories, the book aims to provide insights into the developmental aspects of lexical learning in second languages. The ultimate goal is to offer a network-theoretical description of word form networks and their growth in learners of English as a second language. The structure of the book is designed as follows.

The opening chapter explores word form relationships within the mental lexicon, as outlined in widely accepted psycholinguistic theories of lexical access. At the core of this discussion is the notion of 'phonological neighbor', a measure of the relationship between word forms. Much explanatory weight of network science is placed on the quality and quantity of relationships between entities along known similarity dimensions, and phonological neighbors are the logical starting point for a network-theoretical approach to word forms. The chapter systematically surveys various concepts of network science and their application to the description of phonological networks. Special attention is given to the different levels of network organization, including micro, meso, and macro levels of analysis. Characteristics of individual nodes, small clusters of connected nodes (communities), and the overall topology of a lexical network all bear systemic relevance for network connectivity and can provide information about lexical processes. The chapter further explores theories on activation spreading in lexical networks. This is particularly important as patterns of co-activation are expected to align with network principles, potentially differing from predictions based on traditional models of lexical access.

Chapter 2 outlines the construction process of the phonological networks of English. Vocabulary data associated with different proficiency levels in second language English were collected, and phonological distances between word forms were calculated as the foundation of network creation. To provide a point of comparison, a separate phonological network with data from British English first language users was computed. The subsequent sections of the chapter describe network-mathematical analyses, covering all levels of analytical detail for the networks examined. Throughout, the implications that these findings hold for lexical processing are discussed.

In the third chapter, network growth algorithms that are of potential significance for phonological networks are reviewed. A specific focus is placed on scale-free networks and how new links can be accumulated in a way consistent with the scale-free assumption of phonological networks. A discussion of various factors influencing the growth of scale-free networks follows, including uniform and preferential attachment,

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linker, 2008). The terms ESL or "English as a second language" and EFL or "English as a foreign language" will thus be used synonymously.

fitness models, and aging effects. The discussion extends to the application of these network growth algorithms in the second language networks, where vocabulary gains across proficiency levels are analyzed in terms of which network growth principle can best explain the observed patterns. Growth rates within distinct network parts, communities, and individual nodes are discussed. Additionally, the developmental trajectory of growth over the course of language learning at the micro, meso, and macro level of the evolving second language network is charted. Theoretical extensions of the Barabási-Albert evolving network model are tested in the networks.

The conclusion summarizes the findings and presents future directions for the application of network sciences to the study of the mental lexicon and word learning in second languages. The potential of network theoretical approaches to lexical organization and lexical access in language users is in its nascent stage, with ongoing development of new theories. Emerging hypotheses seek to integrate traditional knowledge about the mental lexicon with novel insights derived from the principles of network science.

Hopefully, this book will inspire researchers to apply network-mathematical concepts to the psycholinguistic study of word relationships in the mental lexicon. This integrated approach across research specialties can be intellectually fruitful and lead to a deeper understanding of the cognitive underpinnings of linguistic representations in the human mind. By embracing different theoretical perspectives and exploring innovative research questions, we can make significant strides toward elucidating the structural organization of human word memory.

1.

THE NETWORK REVOLUTION IN THE MENTAL LEXICON

1.1 VIEWS OF LEXICAL CONNECTIVITY

The mental lexicon is the human repository of lexical knowledge (Oldfield, 1966). It is the cognitive system that organizes lexical activity and forms the basis of expression by providing storage to all vocabulary items that are known by a language user (Dóczi, 2019). A lexical representation is believed to contain information about a word's form, meaning, and syntactic properties, which become accessible upon lexical access (Yelland, 1994). How words are represented and processed in the mental lexicon is crucial not only for theories on language acquisition and development but can more generally shed light upon universal principles by which humans mentally categorize language. The mental lexicon is best conceptualized as an ideal, abstract notion, rather than a mere catalogue of word knowledge (Aitchison, 2012; He & Deng, 2015). In essence, it functions as a dynamic memory system supporting linguistic processing, continually adapting in response to experience.

Virtually all psycholinguistic accounts of lexical processing acknowledge that information in the mental lexicon is organized according to phonological similarity (Buchwald, 2011; Schweppe, Grice, & Rummer, 2011; Vitevitch, 2002b). Studies have consistently revealed an advantage of phonologically similar word forms for word learning, underscoring the strong influence of phonology on lexical processing in first language acquisition and second language learning (e.g., Aitchison, 2012; Arutiunian & Lopukhina, 2020; Beckage & Colunga, 2019; Dell & Gordon, 2003; Fourtassi, Bian, & Frank, 2020; Gahl, Yao, & Johnson, 2012; Harley & Bown, 1998; Havas et al., 2018; James & Burke, 2000; Siew & Vitevitch, 2016; Vitevitch & Luce, 2016). Therefore, understanding the role of phonological similarity in the mental lexicon can illuminate processes involved in the organizational structure of lexical cognition.

1.1.1 PHONOLOGICAL NEIGHBORS

The phonological similarity bias in the mental lexicon is governed by 'phonological neighbors', a well-studied notion of lexical relationships (Goldrick, Folk, & Rapp, 2010; Landauer & Streeter, 1973). In their seminal study of lexical frequency in word recognition, Streeter and Landauer (1973) defined phonological (in their term “lexical”) similarity as the distance of one piece of information (a phoneme or grapheme) between two words. What was referred to as “neighbors” and “similarity neighborhoods” have evolved into today’s concepts of “phonological neighbors” and “phonological neighborhoods” (see, e.g., Vitevitch & Luce, 2016). Phonological neighbors are commonly considered to be words that share the majority of phonological segments and differ by just one segment through substitution, deletion, or addition (the so-called Hamming or Levenshtein distance, Landauer & Streeter, 1973; Luce & Pisoni, 1998). What lies at the core of lexical activation is competition for activation between segments and, consequently, among phonological neighbors. Activation of a target word, either through production or perception, leads to co-activation of other words sharing phonemes with the target. Since co-activation spreads through common phonology, the more phonemes are shared within a neighborhood, the more activation spreads within a neighborhood. This results in the “phonological neighborhood effect” on the lexical level (Vitevitch & Luce, 2016). The impact of the effect varies in speech production and in perception. In perception, competition among lexical candidates results in slower access to the target word (Luce & Pisoni, 1998; Magnuson, Dixon, Tanenhaus, & Aslin, 2007; Vitevitch, 2002a; Vitevitch & Rodriguez, 2004). In speech production the opposite is observable, and words from denser neighborhoods are produced faster and more accurately (Vitevitch, 2002b; Vitevitch, Armbruster, & Chu, 2004; Vitevitch & Sommers, 2003). In speech recognition, listeners have limited semantic information and rely solely on phonemic input to determine a phonological word form. In production, speakers have access to semantic information, which they can use to prevent co-activation of certain phonological neighbors. It has been proposed that in speech production, articulation-relevant features of phonological representations become strengthened through co-activation (Vitevitch, 2002b). Phonological neighborhood effects are well-documented phenomena in psycholinguistic research, observable across various languages and populations (e.g., Arutiunian & Lopukhina, 2020; Gordon, 2002; Marian & Blumenfeld, 2006; Stamer & Vitevitch, 2012). They constitute a central component of lexical processing (see Vitevitch & Luce, 2016, for an overview of neighborhood effects in perception and production).

Phonological neighborhoods play an important role in word learning. Words which find many potential neighbors or ‘anchor words’ in the vocabulary of a learner are more easily and rapidly integrated (Gaskell & Dumay, 2003; Storkel, Armbruster, & Hogan, 2006). Thus, dense phonological neighborhoods with numerous words connected via the one-segment distance can exert a pull-effect on new words sharing phonological features with these neighborhoods. Clusters of phonologically related words constitute particularly strong attraction points for new words (Stamer & Vitevitch, 2012; Storkel et al., 2006). Research indicates that adult word learning is facilitated by high-density neighborhoods, while challenges arise when target words belong to sparse neighborhoods (Storkel et al., 2006). The phonological homogeneity bias essentially skews the learner’s perceptions and word memory in a way that favors accumulations of phonologically similar words. While most word learning research has focused on first languages (or ‘L1’), the phenomenon of phonologically guided word learning can also be found in second languages (‘L2’; see, e.g., Bialystok, 2010; Kaushanskaya, Yoo, & Van Hecke, 2013; Leach & Samuel, 2007; Smits, Sandra, Martensen, & Dijkstra, 2009; Stamer & Vitevitch, 2012; Yates, 2013). New L2 words that share phonological similarities with existing words in a learner’s L2 vocabulary are acquired more efficiently and retained more accurately (Dijkstra, Miwa, Brummelhuis, Sappelli, & Baayen, 2010). Conversely, acquiring and retaining new words that embed in sparse neighborhoods proves to be more challenging. The phonological similarity bias in learning is not restricted to one language but operates across different languages, as evidenced by parallel activation of L1 phonological forms when L2 is being processed (Broersma & Cutler, 2008). Phonologically similar L1 and L2 words are frequently co-activated, even when this activation is irrelevant to the task (Carrasco-Ortiz, Midgley, & Frenck-Mestre, 2012; Schulpen, Dijkstra, Schriefers, & Hasper, 2003). Third language (‘L3’) studies have yielded similar results, and L3 words tend to activate words from the first and second languages of speakers (Van Hell & Dijkstra, 2002), suggesting that similarity in word forms across languages can provide benefits for L3 lexical processing (Mulík, Carrasco-Ortiz, & Amengual, 2018). Co-activation between L3 and L1 words is commonly reported, but co-activation between L3 and L2 seems to be more dependent on the proficiency level of the learners (Mulík et al., 2018). This has implications for phonological pull-effects in word learning: higher L2 proficiency leads to increased L3 neighborhood effects. The typological and phonological relationship of L1, L2, and L3 languages certainly plays a role, too. Additionally, semantic relatedness of the similar phonological forms needs to be considered, as cross-language homophones and cognates can lead to different neighborhood effects (Carrasco-Ortiz et al., 2012; Dijkstra et al., 2010; Dijkstra, Timmermans, & Schriefers, 2000; Haigh & Jared, 2007; Midgley, Holcomb, & Grainger, 2011; Van Heuven, Dijkstra, & Grainger, 1998).

Perceived phonological similarity is tightly linked to the notion of phonological confusability and the question of how individual language users assess similarity of phonemes. Phonological confusability may extend beyond the one-segment neighborhood and encompass a broader spectrum of similarity relationships, including the PLD20, which gives the mean number of steps that are required to transform a word into its 20 closest neighbors (Suarez, Tan, Yap, & Goh, 2011). Suarez and colleagues demonstrated that co-activation extends to the wider neighborhood separated by more than one segment of distance between words (also see Chan & Vitevitch, 2009, for similar findings), even in the absence of one-segment neighbors. Their research uncovered what they termed “neighborhood effect without neighbors” (Suarez et al., 2011: p. 605).

The one-segment phonological distance has proven to be a useful concept for psycholinguistics over the last few decades. Over time, a more nuanced view of phonological neighbors has emerged. One line of research focuses on locus-oriented notions of phonological neighborhoods that consider the serial order of phonemes in words, suggesting that not all phonemes are equal when it comes to neighborhood construction (e.g., Desroches, Newman, & Joanisse, 2009; Simmons & Magnuson, 2018). Typically, word-initial phonemes are attributed a higher conceptual importance in the sense that stronger neighborhood connections exist between words that share onsets (so-called "cohort effects), such as *cat-cab*. In contrast, rhyme neighbors differing in the onset phoneme, for instance *cat-hat*, show weaker competition effects (Simmons & Magnuson, 2018). Another measure of phonological neighbors is captured by the so-called *P-metric* (or phonological neighborhood spread), which counts the phonemic possibilities for a word to form neighbors (Vitevitch, 2007). As exemplified by Vitevitch (2007), the English word *mop* has three phoneme positions where neighbors can form (P=3), e.g., *hop, map, mock*. Its phonological neighbor word *mob*, however, has only two phoneme positions for neighborhood formation (P=2), e.g., *rob, mock*. Conflicting findings regarding the phonological neighborhood spread exist in the literature. Yates (2009) found faster responses to words with numerous phonemic positions changeable for creating neighbors, while Vitevitch (2007) reported the opposite – faster recognition for words with smaller P-values, supporting assumptions of activation-competition theories. Fewer neighbor formation possibilities mean less cognitive effort involved in processing words. Higher degrees of certainty in word recognition (in the case of a smaller P) correlate with faster recognition rates, whereas more uncertainty due to a higher rate of variation probability (in the case of a larger P) slows down processing. These findings indicate that the probability of phonemic overlap with neighbors across different phonemic positions effects on lexical processing and potentially the structural organization of word forms in the mental lexicon.

Phonological similarity can also be described across different phonological dimensions, as shown by feature-based analyses measuring the closeness of phonological neighbors (Bailey & Hahn, 2001). For instance, the phonological distance between voiced and unvoiced variants of a consonant is arguably closer than that between a vowel and a consonant, as seen in examples like *bat-pat* vs. *ball-boy*. A study by Fricke, Baese-Berk, and Goldrick (2016) shows that the English word *cod* has a multitude of neighbors (27 overall) with which it shares different phonological features: *God* differs only in the voicing parameter of the word-initial plosive, while the word-initial sibilant in *sod* represents a larger phonological distance to the target word *cod*. The authors demonstrated that considering position-specific similarity of segments can predict the spreading of activation in a phonological neighborhood (in their case, in word-initial position). These findings underscore the importance of further quantifying phonological neighbors for understanding crucial aspects of lexical processing.

Phonology-based models of lexical access tend to view the mental lexicon as "a collection of arbitrarily ordered phonological representations and the process of lexical retrieval as a special instance of pattern matching" (Chan & Vitevitch, 2009: p. 1934). The majority of current models of spoken word recognition share the assumption that phonological overlap is the central force driving competition and activation in lexical processing (Weber & Scharenborg, 2012). Phonemic input activates all similar phonemes within a phonological neighborhood and words containing those shared phonemes compete for overall activation. The way phonological connections between words can further or hinder activation spreading is a crucial question in theoretical models of lexical access.

1.1.1.1 SPOKEN WORD RECOGNITION

Models of spoken word recognition rely on various notions of phonological neighbors. One of the earliest models, the cohort model of lexical access, focuses on word-initial segments (Marslen-Wilson, 1987; Marslen-Wilson & Warren, 1994). The model predicts co-activation based on temporal phonemic overlap, starting from the initial phoneme and progressing with each succeeding, similar phoneme in a sequential manner as speech unfolds in time. In this context, phonological neighbors are those words sharing onset phonemes, and non-onset phonological neighbors are excluded as candidate words early in the chronological perception of phonemes. The cohort model operates under the assumption that the human brain, and consequently the mental lexicon, follows the principle of greatest efficiency (Marslen-Wilson & Welsh, 1978). Initially, a broad range of lexical candidates is considered (with activation of the first few phonemes). However, this range quickly narrows, and mismatches are excluded from the candidate list. For example, upon hearing /s/, the whole cohort of s-initial words is activated, and gradually, with each subsequent phoneme, different words are dismissed until the target word is identified. Recognition occurs when a word reaches a unique identifying phoneme, such as the English phonemic string /fɛb/, which unmistakably identifies the only English word that begins with it, *February* (Weber & Scharenborg, 2012). Following this initial access process, the integration stage checks for syntactic and semantic suitability of a word, removing contextual mismatches from the cohort.

The structural organization predicted by the model resembles a computerized feed-forward string-matching process. However, it is unclear how different strings (=words) are related to one another. Since cohorts are formed based on the initial phoneme, each word-initial phoneme in a lexicon constitutes the first layer of its cohort. Word-initial biphones, triphones, and so forth each form their own cohorts. This means that each word is a member of different cohorts; for example, *bean* belongs to the /b/-cohort, the /bi/-cohort, and the /bin/-cohort). The likelihood of belonging to various cohorts increases with phonemic length of a word. However, cohort size decreases simultaneously.

The special status of the word-initial phonological portion for lexical processing has been consistently highlighted by numerous studies (e.g., Friedrich, Felder, Lahiri, & Eulitz, 2013; Treiman & Danis, 1988; Vitevitch, 2002a). High onset density or a high number of phonological neighbors sharing the same onset phoneme generally slow down lexical processing, as a large number of competitor words become activated (Vitevitch, 2002a). Interestingly, no similar effect has been observed for rhyme neighbors, emphasizing the sequential left-to-right activation of phonemes in speech recognition (Sevald & Dell, 1994; Vitevitch, 2002a). Competition remains high at word onsets but decreases as more phonemes are added to the word selection process (Chen & Mirman, 2014). In the cohort model, competition is restricted to phonemic access but it is not explicitly postulated that words in a cohort compete with one another. According to Marslen-Wilson (1987, p. 84), “the timing of word-recognition processes is not affected by the number of alternatives that need to be considered." Thus, the speed and accuracy of word retrieval are not influenced by the number of competitors. The cohort model has been challenged by findings that (English) listeners can rarely uniquely identify a word before its offset (Bard, Shillcock, & Altmann, 1988; Luce, 1986). As a consequence, the idea of onset matching as the singularly most crucial mechanism of lexical access has been questioned (Weber & Scharenborg, 2012).

Alternative models of word recognition acknowledge a contribution of non-initial phonological segments to neighborhood formation. One notable activation-competition model of spoken word recognition, the Neighborhood Activation Model (or NAM, Luce & Pisoni, 1998) and its connectionist counterpart PARSYN (Luce, Goldinger, Auer, & Vitevitch, 2000), posit that phonological co-activation occurs within a group of words that share the majority of phonological segments but differ in a minimal number (N=1) of segments. In the original NAM model, neighborhoods can be established through any segmental position in a word, and differences in phonemic neighborhood formation do not impact the strength of a neighborhood. An addendum to the model recognizes different variations in acoustic-phonetic distances between phonological neighbors, affecting neighborhood strength. As demonstrated by Goldinger, Luce and Pisoni (1989), phonologically close neighbors have an amplifying effect on phonemic competition, inhibiting word recognition (see Gahl et al., 2012; Scarborough, 2013; Suarez et al., 2011, for similar findings). For example, *cap* and *cab* are more influential neighbors and share more activation (and competition) compared to *cab* and *fab*.

In general, NAM assumes that competition arises between the co-activated lexical candidates from which the best-fitting word is then chosen for final selection. As lexical selection is inherently competitive, words with strengthened activation, resulting for instance from high frequency rates, facilitate word recognition (Frisch, 2011). The neighborhood probability equation is defined as follows:

$p=(\text{target} * \text{frequency}_t) / (\text{target} * \text{frequency}_t)+(\sum(\text{neighbors}_j * \text{frequency}_{Nj})$

Here, the activation level of the target word *t*, the sum of neighbor word probabilities (=neighbors_j, i.e., the overall level of activity in the lexical neighborhood), and lexical frequency information are considered (Chan & Vitevitch, 2009; Luce & Pisoni, 1998). Low-density neighborhoods with few neighbors experience less competition, resulting in faster recognition rates for the target word. As a result, words with fewer neighbors are responded to and recognized more quickly than those with a high number of neighbors. Numerous studies have validated the predictions of NAM for word recognition, solidifying its prominent place in spoken word recognition (e.g., Goh, Suarez, Yap, & Tan, 2009; Luce et al., 2000; Vitevitch, 2002c; Ziegler, Muneaux, & Grainger, 2003). Figure 1 illustrates the connectivity of phonological neighborhoods as conceived by NAM.

Luce and Pisoni (1998, p. 1) explicitly acknowledge a "structural organization of the lexicon" based on "similarity relations among the sound patterns of spoken words". However, they do not provide hints regarding any larger structural design beyond linking words in one-segment neighborhoods. It is a logical assumption that each of

Figure 1: Phonological neighborhood structure according to NAM. Node size corresponds to lexical frequency rate, with larger nodes representing more frequent words. Link strength corresponds to phonological distance, with thicker links indicating closer neighbors.

the neighbors of *way* in Figure 1 also has a neighborhood, with potential implications for further spreading of co-activation outside of the immediate neighborhood. Ultimately, a large number of words in a lexicon could be interlinked in one large web. NAM does not address this issue, nor does this idea factor into the NAM account of activation spreading. The central tenet of activation spreading in this model revolves around the immediate, one-segment-distance neighborhood of target words.

These two classical models of spoken word recognition make different predictions about the spread of co-activation in the mental lexicon. Both NAM and the cohort model posit that activated candidate words do not interact at the lexical level. Instead, these models propose decision rules that determine which lexical entry received the most activation relative to the other activated candidate words. The models specifically make predictions about immediate phonological neighbors, separated by a minimal number of phonological segments, and how they influence and compete with each other. However, they do not make predictions concerning activation spreading in neighbors of neighboring words. The larger organizational design of a full lexicon and the phonological relationships between all words contained in it remain unaddressed.

1.1.1.2 SPOKEN WORD PRODUCTION

A salient feature of phonological neighborhood effects is that they fulfil dual functions. In spoken word recognition, neighbors inhibit lexical processing, while in spoken word production, neighbors facilitate the process (Chen & Mirman, 2012; Dell & Gordon, 2003). Explanations for this discrepancy can be found in models of speech processing, in particular interactive models where lexical and phonological levels of word recognition provide feedback to each other. This interaction is captured by Dell's interactive two-step model of lexical access and retrieval (Dell, 1986; Dell, Schwartz, Martin, Saffran, & Gagnon, 1997), where lexical and phonological retrieval are distinct and ordered categories but interact through bi-directional spreading of activation. This means that semantic information can influence phonological retrieval, and phonological information can affect lexical retrieval (Dell, Martin, & Schwartz, 2007). In word production, the first step is lexical selection, mapping the conceptual representation of a word to a lexical representation (the 'lemma', Foygel & Dell, 2000). Phonological information is not required at this point (Levelt, Roelofs, & Meyer, 1999). Subsequently, phonological encoding is initiated, retrieving the phonemes used to form the target word. Phonological encoding is the process of constructing the phonological form of a target word before articulatory gestures can be prepared in spoken word production (Caramazza, Costa, Miozzo, & Bi, 2001; Dell, 1986; Levelt et al., 1999). Phonological components (phonemes) of target words are sequentially activated after speakers have selected words (Oppermann, Jescheniak, & Schriefers, 2010), mostly independently of the whole word representation (O'Séaghdha & Frazer, 2014; Roelofs, 2006). In word production, the initial semantic activation provides a baseline, further boosted by the activation of phonological neighbors. In contrast, word recognition begins with the activation of phonological segments, boosting activation of all phonological neighbors, including the target word. As a result, activation spreads more evenly within the phonological neighborhood in recognition and is less focused on the target word. This leads to the well-known effect of greater lexical activation competition in word recognition than in production (e.g., Vitevitch & Luce, 2016). Figure 2 depicts the interactive-feedback model proposed by Dell (1986).

An unresolved issue in speech production models concerns the flow of information from the semantic to the phonological domain and whether it can be characterized as discrete, cascading, or fully interactive (Schriefers & Vigliocco, 2015). This has direct implications for neighborhood activation. In discrete serial models of lexical access, the target lemma and a set of semantically related lemmas are initially activated. After exclusion of the non-target lemmas, phonological encoding of the target is initiated,