REVIEWS IN ADVANCE

Phonological Neighborhood Effects in Spoken Word Perception and Production

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Abstract

Research on spoken word perception and production has identified two hallmarks of spoken word processing: multiple activation of representations of the sound patterns of words in memory and subsequent competition among these patterns. Evidence for this activation-competition process has come, in part, from experimental studies examining the effects of phonological neighborhoods, which are collections of similar-sounding words that are activated in memory during both perception and production. In this article, we review more than 20 years of research on phonological neighborhood effects in spoken word processing that has demonstrated that the speed and accuracy of spoken word perception and production are, in large part, a function of the density and frequency of neighborhoods of spoken words. We conclude our review with a discussion of new avenues of research—based on recent advances in network science—that hold the promise of deepening our understanding of the mental operations involved in our uniquely human capacity for communicating with the spoken word.

1. INTRODUCTION

The phonological forms of spoken words exemplify the generative capacity of natural languages: From a small set of elements consisting of consonants and vowels come the hundreds of thousands of phonological representations stored in the lexical memory of a typical adult. Although the combinatorial calculus of phonological elements that are responsible for generating spoken words is governed by both universal and language-specific phonotactic constraints, this calculus is nonetheless a powerful mechanism for creating the myriad phonological forms through which our meanings are conveyed.

The combinatorial properties of a generative phonology that give rise to the panoply of lexical forms are not without consequences for the language user. The small set of building blocks used to construct spoken words necessarily results in many similar word forms, thus requiring that both the speaker and the listener possess the perceptual and cognitive capacities necessary to rapidly and accurately discriminate among many similar sounding phonological patterns. To understand the nature of these capacities, psycholinguists have devoted substantial effort over the past few decades to the study of phonological neighborhood effects in both speech perception and production.

1.1. Phonological Neighborhoods

Broadly defined, a phonological—or similarity—neighborhood consists of a set of similar-sounding words. (Throughout our discussion, we rely on the reader's intuitions about what exactly constitutes a word without attempting a more technical definition.) Much research has been devoted to understanding the implications of the number and nature of words in a phonological neighborhood for lexical processing, and it is now widely accepted that spoken word perception and production are demonstrably and strongly affected by the degree to which the sound pattern of a given word is similar to other phonological patterns in memory. In studies of word perception, the dominant finding is that words that are similar to many other words are processed more slowly and less accurately than words that are similar to fewer other words. Indeed, research on phonological neighborhood effects over the past few decades has shown that they are as robust and pervasive as classic word frequency effects.

1.2. Origins

Interest in the effects of phonological neighborhoods on spoken word processing can be most directly traced to Marslen-Wilson's (1987) groundbreaking research on cohort theory, which was the first widely accepted theory of spoken word recognition to emphasize the effects of similar-sounding words on the time course of recognition. Prior to this foundational research, speech researchers had largely assumed that recognition of spoken words would simply fall out of a theory of phoneme perception: Word recognition was thought to be tantamount to phoneme perception (Luce & Pisoni 1987). Contrary to this prevailing view, Marslen-Wilson (1987) argued that feature or phoneme perception was not sufficient to explain the ease and rapidity of spoken word recognition. Partly on the basis of a series of innovative shadowing studies in which listeners repeated spoken stimuli as quickly as possible, Marslen-Wilson & Welsh (1978) demonstrated that spoken word recognition is strongly temporal, proceeding from the onset of acoustic-phonetic information at the beginning of a word. But most importantly for our purposes, they demonstrated that the listener entertains all possible similar-sounding words on the basis of information in the first few hundred milliseconds of the signal. For example, according to cohort theory, the spoken word /ɛlʌfənt/ (*elephant*) activates all similar-sounding word forms in memory that begin with /ɛ/ (e.g., *elephant*, *elevator*, *entertain*, *escalator*). The set of words activated on the basis of the initial portion of a word is called the word-initial cohort (hence the moniker cohort theory). As further acoustic-phonetic input is processed, those words that are inconsistent with the unfolding input drop out of contention for recognition. Thus, once information for /l/ in /ɛlʌfənt/ becomes available to the listener, words such as *escalator* and *entertain* are no longer viable candidates for recognition. According to cohort theory, once sufficient acoustic-phonetic information has accrued to uniquely specify a single word in the cohort, recognition of the word *elephant* occurs (roughly around /f/). In short, Marslen-Wilson's theory proposed that spoken words are recognized in the context of other similar sounding words activated in memory (also see Morton 1969).

Although cohorts and phonological neighborhoods are somewha t different theoretical entities, Marslen-Wilson & Welsh's (1978) early research nonetheless laid the groundwork for subsequent investigations of effects of similarity neighborhoods. Indeed, Marslen-Wilson's early theoretical statements provided the impetus for the original empirical work on neighborhoods of spoken words. According to the original cohort theory, activation of the word-initial cohort was hypothesized to be cost free for the processing system. That is, the number of words activated in the cohort was initially proposed to have no implications for either processing time or accuracy. Instead, speed of processing was hypothesized to depend solely on the point at which a word diverges—or becomes unique—from all other words in the cohort, and not on the number or nature (e.g., frequencies of occurrence) of words in the active cohort.

Various sources of evidence proved problematic for the claim in the early cohort theory that the time course of word recognition is primarily a function of the point at which a given word becomes unique in its cohort. For example, a computational analysis of uniqueness points of words (Luce 1986) demonstrated that a high percentage of short words (among the most frequently occurring in the language) have uniqueness points that occur after the end of the word, indicating that there are many short words that completely overlap with the initial portions of longer words (e.g., *car* with *carbohydrate*). This analysis questioned the applicability of the concept of divergence in the cohort as a primary determinant of the speed with which spoken words are recognized, demonstrating that most short words do not, in fact, possess uniqueness points.

However, the most problematic evidence against the cohort theory came from the earliest systematic research on similarity neighborhoods, which challenged cohort theory's cost-free assumption of cohort activation (as discussed in detail in Section 2). Nonetheless, the idea that spoken word recognition is best understood as a process of winnowing candidates from a set of similar-sounding words finds its origin in the early cohort theory.

1.3. Theory and Implementation

Before beginning our discussion of phonological (or similarity) neighborhood effects in spoken word processing, we need to clarify two aspects of phonological neighborhoods that have engendered some confusion in the literature. In theory, a phonological neighborhood is proposed to be a set of similar-sounding form-based representations that are activated in memory on the basis of stimulus input and compete for recognition. Details of the nature of these activated forms and the means by which they compete are theory specific. In implementation, either for the purposes of generating stimuli for behavioral experiments or for running computational simulations of predicted effects of phonological neighborhoods on recognition, neighborhoods have been defined in various ways, some of which are discussed below. Note that metrics for computing similarity neighborhoods are not the same as theoretical statements about the proposed effects of similarity neighborhood activation on recognition. A given metric for estimating the degree of lexical competition posed by the neighborhood of a given spoken word should not be taken as a theoretical claim about the precise nature of phonological neighbors: All metrics used to estimate the composition of similarity neighborhoods are approximations used to test theoretical claims.

In most cases, the research we describe is psycholinguistic in nature, examining the psychological processes involved in the perception or production of spoken words. This goal is not necessarily isomorphic with the goals of phonology, or linguistics more generally, where one seeks, among other things, to find the basic rules that define what a possible word is in a given language, and how those rules are acquired. Although our research may have influenced work to discover the basic rules that define a word (e.g., Albright 2007, Bailey & Hahn 2001, Frisch et al. 2000, Hahn & Bailey 2005), an in-depth discussion of that literature is beyond the scope of this review.

1.4. The One-Phoneme Metric

As discussed above, there are a variety of ways to operationally define a neighbor of a given word based on phonological similarity, but the simplest and most commonly employed method uses a variant of what is known as the Hamming or Levenshtein distance. According to this method, a neighbor of a target word is determined on the basis of the addition, deletion, or substitution of a phoneme in any position of the target word (Greenberg & Jenkins 1964, Landauer & Streeter 1973). Use of this metric shows that the target word *cat* has neighbors such as *scat* (via one-phoneme addition); *_at* (via one-phoneme deletion); and *fat*, *cot*, and *cab* (via one-phoneme substitutions). Again, the collection of neighbors computed in this manner is referred to as the phonological similarity neighborhood. The number of neighbors is referred to as neighborhood density. By computing the mean of the frequency of occurrence of the neighbors, one obtains a value referred to as neighborhood frequency.

Despite the computational simplicity of this metric, it captures much of listeners' judgments of what constitutes similarity among spoken words. For example, Luce & Large (2001) found that when listeners were presented with a spoken nonsense word, such as /fin/, and asked to say the first real English word that came to mind, more than 70% of the responses differed from the stimulus word by a single phoneme (also see Vitevitch et al. 2014a).

Although more complex metrics account for greater proportions of variance in reaction time measures of (visual) lexical decision and (visual) word naming (e.g., Yarkoni et al. 2008; also see Luce & Pisoni 1998, Luce et al. 2000), the simple one-phoneme metric has proven enormously useful in research on the effects of phonological neighborhood composition on word perception and production. For example, studies using this metric have demonstrated effects of neighborhood density in such disparate areas as word learning (Charles-Luce & Luce 1990, 1995; Storkel 2004), visual word recognition (Yates et al. 2004), and both short-term (Roodenrys et al. 2002) and long-term memory (Sommers & Lewis 1999). However, in the present review, we focus on the processes of spoken word perception and production.

2. SPOKEN WORD PERCEPTION

It is now widely accepted that spoken word perception is characterized by two fundamental processes: (*a*) multiple activation of similar-sounding form-based representations in memory (i.e., activation of the neighborhood) and (*b*) subsequent competition for recognition among these activated representations. Indeed, all current viable models of spoken word recognition implement, in one way or another, the activation of and subsequent competition among multiple form-based candidates (e.g., McClelland & Elman 1986, Marslen-Wilson 1987, Luce & Pisoni 1998, Luce et al. 2000, Norris & McQueen 2008).

2.1. Initial Evidence

Evidence demonstrating the influence of similarity neighborhoods on spoken word recognition comes from a number of sources. In the first extensive behavioral research on similarity neighborhood effects in spoken word perception, Luce & Pisoni (1998; also see Luce 1986) conducted three large-scale studies examining the effects of similarity neighborhood density and frequency on spoken word perception. For each of their studies, these authors estimated the similarity neighborhood densities and frequencies for a large number of consonant-vowel-consonant (CVC) words in English using a lexicon consisting of computer-readable phonemic transcriptions and word frequencies. They then assessed the influence of these computed neighborhoods on word perception in three standard word recognition tasks: perceptual identification, lexical decision, and single-word shadowing (or naming).

For the perceptual identification experiment, listeners were presented with spoken CVC words embedded in white noise and asked to type the word they heard. Because of the stimulus degradation employed, Luce & Pisoni (1998) used a unique means of computing similarity neighborhoods that took into account the specific effects of the white noise on their spoken stimuli (i.e., for this study, they did not use the one-phoneme metric). They first collected confusion matrices for all vowels and syllable-initial and -final consonants that constituted their CVC word stimuli. The confusion matrices were obtained using (primarily) nonsense CV or VC syllables presented to listeners in the same noise conditions in which they would present their word stimuli. After obtaining independent confusions for all of the relevant vowels and initial and final consonants, the authors then used the confusions to compute similarities among the words in their lexicon. For example, to compute the similarity of the target word *cat* /kæt/ to the potential neighbor *pick* /pɪk/, they used the previously obtained confusion matrices to determine the similarity of the initial consonants (/k/ and /p/), vowels (/æ/ and /ɪ/), and final consonants (/t/ and /k/). The individual conditional probabilities of segmental identification estimated from the confusion matrices [e.g., p(p|k), p(ɪ|æ), and p(k|t) for *pick* as a neighbor of *cat*] were then multiplied to produce a single similarity score for the neighbor *pick* relative to the target *cat* (pɪk|kæt). Finally, each similarity score for a given neighbor of a target was weighted by the neighbor's frequency of occurrence (based on the Kučera & Francis 1968 norms). Again, because Luce & Pisoni (1998) used confusions as proxies for similarities among segments, their neighborhood computations were not based on the one-phoneme metric. Instead, all CVC words in their lexicon served as potential neighbors of one another, with varying degrees of estimated similarities based on the confusions of the component segments. In this manner, the authors calculated similarity neighborhood scores for more than 800 CVC words (we refer the reader to Luce & Pisoni 1998 for additional details regarding the similarity calculations). These calculations produced wide variation in the predicted degree of neighborhood competition that depended on the degree of similarity of a target word to its neighbors as well as the frequencies of the targets and neighbors themselves.

Luce and Pisoni regressed their predicted neighborhood similarity scores against the accuracies of identification of the more the 800 words presented to listeners in noise. Their results showed a strong and predictable effect of similarity neighborhoods on identification: Words that were predicted to be highly similar to other words were identified less accurately than words predicted to be less similar. Moreover, words that were similar to high-frequency (i.e., common) words were also identified less accurately than words that were similar to less frequently (i.e., less commonly) occurring words. In short, words in high-similarity, high-frequency neighborhoods were identified less accurately than words in low-similarity, low-frequency neighborhoods.

Subsequently, Luce & Pisoni (1998) validated their findings in two other experiments—using the lexical decision and single-word shadowing experimental paradigms—that were designed to test the generalizability of the observed effects. In both experiments, the stimuli were presented in the absence of noise to demonstrate that degradation of the stimuli was not a requirement for obtaining neighborhood effects. In addition, the two follow-up experiments focused on reaction time measures to assess the effects of similarity neighborhoods on processing times. Finally, the authors used the one-phoneme metric to determine neighborhood density and frequency, thus testing the robustness of the effects across two different metrics for determining neighborhood composition. The results of both the lexical decision and single-word shadowing experiments supported and amplified the findings of the original perceptual identification experiment.

Luce and Pisoni modeled their results on the basis of an adaptation of Luce's (1961) choice rule. Briefly, this rule predicts that word processing time and accuracy are a function of the target word and its frequency relative to its neighbors and their frequencies:

$$p(\text{target identification}) = \frac{p(\text{target word}) * \text{frequency}}{\Sigma[p(\textit{neighbor}) * \text{frequency}_i]}.$$

This neighborhood probability rule predicts that increases in the denominator—which estimates the degree of neighborhood competition in the form of more similar and/or more frequent neighbors—will result in slower and less accurate processing, as observed in Luce and Pisoni's three experiments.

2.2. Priming

Further evidence for the effects of neighborhood competition comes from two early form-based priming experiments (Goldinger et al. 1989, Luce et al. 2000). In these investigations, the researchers hypothesized that raising the activation level of a specific neighbor in memory should affect processing of a target word. In the first set of studies, Goldinger et al. presented spoken neighbors as primes of target words. For example, listeners heard the prime *bull* followed by the target word *veer*. The target word, but not the prime, was embedded in noise, and the listeners' task was to identify the target only. A neighbor, or prime, for a given target word was determined using the same computational method employed by Luce & Pisoni (1998) in their first, perceptual identification experiment (see the previous section). Primes and targets were selected such that no actual phonemes overlapped between neighbor prime and target word, preventing listeners from developing conscious strategies based on the similarities of the primes and targets. (Indeed, a phonetically naïve listener would be hard-pressed to determine how two words such as *bull* and *veer* are similar.)

Goldinger et al. (1989) reasoned that a neighbor prime should briefly raise the activation level of the neighbor (*bull*) in memory, thus producing increased competition when a related target (*veer*) is immediately presented after the prime. In essence, they attempted to directly increase the value of the denominator of the neighborhood probability rule via increasing activation of a single neighbor. As predicted, when a related neighbor prime was presented immediately prior to the target, target identification was suppressed. The neighbor priming effect was transient (as predicted), disappearing when a short delay was introduced between the offset of the prime and onset of the target.

In a subsequent experiment, Luce et al. (2000) demonstrated that the neighbor priming effect could be obtained in a timed task (in this case, single-word shadowing) in which the stimuli were not degraded by noise. Moreover, Luce et al. used yet another method for computing neighborhood similarity based not on confusion matrices (which would have been inappropriate, given that the stimuli in this experiment were not degraded by white noise) but rather on subjective judgments of consonant and vowel similarities obtained in an independent experiment. Thus, the

Luce et al. study extended the empirical evidence for the effects of phonological neighborhoods on word processing to yet another paradigm using yet another metric for determining neighborhood similarity.

2.3. Phoneme Perception

Neighborhood density may influence multiple levels of processing and representations during spoken word recognition. For example, Newman et al. (1997) demonstrated an influence of neighborhood density on phoneme perception in an experiment that exploited the well-known Ganong effect. In the Ganong effect, listeners hear a sound that is engineered to have acoustic-phonetic properties that lie somewhere between two phonemes (e.g., a speech sound that lies between /g/ and /k/). When the ambiguous sound is placed in a context such as /_ɪft/, listeners report hearing more /g/s than /k/s, because only *gift* is a real word in English. Similarly when the context is /_ɪs/, listeners hear more /k/s than /g/s, again because only *kiss* is a real word in English.

In a variation on the Ganong paradigm, Newman et al. (1997) placed ambiguous segments (e.g., a segment ambiguous between /g/ and /k/) in word-initial contexts that formed nonsense words. However, in some instances the /g/ nonwords were similar to many real words in English (e.g., /gɑɪs/-/kɑɪs/, or *gice-kice*), whereas in other instances the /k/ nonwords were similar to many real words in English (e.g., /gɑɪp/-/kɑɪp/, or *gipe-kipe*). Newman et al. found that perception of the ambiguous segment shifted toward the nonword that had a denser neighborhood. That is, listeners heard more /g/s in the /gɑɪs/ (dense)–/kɑɪs/ (sparse) stimuli and more /k/s in the /gɑɪp/ (sparse)–/kɑɪp/ (dense) stimuli. These results demonstrated that lexical neighborhood density influences not only the recognition of words, but also the perception of phonetic segments themselves.

2.4. Probabilistic Phonotactics

At the same time that researchers were investigating the effects of phonological neighborhoods on segmental perception, Vitevitch and colleagues launched another series of studies examining the interplay between phonological lexical neighborhoods and segmental probabilistic phonotactics (Vitevitch et al. 1997; Vitevitch & Luce 1998, 1999, 2005; Vitevitch 2003). Vitevitch et al. defined phonotactic probability as the position-specific frequencies of segments and biphones. For example, *cat* is high in phonotactic probability because it has high-frequency segments in initial (/k/), medial (/æ/), and final (/t/) positions, as well as high-frequency biphones (/kæ/ and /æt/). Phonotactic probability and neighborhood density are positively correlated (Vitevitch et al. 1999), such that word forms with high phonotactic probability tend to have many phonological neighbors. As reported by Vitevitch et al. (1999), the analysis of 1,041 CVC words showed that the sum of the frequency of the segments in each word was positively correlated with the neighborhood density of the word ($r = .61$; $p < .0001$). The correlation between phonotactic probability and neighborhood density poses a conundrum: Previous research had clearly demonstrated that increases in neighborhood density are associated with less accurate and slower processing, although these same words in dense neighborhoods are composed of commonly occurring segments and biphones, which—by dint of their frequencies—should be perceived more accurately and more quickly.

Vitevitch & Luce (1999) suggested that this apparent contradiction could be accounted for if one assumes that probabilistic phonotactics govern the processing of sublexical representations, whereas effects of neighborhood density emerge from the processing of lexical representations (see Siew 2013 for a slightly different account). To test this hypothesis, they performed a series of experiments examining the simultaneous effects of neighborhood density and probabilistic phonotactics on both words and nonwords. Specifically, they generated words and nonwords that were high in both neighborhood density and probabilistic phonotactics or low in density and phonotactics (i.e., the two variables covaried, as is typically the case). For their word stimuli, they obtained the standard neighborhood density effect by using a single-word shadowing task: Words in densely populated neighborhoods were shadowed less quickly than words in sparsely populated neighborhoods. However, nonword processing reflected the probabilistic phonotactics: Nonwords that were high in segment and biphone frequency (and thus high in neighborhood density) were responded to more quickly than nonwords low in phonotactic probability (and thus low in neighborhood density). Partly on the basis of these results, Vitevitch & Luce (1999) argued that when lexical word forms are strongly activated by the input of a real word, competition occurs among the phonological word forms, resulting in the inhibitory effects of neighborhood density that are typically observed. When lexical word forms are not strongly activated, because of either the input of a nonword or the nature of the processing task (also see Vitevitch 2003), the sublexical segmental and biphone frequencies govern processing, producing facilitative effects of increased probabilistic phonotactics.

2.5. Beyond Behavior

Demonstrations of effects of similarity neighborhoods and probabilistic phonotactics are not exclusive to strictly behavioral paradigms (see Chen et al. 2011). Additional evidence that sublexical representations are responsible for the effects of phonotactic probability and that lexical representations are responsible for the effects of neighborhood density comes from a study by Pylkkänen et al. (2002) using magneto-encephelography (MEG). They found that the M350 component, an MEG component peaking at 300–400 ms, was affected by changes in phonotactic probability in the stimuli, but not by changes in neighborhood density. This finding not only replicated the results of Vitevitch & Luce (1999), but also established the M350 as an indicator of lexical processing (rather than a component evoked by postlexical processing). In addition, Dufour et al. (2012) and Hunter (2013) have demonstrated that effects of both probabilistic phonotactics and neighborhood activation are evident in event-related potentials. In particular, Hunter showed that the amplitude of the P2 potential is greater for high- versus low-density words (and nonwords) and that the latency of the P2 potential is shorter for words with high phonotactic probability (defined over the initial segment), providing electrophysiological evidence for previously demonstrated effects of both neighborhood density and probabilistic phonotactics.

2.6. Longer Words

Although the research on phonological neighborhoods discussed thus far has used a variety of paradigms (e.g., perceptual identification, lexical decision, single-word shadowing, and priming; also see Allopenna et al. 1998), stimulus presentation conditions (in noise and in the clear), and dependent variables (accuracy and reaction time), all the stimuli used were CVC words. Also, although these words constitute some of the most frequently used items in English, it is well known that longer words tend to have fewer phonological neighbors than shorter words, especially when the one-phoneme metric is used to determine neighborhood composition. Are effects of phonological neighborhoods restricted to short words?

Despite the relatively smaller neighborhoods of longer words, the competitive influence of neighborhood density has also been observed in bisyllabic words. For example, Cluff & Luce (1990) demonstrated that the neighborhood densities of individual syllables in bisyllabic words affect perception much the same as they do for shorter words. Using a perceptual identification task, Vitevitch et al. (2008) demonstrated that bisyllabic words in sparse neighborhoods (e.g., *badger*) were more accurately identified than bisyllabic words in dense neighborhoods (e.g., *babble*). Similarly, in a lexical decision task, longer words with sparse neighborhoods were responded to more quickly and more accurately than words with dense neighborhoods.

2.7. Slips of the Ear

An influence of neighborhood density can also be observed in the naturally occurring perceptual errors known as slips of the ear, in which the speaker produces the word correctly but the listener misperceives it. In an analysis of a slips-of-the-ear corpus published by Bond (1999), Vitevitch (2002b) found that words that were misperceived had denser neighborhoods than randomly selected words that were matched on a variety of factors, such as word length or part of speech, providing ecologically valid evidence of the influence of neighborhood density on spoken word recognition to complement the many findings of such influences from conventional psycholinguistic tasks performed in the laboratory.

2.8. Other Listeners and Other Languages

Although most of the work investigating neighborhood density in spoken word recognition (indeed, in much of psycholinguistics) has been done with college-aged native speakers of English, effects of neighborhood density on spoken word recognition have also been observed in other populations. For example, Dirks et al. (2001) found that adults with hearing impairment recognized words in sparse neighborhoods more quickly and accurately than words in dense neighborhoods. Likewise, Sommers & Danielson (1999; also see Sommers 1996) demonstrated that older adults show stronger effects of neighborhood density than younger adults—even when differences in hearing are taken into account. Sommers and Danielson argued that the greater sensitivity to neighborhood density in older adults is due to a more general deficit in inhibiting multiple activated items in memory.

The picture becomes more complicated, however, when we look at neighborhood density effects in spoken word recognition in other languages. Dufour & Frauenfelder (2010) have replicated the standard effect of neighborhood density in French. However, Vitevitch & Rodríguez (2005) observed a different pattern of results for Spanish words and listeners: Words in dense neighborhoods were responded to more quickly and accurately than words with sparse neighborhoods. Differences in how neighborhood density influences processing across languages should be viewed not as discrepancies, but as opportunities to increase our understanding of the variety of strategies used to process spoken language (Vitevitch et al. 2014b).

As is the case with spoken word production (see Section 3), it is unclear which factor (or factors) determines whether phonological neighbors will facilitate the retrieval of or compete with a phonological word form during spoken word recognition in a particular language. Given the wide variation in certain linguistic parameters among languages, it is not unreasonable to suggest that different solutions might be found to solve the processing problem at hand. Consider, for example, the different word segmentation strategies found in stress-timed languages such as English (Cutler & Norris 1988), in syllable-timed languages such as French (Mehler et al. 1981), and in mora-based languages such as Japanese (Otake et al. 1993), in which different strategies are used to solve the problem of segmenting a word from continuous speech. Vitevitch & Rodríguez (2005) suggested that the typical length of words in English and Spanish could be a reason for the different effects of neighborhood density: Words in Spanish tend to be longer than words in English (Vitevitch 2012). The additional processing demands of longer versus shorter words may lead to a different solution to the problem of word recognition—facilitation among neighbors instead of competition—in Spanish versus English.

Another factor that may influence whether competitive or facilitative influences are observed in a given language may lie in where in the word most of the neighbors overlap. Vitevitch & Stamer (2006) observed that morphological inflections typically affect the ends of the words in Spanish—a language that is more morphologically productive than English—leading to increased amounts of phonological overlap in the beginnings of Spanish neighbors and target words compared with English. Note that Vitevitch (2002a) observed more rapid responses to English words with few neighbors that shared the initial phoneme of the target word versus words with many neighbors that shared the initial phoneme of the target word. Given the influence of where neighbors overlap with the target word within a language, as well as the processing effects observed across words, it is not unreasonable to suggest that differences across languages in where phonological neighbors typically overlap with the target word might lead to different effects—competition or facilitation—in different languages.

Arbesman et al. (2010) observed that phonologically similar words in Spanish also tend to be semantically similar, whereas phonologically similar words in English tend to be simply phonologically similar. This cross-language difference in the additional relationships (morphological, semantic, etc.) found among phonological neighbors could also contribute to the different influence of neighborhood density observed in English and in Spanish. Examining the influence of phonological neighbors in a broader range of languages that differ from each other in specific ways (e.g., phoneme inventory, typical length of words, morphological productivity) may help answer this question.

Finally, the different influences of neighborhood density on spoken word recognition in English and Spanish raise some interesting questions for bilingual speakers of those two languages. For example, if Spanish neighbors facilitate recognition and English neighbors compete among each other during recognition, what happens when acoustic-phonetic input activates some Spanish word forms and some English word forms? An analysis of phonological word forms in a Spanish and an English dictionary shows that there are actually very few words in Spanish that have English words as neighbors (4%) and very few words in English that have Spanish words as neighbors (2%) (Vitevitch 2012). Furthermore, the increase in size of the neighborhood due to the addition of "foreign" neighbors is, on average, quite small—less than 5% (Vitevitch 2012; also see Marian et al. 2012). Thus, such crosslinguistic influences of phonological neighbors might be very small at best and are likely to be outweighed by various lexical characteristics within a language (Lemhöfer et al. 2008).

3. SPOKEN WORD PRODUCTION

A classic division in psycholinguistic models separates models in which processing proceeds in a strictly feed-forward manner from those that allow information (or activation) to flow back and forth between adjacent processing components or levels of representation in a feedback loop. In the domain of spoken word production, that division separates the speech production model by Levelt et al. (1999), which accounted for the chronometric aspects of speech production from conception to articulation, from the interactive-activation models by Dell (1986, 1988), which were designed to account for various types of speech production errors.

This classic division between feed-forward and interactive models in the domain of spoken word production yields different predictions about the influence of phonologically similar words on processing. In the strictly feed-forward model of speech production proposed by Levelt et al., once a concept and a lemma are selected, activation of the associated phonological word form proceeds automatically. There is no way that other, similar-sounding words can be activated or affect speech production. In contrast, in the interactive models by Dell, the intended word activates its constituent phonological segments, and activation from the phonological segments then flows back to other words that share those segments with the intended word, providing a mechanism for several similar-sounding words to affect production. Thus, neighborhood effects in speech production, should they exist, may help discriminate among feed-forward and interactive models.

3.1. Malapropisms

An analysis of word substitution errors known as malapropisms provides some evidence that the number of words that are phonologically similar to a target word could affect speech production (Vitevitch 1997). Malapropisms are whole-word substitutions that are phonologically but not semantically related. An example is saying *octane* instead of *octave* in a discussion about music. In an analysis of a corpus of malapropisms, Vitevitch (1997) found that malapropisms tended to have sparser neighborhoods compared with a randomly sampled set of control words (matched in word length and part of speech), suggesting that words that have few phonological neighbors may be more prone to speech production errors than words that have many phonological neighbors.

3.2. Spoonerisms of Laboratory-Induced Predisposition and Tongue Twisters

Additional evidence that having many phonological neighbors may facilitate the speed and accuracy with which a word is produced comes from a study that used two different speech error elicitation techniques—Spoonerisms of laboratory-induced predisposition (SLIP) and tongue twisters—as well as the picture-naming task (Vitevitch 2002b; also see Stemberger 2004). In the SLIP and tongue twister tasks, participants are presented with words that have alternating onsets. An example of a tongue twister from Vitevitch (2002b) is *peach balm bull pig* (note the alternation of /p/-/b/ and /b/-/p/ in the onset position of the words). When put under time pressure to produce the words ("Say the words seven times as quickly as you can"), participants often switch the initial phonemes of adjacent words, producing an error such as *beach palm bull pig*.

In the error elicitation tasks, Vitevitch (2002b) found that more speech errors were elicited in words that had sparse phonological neighborhoods than dense phonological neighborhoods (despite the similarity among the words in a variety of other relevant linguistic characteristics), demonstrating that dense neighborhoods support or strengthen production-relevant representations. In the picture-naming task, words with sparse phonological neighborhoods were named more slowly than words with dense phonological neighborhoods, providing evidence that phonological neighbors influence the accuracy and, importantly, the speed with which words are produced.

3.3. Tip of the Tongue

Additional evidence that phonological neighbors influence the retrieval of words during speech production comes from studies examining the tip-of-the-tongue (ToT) phenomenon. In the ToT state, the speaker attempts to retrieve a word from the lexicon but is unable to do so. Often the speaker can retrieve some information about the word, such as its meaning (e.g., "the thing you use in a submarine to look above the water"), the number of syllables in the word (e.g., three), the first letter or sound of the word, and perhaps other words that sound like the target word (e.g., microscope, telescope), but not the intended word (e.g., periscope). ToT states have been documented in diary studies (Burke et al. 1991; see also Vitevitch et al. 2015), in which participants kept a journal detailing each occurrence of a ToT state, and they have been elicited in the laboratory by giving participants a definition and asking them to provide the best-fitting word (Brown & McNeill 1966): for example, “What do you call an onion-like spice?” (chive, oregano, mint, curry). In ToT elicitation tasks, more ToTs were elicited for words with sparse phonological neighborhoods than for words with dense phonological neighborhoods (Vitevitch & Sommers 2003; also see Harley & Bown 1998, James & Burke 2000).

3.4. Aphasia

A similar influence of neighborhood density on speech production has also been observed in patients with aphasia (Gordon & Dell 2001, Gordon 2002, Vitevitch & Castro 2015). To further examine the influence of neighborhood density on (normal and aphasic) speech production, Dell & Gordon (2003) conducted computer simulations in a two-step interactive-activation model in which semantic features activated the associated lemma, and the activated lemma activated its constituent phonemes. The results of their simulations—with “normal” parameters and with parameters that represented “lesions” to the model—showed more speech production errors for words with few phonological neighbors versus words with more phonological neighbors, consistent with the behavioral data from aphasics.

3.5. Other Languages

Note that all of the studies described above examined the production of English words by native English speakers. Whereas the influence of word frequency and many other lexical characteristics is the same across languages (e.g., high-frequency words are produced more quickly and accurately than low-frequency words), the influence of phonological neighborhood density in spoken word production and spoken word recognition may differ (as discussed above). Vitevitch & Stamer (2006) asked native speakers of Spanish to produce Spanish words that named various objects in a picture-naming task. Crucially, the names of the objects varied in the number of Spanish words that were phonological neighbors.

Instead of obtaining the expected facilitative influence typically observed in English, Vitevitch & Stamer (2006) found that their participants named Spanish words with few phonological neighbors more quickly than Spanish words with many phonological neighbors (a reversal of the typical neighborhood effect in production that is reminiscent of the reversal in perceptual results for Spanish); this effect was also replicated by Sadat et al. (2014). A reanalysis of reaction times from Spanish speakers in the Bates et al. (2003) picture-naming database was also consistent with this observation (Vitevitch & Stamer 2009). As in the case of spoken word recognition, it is not clear what factor (or factors) determines whether phonological neighbors facilitate the retrieval of or compete with a phonological word form during speech production. Presumably the same factors that influence spoken word recognition also account for the different influence of neighborhood density observed in spoken word production.

3.6. Other Populations

Speaker-specific factors, such as the age of the speaker, whether the speaker has developed along a typical trajectory, or whether the speaker has a speech or language disorder, may also influence whether phonological neighbors facilitate speech production (e.g., German & Newman 2004) or compete among each other (e.g., Newman & German 2002, 2005). One need also consider the particular task used in the speech production experiment, as different tasks may assess different aspects of the speech production process and neighborhood density may have different influences on processing at different levels of the system. For example, Munson & Solomon (2004; also see Wright 2004) found that neighborhood density influences the formant frequencies of vowels in real words produced by adults. Specifically, vowels in words with dense neighborhoods were more dispersed than the same vowels in words with sparse neighborhoods, suggesting that neighborhood density can influence certain aspects of the articulation of speech in addition to the retrieval of phonological word forms during speech production.

Finally, Hoover et al. (2012) suggest that neighborhood density might also influence "higher" morphosyntactic levels of processing during speech production. Hoover et al. found that (typically developing) children were less likely to use optional infinitives with dense rather than sparse verbs, suggesting that the more robustly represented dense words facilitate accurate finiteness marking. In short, there remain many interesting and open questions regarding the influence of phonological neighborhood density on speech production.

4. BEYOND THE NEIGHBORHOOD

The studies reviewed above have increased our understanding of lexical processing during the production and perception of spoken words by elucidating the role of phonological neighborhoods in multiple activation of and subsequent competition among sound-based patterns in memory (also see computational work in Chen & Mirman 2012). More recent work employing computational tools from network science has allowed language researchers to expand the way that phonological neighborhoods can be measured and to assess the influence of those alternative measures on lexical processing.

Network science draws on work from mathematics, sociology, computer science, physics, and other fields that examine complex systems by using nodes (or vertices) to represent individual entities, and connections (or edges) to represent relationships between entities to form a weblike structure, or network, of the entire system. This approach has been used to examine complex systems in economic, biological, social, and technological domains (Barabási 2009) and has recently been used to examine semantic information in the lexicon (Hills et al. 2009) as well as phonological relationships among words in the lexicon (Vitevitch 2008).

4.1. Degree

In network science, a common measurement of the structure of a network is known as degree, which refers to the number of connections incident to a given node. In the context of a phonological network such as that of Vitevitch (2008), in which a node corresponds to a word form, degree corresponds to the number of word forms that sound similar to a given word. In other words, degree corresponds to phonological neighborhood density (based on the widely used one-phoneme metric); thus, we use the terms degree and phonological neighborhood density interchangeably.

4.2. Clustering Coefficient

Another measurement employed in network science is the clustering coefficient, C (Watts & Strogatz 1998), which, in the context of a phonological network, measures the extent to which neighbors of a given node are also neighbors of each other. The clustering coefficient has a range from zero to one; when $C = 0$, none of the neighbors of a target node are neighbors of each other, and when $C = 1$, every neighbor of a target word is also a neighbor of all of the other neighbors of a target word. In **Figure 1**, degree corresponds to the number of connections between the words *badge* and *log* to their respective neighbors (both words have 13 neighbors). In the figure, the

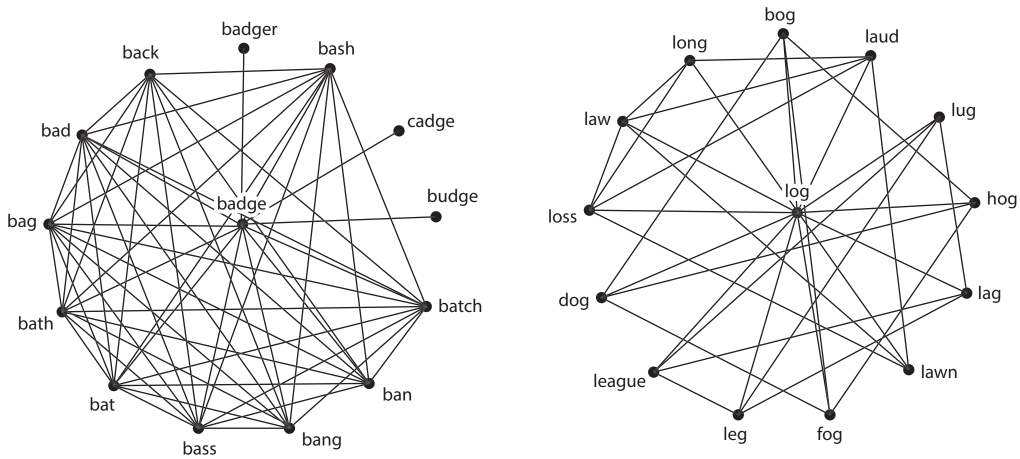

Figure 1

(*a*) The word *badge* has high *C*, (*b*) and the word *log* has low *C*. Both words have the same number of neighbors (i.e., the same degree). Connections are placed between words that are phonologically similar. For visual clarity, connections from the neighbors to other words in the network are not shown. Modified from Chan & Vitevitch (2009).

clustering coefficient is represented by the connections between a neighbor of *badge* to another neighbor of *badge* (e.g., the connection between *bass* and *bat*) or between a neighbor of *log* to another neighbor of *log* (e.g., the connection between *league* and *leg*).

The clustering coefficient is computed for a word (i.e., the local clustering coefficient for an undirected graph) as follows:

$$C_i = \frac{2|\{e_{jk}\}|}{k_i(k_i - 1)}, \tag{1}$$

where e_{jk} refers to the presence of a connection (or edge) between two neighbors (j and k) of node i; $|\cdots|$ is used to indicate cardinality, or the number of elements in the set (not absolute value); and k_i refers to the degree (i.e., neighborhood density) of node i. By convention, a node with degree of zero or one (which results in division by zero—an undefined value) is assigned a clustering coefficient value of zero. Thus, the (local) clustering coefficient is the proportion of connections that exist among the neighbors of a given node divided by the number of connections that could exist among the neighbors of a given node.

Although degree/neighborhood density and the clustering coefficient may appear to be conceptually related, Vitevitch et al. (2012) showed that they are not correlated in the phonological network of English. The results of several studies—using a variety of conventional psycholinguistic and memory tasks, as well as computer simulations—demonstrated that the clustering coefficient influences language-related processes such as spoken word recognition, word production, retrieval from long-term memory, and reintegration in short-term memory (Chan & Vitevitch 2009, 2010; Vitevitch et al. 2011, 2012). Furthermore, a computer simulation reported by Vitevitch et al. (2011), which implemented a very simple diffusion mechanism on a network representation of the lexicon, found independent effects of degree/neighborhood density and clustering coefficient, further demonstrating that these variables have distinct influences on spoken word recognition.

Recent work on the clustering coefficient in the context of network models of spoken word processing demonstrates that the traditional notion of a phonological neighborhood fails to account for the complexities of form-based lexical competition. Recall that Luce & Pisoni (1998) proposed that competition within a phonological neighborhood can be captured by a simple application of

Luce's choice rule, in which individual activation levels of neighbors are simply summed (and weighted) as a measure of competition. However, such an account ignores the possibility that interactions among the activated neighbors themselves influence processing.

Interactive-activation models of spoken word perception such as TRACE, Shortlist, and even PARSYN (a connectionist instantiation of Luce and Pisoni's neighborhood probability rule) all propose that neighbors interact with and inhibit one another as well as the target word. Such interactions suggest that neighbors of neighbors may mitigate the effects of lexical competition. If a similar-sounding neighbor has the ability to inhibit the recognition of a target word, as repeatedly demonstrated in the literature reviewed above, these neighbors may also inhibit one another. That is, if the neighbors of a target word themselves have inhibiting neighbors, might a cascading effect of inhibition be observed on target processing?

To address this question, M. Geer & P.A. Luce (manuscript submitted) presented listeners with two sets of words matched on the traditional one-phoneme metric of phonological neighborhood density. In one set, the neighbors of the target words had few neighbors of their own—the "low neighbors of neighbors" condition. In the other set, the direct neighbors of the target words had many potentially inhibitory neighbors of their own—the "high neighbors of neighbors" condition. The authors reasoned that if the neighbors themselves have many inhibiting neighbors, their influence on the target word should be attenuated. That is, neighbors of neighbors should weaken competitive neighborhood effects on the target itself. This is precisely what they found: Words with neighbors that themselves have many neighbors were responded to more quickly than words with neighbors with few neighbors, demonstrating that neighbors inhibit one another, as predicted by interactive-activation models. These results thus provide a direct challenge to the simple neighborhood probability rule proposed by Luce & Pisoni (1998), suggesting that more sophisticated conceptualizations of neighborhood dynamics—such as those elucidated by the network models discussed above—are required to fully capture the complexities of phonological neighborhood activation.

Clearly, additional research is required to evaluate whether widely accepted models of spoken word recognition can account for the observed influences that other relationships among phonological neighbors have on word recognition. Whereas some influences may still be accounted for by these models (see the simulation of assortative mixing by degree in Vitevitch et al. 2014a,b), Chan & Vitevitch (2009) demonstrated in a computer simulation using jTRACE (Strauss et al. 2007) that the processes and representations described in widely accepted models of spoken word recognition were not able to account for the influence of clustering coefficient on spoken word recognition. Such challenging findings to widely accepted models of spoken word recognition—many of which are more than 25 years old—suggest that it may be time to reconsider some of the assumptions of these models.

5. CONCLUSION

Over the past few decades, much research on spoken word processing has been devoted to understanding multiple activation of and competition among form-based lexical representations in memory. In particular, a significant portion of this research has examined the effects of phonological neighborhoods (and the concomitant effects of phonotactic probability) on a number of language and cognitive processes in a variety of populations. Research on phonological neighborhoods has directly informed a number of current models of spoken word recognition—in particular, the Neighborhood Activation Model (Luce & Pisoni 1998), Shortlist (Norris 1994), and their descendants (Luce et al. 2000, Norris & McQueen 2008)—and has spawned new conceptualizations of the activation-competition process (Chan & Vitevitch 2009).

Despite the large number of studies that have examined effects of phonological neighborhoods and phonotactic probability, many questions, of course, remain: How do we best account for the seemingly contradictory effects of phonotactic probability and neighborhood density? Are the effects of similarity neighborhoods and probabilistic phonotactics the same across languages? How do these sublexical and lexical characteristics influence other levels of processing? It is also important to consider how current models of spoken word recognition and speech production account for the wide-ranging influence of these variables—or even if certain models of language processing can account for the influence of these variables. Whether our tried and trusted models can accommodate these new findings and further increase our understanding of language processing, or whether these approaches have reached their limit, remains to be determined.

Throughout history, the major technology that defined that particular era—water power, the clock, the steam engine, the digital computer—provided a useful metaphor for understanding how the mind works. The current prevalence of Internet-related technologies may have led some researchers in the language and cognitive sciences to adopt a network metaphor. The network approach has increased our understanding of various aspects of human cognition, and holds much promise to provide new accounts of the questions that have been the focus of much previous and contemporary language research. Most importantly, this approach may provide new insights that spur researchers to ask novel questions about the representation and processing of spoken language.

Network science differs from alternative approaches in that network science is equal parts theory and methodology: "[N]etworks offer both a theoretical framework for understanding the world and a methodology for using this framework to collect data, test hypotheses, and draw conclusions" (Neal 2013, p. 5). The network approach forces us to focus on more than a single characteristic of an individual word at time, such as word frequency or uniqueness point (Cutler 1981). Instead, this approach prompts us to consider how the structure of the network influences dynamics within the network. That is, lexical processing is influenced by the relationships that a word has with other words in the lexicon—and the large-scale structure of the lexicon—not simply the characteristics of the word itself. We hope that, like research on phonological neighborhoods, the perspective afforded by the network approach will inspire the next generation of language scientists to theorize about language processing in novel ways, develop new computational models, and successfully apply our knowledge of language processing in humans to a wide variety of uses.

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LITERATURE CITED

Albright A. 2007. *Gradient phonological acceptability as a grammatical effect*. Work. pap., Dep. Linguist., MIT

Allopenna PD, Magnuson JS, Tanenhaus MK. 1998. Tracking the time course of spoken word recognition using eye movements: evidence for continuous mapping models. *J. Mem. Lang.* 38:419–39

Arbesman S, Strogatz SH, Vitevitch MS. 2010. Comparative analysis of networks of phonologically similar words in English and Spanish. *Entropy* 12:327–37

Bailey T, Hahn U. 2001. Determinants of wordlikeness: phonotactics or lexical neighborhoods? *J. Mem. Lang.* 44:568–91

Barabási AL. 2009. Scale-free networks: a decade and beyond. *Science* 325:412–13

Bates E, D'Amico S, Jacobsen T, Szekely A, Andonova E, et al. 2003. Timed picture naming in seven languages. *Psychon. Bull. Rev.* 10:344–80

Bond ZS. 1999. *Slips of the Ear: Errors in the Perception of Casual Conversation*. New York: Academic

Brown R, McNeill D. 1966. The "tip of the tongue" phenomenon. *J. Verbal Learn. Verbal Behav.* 5:325–37

Burke DM, MacKay DG, Worthley JS, Wade E. 1991. On the tip of the tongue: What causes word finding problems in young and older adults? *J. Mem. Lang.* 30:542–79

Chan KY, Vitevitch MS. 2009. The influence of the phonological neighborhood clustering-coefficient on spoken word recognition. *J. Exp. Psychol. Hum. Percept. Perform.* 35:1934–49

Chan KY, Vitevitch MS. 2010. Network structure influences speech production. *Cogn. Sci.* 34:685–97

Charles-Luce J, Luce PA. 1990. Some structural properties of words in young children's lexicons. *J. Child Lang.* 17:205–15

Charles-Luce J, Luce PA. 1995. An examination of similarity neighbourhoods in young children's receptive vocabularies. *J. Child Lang.* 22:727–35

Chen Q, Mirman D. 2012. Competition and cooperation among similar representations: toward a unified account of facilitative and inhibitory effects of lexical neighbors. *Psychol. Rev.* 199:417–30

Chen HC, Vaid J, Boas DA, Bortfeld H. 2011. Examining the phonological neighborhood density effect using near infrared spectroscopy. *Hum. Brain Mapp.* 32:1363–70

Cluff M, Luce PA. 1990. Similarity neighborhoods of spoken two-syllable words: retroactive effects on multiple activation. *J. Exp. Psychol. Hum. Percept. Perform.* 16:551–63

Cutler A. 1981. Making up materials is a confounded nuisance, or: Will we able to run any psycholinguistic experiments at all in 1990? *Cognition* 10:65–70

Cutler A, Norris D. 1988. The role of strong syllables in segmentation for lexical access. *J. Exp. Psychol. Hum. Percept. Perform.* 14:113–21

Dell GS. 1986. A spreading-activation theory of retrieval in sentence production. *Psychol. Rev.* 93:283–321

Dell GS. 1988. The retrieval of phonological forms in production: tests of predictions from a connectionist model. *J. Mem. Lang.* 27:124–42

Dell GS, Gordon JK. 2003. Neighbors in the lexicon: friends or foes? In *Phonetics and Phonology in Language Comprehension and Production: Differences and Similarities*, ed. NO Schiller, AS Meyer, pp. 9–37. New York: de Gruyter

Dirks DD, Takayanagi S, Moshfegh A, Noffsinger PD, Fausti SA. 2001. Examination of the neighborhood activation theory in normal and hearing-impaired listeners. *Ear Hear.* 22:1–13

Dufour S, Brunelliere A, Frauenfelder UH. 2012. Tracking the time course of word-frequency effects in spoken word recognition with event-related potentials. *Cogn. Sci.* 37:489–507

Dufour S, Frauenfelder UH. 2010. Phonological neighbourhood effects in French spoken-word recognition. *Q. J. Exp. Psychol.* 63:226–38

Frisch SA, Large NR, Pisoni DB. 2000. Perception of wordlikeness: effects of segment probability and length on the processing of nonwords. *J. Mem. Lang.* 42:481–96

German DJ, Newman RS. 2004. The impact of lexical factors on children's word-finding errors. *J. Speech Lang. Hear. Res.* 47:624–36

Goldinger SD, Luce PA, Pisoni DB. 1989. Priming lexical neighbors of spoken words: effects of competition and inhibition. *J. Mem. Lang.* 28:501–18

Gordon JK. 2002. Phonological neighborhood effects in aphasic speech errors: spontaneous and structured contexts. *Brain Lang.* 82:113–45

Gordon JK, Dell GS. 2001. Phonological neighborhood effects: evidence from aphasia and connectionist models. *Brain Lang.* 79:21–23

Greenberg JH, Jenkins JJ. 1964. Studies in the psychological correlates of the sound system of American English. *Word* 20:157–77

Hahn U, Bailey TM. 2005. What makes words sound similar? *Cognition* 97:227–67

Harley TA, Bown HE. 1998. What causes a tip-of-the-tongue state? Evidence for lexical neighbourhood effects in speech production. *Br. J. Psychol.* 89:151–74

Hills TT, Maouene M, Maouene J, Sheya A, Smith L. 2009. Longitudinal analysis of early semantic networks: preferential attachment or preferential acquisition? *Psychol. Sci.* 20:729–39

Hoover JR, Storkel HL, Rice ML. 2012. The interface between neighborhood density and optional infinitives: normal development and specific language impairment. *J. Child Lang.* 39:835–62

Hunter CR. 2013. Early effects of neighborhood density and phonotactic probability of spoken words on event-related potentials. *Brain Lang.* 127:462–74

James LE, Burke DM. 2000. Phonological priming effects on word retrieval and tip-of-the-tongue experiences in young and older adults. *J. Exp. Psychol. Learn. Mem. Cogn.* 26:1378–91

Kučera H, Francis WN. 1967. *Computational Analysis of Present Day American English*. Providence, RI: Brown Univ. Press

Landauer TK, Streeter LA. 1973. Structural differences between common and rare words: failure of equivalence assumptions for theories of word recognition. *J. Verbal Learn. Verbal Behav.* 12:119–31

Lemhöfer K, Dijkstra T, Schriefers H, Baayen RH, Grainger J, Zwisterlood P. 2008. Native language influences on word recognition in a second language: a megastudy. *J. Exp. Psychol. Learn. Mem. Cogn.* 34:12–31

Levelt WJM, Roelofs A, Meyer AS. 1999. A theory of lexical access in speech production. *Behav. Brain Sci.* 22:1–75

Luce PA. 1986. A computational analysis of uniqueness points in auditory word recognition. *Percept. Psychophys.* 39:155–58

Luce PA, Goldinger SD, Auer ET Jr, Vitevitch MS. 2000. Phonetic priming, neighborhood activation, and PARSYN. *Percept. Psychophys.* 62:615–25

Luce PA, Large NR. 2001. Phonotactics, density and entropy in spoken word recognition. *Lang. Cogn. Process.* 16:565–81

Luce PA, Pisoni DB. 1987. Speech perception: new directions in research, theory, and applications. In *Human Communication and Its Disorders*, *A Review*, Vol. 1, ed. H Winitz, pp. 1–87. Westport, CT: Ablex

Luce PA, Pisoni DB. 1998. Recognizing spoken words: the neighborhood activation model. *Ear Hear.* 19:1–36

Luce RD. 1961. A choice theory analysis of similarity judgments. *Psychometrika* 26:151–63

Marian V, Bartolotti J, Chabal S, Shook A. 2012. CLEARPOND: Cross-Linguistic Easy-Access Resource for Phonological and Orthographic Neighborhood Densities. *PLOS ONE* 7:e43230

Marslen-Wilson WD. 1987. Functional parallelism in spoken word-recognition. *Cognition* 25:71–102

Marslen-Wilson WD, Welsh A. 1978. Processing interactions and lexical access during word recognition in continuous speech. *Cogn. Psychol.* 10:29–63

McClelland JL, Elman JL. 1986. The TRACE model of speech perception. *Cogn. Psychol.* 18:1–86

Mehler J, Dommergues JY, Frauenfelder U, Segui J. 1981. The syllable's role in speech segmentation. *J. Verbal Learn. Verbal Behav.* 20:298–305

Morton J. 1969. Interaction of information in word recognition. *Psychol. Rev.* 76:165–78

Munson B, Solomon NP. 2004. The effect of phonological neighborhood density on vowel articulation. *J. Speech Lang. Hear. Res.* 47:1048–58

Neal ZP. 2013. *The Connected City: How Networks Are Shaping the Modern Metropolis*. New York: Routledge

Newman RS, German DJ. 2002. Effects of lexical factors on lexical access among typical language-learning children and children with word-finding difficulties. *Lang. Speech* 45:285–317

Newman RS, German DJ. 2005. Life span effects of lexical factors on oral naming. *Lang. Speech* 48:123–56

Newman RS, Sawusch JR, Luce PA. 1997. Lexical neighborhood effects in phonetic processing. *J. Exp. Psychol. Hum. Percept. Perform.* 23:873–89

Norris D. 1994. Shortlist: a connectionist model of continuous speech recognition. *Cognition* 52:189–234

Norris D, McQueen JM. 2008. Shortlist B: a Bayesian model of continuous speech recognition. *Psychol. Rev.* 115:357–95

Otake T, Hatano G, Cutler A, Mehler J. 1993. Mora or syllable? Speech segmentation in Japanese. *J. Mem. Lang.* 32:258–78

Pylkkänen L, Stringfellow A, Marantz A. 2002. Neuromagnetic evidence for the timing of lexical activation: an MEG component sensitive to phonotactic probability but not to neighborhood density. *Brain Lang.* 81:666–78

Roodenrys S, Hulme C, Lethbridge A, Hinton M, Nimmo LM. 2002. Word-frequency and phonological-neighborhood effects on verbal short-term memory. *J. Exp. Psychol. Learn. Mem. Cogn.* 28:1019–34

Sadat J, Martin CD, Costa A, Alario FX. 2014. Reconciling phonological neighborhood effects in speech production through single trial analysis. *Cogn. Psychol.* 68:33–58

Siew CSQ. 2013. Community structure in the phonological network. *Front. Psychol.* 4:533
Sommers MS. 1996. The structural organization of the mental lexicon and its contributions to age-related declines in spoken word recognition. *Psychol. Aging* 11:333–41
Sommers MS, Danielson SE. 1999. Inhibitory processes and spoken word recognition in young and older adults: the interaction of lexical competition and semantic context. *Psychol. Aging* 14:458–72
Sommers MS, Lewis BP. 1999. Who really lives next door: creating false memories with phonological neighbors. *J. Mem. Lang.* 40:83–108
Stemberger JP. 2004. Neighbourhood effects on error rates in speech production. *Brain Lang.* 90:413–22
Storkel HL. 2004. Do children acquire dense neighborhoods? An investigation of similarity neighborhoods in lexical acquisition. *Appl. Psycholinguist.* 25:201–21
Strauss TJ, Harris HD, Magnuson JS. 2007. jTRACE: a reimplementation and extension of the TRACE model of speech perception and spoken word recognition. *Behav. Res. Methods* 39:19–30
Vitevitch MS. 1997. The neighborhood characteristics of malapropisms. *Lang. Speech* 40:211–28
Vitevitch MS. 2002a. Influence of onset density on spoken-word recognition. *J. Exp. Psychol. Hum. Percept. Perform.* 28:270–78
Vitevitch MS. 2002b. Naturalistic and experimental analyses of word frequency and neighborhood density effects in slips of the ear. *Lang. Speech* 45:407–34
Vitevitch MS. 2003. The influence of sublexical and lexical representations on the processing of spoken words in English. *Clin. Linguist. Phon.* 17:487–99
Vitevitch MS. 2008. What can graph theory tell us about word learning and lexical retrieval? *J. Speech Lang. Hear. Res.* 51:408–22
Vitevitch MS. 2012. What do foreign neighbors say about the mental lexicon? *Biling. Lang. Cogn.* 15:167–72
Vitevitch MS, Castro N. 2015. Using network science in the language sciences and clinic. *Int. J. Speech Lang. Pathol.* 17:13–25
Vitevitch MS, Chan KY, Goldstein R. 2014a. Insights into failed lexical retrieval from network science. *Cogn. Psychol.* 68:1–32
Vitevitch MS, Chan KY, Goldstein R. 2014b. Using English as a 'model language' to understand language processing. In *Motor Speech Disorders A Cross-Language Perspective*, ed. N Miller, A Lowit, pp. 58–73. Bristol, UK: Multiling. Matters
Vitevitch MS, Chan KY, Roodenrys S. 2012. Complex network structure influences processing in long-term and short-term memory. *J. Mem. Lang.* 67:30–44
Vitevitch MS, Ercal G, Adagarla B. 2011. Simulating retrieval from a highly clustered network: implications for spoken word recognition. *Front. Lang. Sci.* 2:369
Vitevitch MS, Luce PA. 1999. Probabilistic phonotactics and neighborhood activation in spoken word recognition. *J. Mem. Lang.* 40:374–408
Vitevitch MS, Luce PA. 1998. When words compete: levels of processing in spoken word perception. *Psychol. Sci.* 9:325–29
Vitevitch MS, Luce PA. 2005. Increases in phonotactic probability facilitate spoken nonword repetition. *J. Mem. Lang.* 52:193–204
Vitevitch MS, Luce PA, Charles-Luce J, Kemmerer D. 1997. Phonotactics and syllable stress: implications for the processing of spoken nonsense words. *Lang. Speech* 40:47–62
Vitevitch MS, Luce PA, Pisoni DB, Auer ET. 1999. Phonotactics, neighborhood activation and lexical access for spoken words. *Brain Lang.* 68:306–11
Vitevitch MS, Rodríguez E. 2005. Neighborhood density effects in spoken word recognition in Spanish. *J. Multiling. Commun. Disord.* 3:64–73
Vitevitch MS, Siew CSQ, Castro N, Goldstein R, Gharst JA, et al. 2015. Speech error and tip of the tongue diary for mobile devices. *Front. Psychol.* 6:1190
Vitevitch MS, Sommers M. 2003. The facilitative influence of phonological similarity and neighborhood frequency in speech production. *Mem. Cogn.* 31:491–504
Vitevitch MS, Stamer MK. 2006. The curious case of competition in Spanish speech production. *Lang. Cogn. Process.* 21:760–70
Vitevitch MS, Stamer MK. 2009. *The influence of neighborhood density (and neighborhood frequency) in Spanish speech production: a follow-up report*. Spoken Lang. Lab. tech. rep., Univ. Kans., Lawrence. 6 pp.

Vitevitch MS, Stamer MK, Sereno JA. 2008. Word length and lexical competition: Longer is the same as shorter. *Lang. Speech* 51:361–83

Watts DJ, Strogatz SH. 1998. Collective dynamics of 'small-world' networks. *Nature* 393:409–10

Wright R. 2004. Factors of lexical competition in vowel articulation. In *Laboratory Phonology 6*, ed. JJ Local, R Ogden, R Temple, pp. 75–87. Cambridge, UK: Cambridge Univ. Press

Yarkoni T, Balota DA, Yap MJ. 2008. Beyond Coltheart's *N*: a new measure of orthographic similarity. *Psychon. Bull. Rev.* 15:971–79

Yates M, Locker L Jr, Simpson GB. 2004. The influence of phonological neighborhood on visual word perception. *Psychon. Bull. Rev.* 11:452–57