Neighbors in the lexicon: Friends or foes?

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1. Introduction

What makes a word easy to say? For the most part, the same things that make a word easy to understand make that word easy to say. Consider word frequency. Common words can be both produced (e.g. Caramazza et al. 2001; Dell 1990; Jescheniak and Levelt 1994) and recognized (e.g. Luce and Pisoni 1998; Oldfield and Wingfield 1965; Soloman and Postman 1952) with greater facility than rare words. One would be quite surprised to learn otherwise, because both production and recognition are adaptive systems designed to process the most likely events with the greatest ease.

Other lexical variables also affect production and recognition similarly. Concrete words are favored over abstract words in both production (e.g. Martin, Saffran, and Dell 1996) and recognition (Strain, Patterson, and Seidenberg 1995). Predictable words can be recognized (Morton and Long 1976) and produced (Griffin and Bock 1998) more quickly than those that are less congruent with their contexts. Even the speed associated with the perception of shorter words has its counterpart in production. The articulation of single-syllable words can begin more quickly than that of two-syllable words (Meyer, Roelofs, and Levelt 2003). None of these results are surprising. Our intuitions as well as our psychological theories are built around assumptions that lead to efficient processing for simple or familiar mental entities, regardless of whether those entities are incoming stimuli or outgoing responses.

This chapter focuses on a lexical property that appears to have opposite effects on receptive and expressive processes. That property is the number of words that are phonologically similar to the targeted word, called *phonological neighborhood density*. A word that is highly similar in sound to many other words is said to come from a *dense* neighborhood; a word with few similar-sounding words inhabits a *sparse* neighborhood. By the most popular current estimation procedure (Luce et al. 1990), two words are considered to be "neighbors" if they differ by only one phoneme, either substituted, added, or omitted. Thus, *cat* has *cast*, *rat*, and *at* among its 35 neighbors and, by most criteria, would be considered to come from a dense neighborhood. In contrast, *dog* has only 8 neighbors. Many long words (e.g. *elephant*) and the occasional short word (e.g. *again*) have no neighbors at all. (Neighborhood densities were determined from the Hoosier Mental Lexicon, an on-line lexicon of almost 20,000 English words, Luce et al. 1990.)

Neighborhood density has been established, then, as another dimension along which words may differ. But what is the implication of this? Does having many neighbors make it easier or harder to process a word? Neighborhood density was originally proposed to be one of the variables underlying the ubiquitous facilitative effects of frequency and familiarity (Eukel 1980; Nusbaum, Pisoni and Davis 1984). Nusbaum and colleagues collected familiarity ratings for the words in the Hoosier Mental Lexicon, and compared these to frequencies gathered from written corpora of text (Kucera and Francis 1967). The weak relationship found between these two measures ($r = 0.43$) led them to propose that impressions of word familiarity may be more strongly related to "the lexical density of the phonotactic spaces in which the words occur in the lexicon" (Nusbaum et al. 1984). If this were the case, having many neighbors would make it easier to process a word, just as greater familiarity does. However, subsequent word recognition studies demonstrated the opposite result, that words from dense neighborhoods are recognized more slowly and less accurately than those from sparse neighborhoods (e.g. Goldinger, Luce, and Pisoni 1989; Luce 1986; Luce and Pisoni 1998; Vitevitch and Luce 1998, 1999). But this finding also has a logical explanation. When one is attempting to determine what word best matches an incoming auditory string, the target word's neighbors are competitors. They may be mistaken for the target or, at minimum, create a temporary distraction. Thus, neighbors are a negative influence.

During expressive processes, then, what would be the predicted effect of neighborhood density? Do phonologically similar words compete with the target for production as they do for recognition? Or do they act to support the retrieval of the target? Are neighbors friends or foes? Although there have been few studies to date, results quite consistently show that neighborhood density has an effect on speech production opposite to its effect on speech recognition (Gordon 2000, 2002; Harley and Bown 1998; Vitevitch 1997, 2002). Having many neighbors makes the production of a word *more* accurate, and possibly faster as well. Somehow, competitive neighbors have become cooperative neighbors.

In this chapter we review studies that have examined the effects of neighborhood density on spoken word processing, concentrating on the findings showing that density promotes accuracy in production. We seek to explain those findings in terms of the two-step interactive-activation model of lexical access (Dell et al. 1997), a model that has been designed to account for speech errors in normal and aphasic individuals. Ultimately, we argue that the interactive property of the model – that activation feeds back from phonological units to lexical units during production – allows for a target word's neighbors to increase the probability with which that word is selected and to promote its accurate encoding at the phonological level.

2. Phonological Neighborhoods in Auditory Word Recognition

All major theories of word recognition propose that representations of structurally similar neighbors of a target word are activated when the target is presented. The activated neighbors may delay or, in extreme circumstances, derail the recognition of the target. This is true for theories concerned with printed words (e.g. Grainger and Jacobs 1996) as well as theories of spoken-word perception (e.g. McClelland and Elman 1986; Norris 1994). Some spoken-word theories propose that interference comes primarily from those neighbors that are similar to the target at the word's beginning, as in the Cohort Model (Marslen-Wilson and Welsh 1978). That is, the neighborhood consists of the "cohort" of words consistent with the incoming auditory stimulus; this cohort shrinks as more and more of the input is perceived, and the target word is distinguished from its competitors. Other theories suggest that words overlapping with the target at any position may be neighbors, as in the Neighborhood Activation Model (NAM; Luce 1986; Luce and Pisoni 1998).

However the neighborhood is defined, studies of spoken-word recognition clearly show the competitive effect of neighbors. In auditory naming (i.e. word repetition) tasks, words with more neighbors are named more slowly than words with fewer neighbors, using either a straightforward density count (Luce and Pisoni 1998) or a frequency-weighted measure of density (Vitevitch and Luce 1998).[1] Dense neighborhoods also slow responses to words in auditory lexical decision (Luce and Pisoni 1998; Vitevitch and Luce 1999) and same-different judgment tasks (Vitevitch and Luce 1999), as well as decreasing the accuracy of word identification when targets are presented under noisy conditions (Goldinger, Luce, and Pisoni 1989; Luce and Pisoni 1998).

The hypothesized mechanism for competition between a target and its neighbors varies. There may be lateral inhibition between units representing similar words (e.g. McClelland and Elman 1986). Alternatively, the competition may be expressed indirectly through either the mathematics of the recognition decision rule (e.g. Luce and Pisoni 1998), or the dynamics of learned connection weights that map between distributed representations of word forms and word meanings (e.g. Gaskell and Marslen-Wilson 1997; Plaut and Shallice 1993). Regardless of the mechanism, though, neighbors detract from recognizing a target word. Word recognition is inherently a process of discriminating the target from other similar words; the fewer similar words there are, the easier the discrimination.

3. Phonological Neighborhoods in Spoken Word Production

Studies of word production tell a very different story. In a series of error studies, Vitevitch (1997, 2002) has shown that, in fact, a dense phonological neighborhood appears to facilitate accurate speech production. In the first of these studies, Vitevitch (1997) compared a corpus of spontaneously occurring form-related word substitutions (collected by Fay and Cutler 1977) to a control corpus randomly selected from a large database of words matched to the error-target corpus on length and grammatical class. He found the error-target corpus to be lower in frequency, and to have lower neighborhood density and neighborhood frequency values than the control corpus. In order to examine these findings in more controlled tasks, Vitevitch (2002) elicited phonological speech errors using two different techniques. In the first, sound exchanges, or spoonerisms, were induced using the SLIPs technique devised by Baars, Motley, and MacKay (1975). The second experiment made use of a tongue-twister task (after Shattuck-Hufnagel 1992) in which strings of similar-sounding words were repeatedly read aloud as quickly as possible. In both of these tasks, significantly fewer errors were made on the stimuli coming from high-density neighborhoods than those from low-density neighborhoods. Furthermore, in the second task, the density effect was maintained when the stimuli in high- and low-density conditions were equated on dimensions of word frequency, neighborhood frequency, word familiarity rating, and the distribution of initial phonemes.

In addition to facilitating the *accuracy* of word production, a dense neighborhood also appears to facilitate the *efficiency* of word production (Vitevitch 2002). In a picture-naming study, Vitevitch found that pictures from high-density neighborhoods were named more quickly (but no less accurately) than those from low-density neighborhoods. As in the tongue-twister task, the two sets of stimuli were equated for word frequency and familiarity, as well as neighborhood frequency. These results were then replicated with stimuli that were also equated on positional segment and biphone probabilities, illustrating that the density effect cannot be attributed solely to sublexical effects of phonotactic probability.[2] In a final experimental manipulation, Vitevitch factored out any potential confounding effects of articulatory ease, by changing the response requirement to a button press indicating retrieval of the name of the picture.

The facilitative effect of density on speech errors has also been supported by studies of the tip-of-the-tongue (ToT) phenomenon (Harley and Bown 1998; see also Vitevitch and Sommers in prep.). Contrary to the *interference hypothesis* (e.g. Jones 1989), which proposes that activated neighbors (or "interlopers") actually block successful access to the target, both Harley and Bown as well as Vitevitch and Sommers found that more ToTs were produced on words from low- than high-density neighborhoods. Together, these results suggest that, in production, lexical items benefit from an accumulation of activation spreading from phonologically related items, which makes them easier to retrieve and less susceptible to error. Furthermore, this facilitation appears to extend beyond sublexical frequency effects.

In studies of aphasic errors, neighborhood variables are also beginning to be considered. The finding of a reverse length effect in the naming responses of one aphasic subject (Best 1995) was hypothesized to be due to the fact that longer words have fewer neighbors, so there is less competition for their access. However, a *post-hoc* analysis assessing the effect of density (dubbed *nness* by Best) unexpectedly showed *greater* accuracy for items with more neighbors. Thus, even for a subject who showed an atypical effect of length on naming performance, a facilitative effect of density was indicated once length was controlled. But does this effect extend beyond this single case? A study by Gordon (2002) suggests that the facilitative effect of neighborhood density in speech production applies more generally to the aphasic population.

Gordon (2002) conducted two different speech production tasks – picture naming and picture description – with a large, unselected group (n = 36) of aphasic subjects, and analyzed the speech errors which were made during the tasks. In the picture-description task, the set of incorrectly produced targets (error-targets) was compared to a similar set of correctly produced targets (correct-targets) gathered from the same speech samples. That is, each target that was produced in error by a given subject was paired with a target of the same length and grammatical class that was produced accurately by that subject. Results showed that the error-targets were less frequent, and came from less dense neighborhoods than the correct-targets.

In the picture-naming task, the accuracy of responses in the Philadelphia Naming Test (Roach et al. 1996) was correlated with characteristics of the stimulus items. Measured across subjects, accuracy showed a moderate positive correlation with frequency ($r = 0.44$) and neighborhood density ($r = 0.41$), and a moderate negative correlation with number of syllables ($r = -0.40$). Because length is highly confounded with neighborhood density ($r = -0.76$), the density correlations were recalculated for items of each syllable length. Although the correlation between accuracy and density for the one-syllable targets was close to zero ($r = 0.08$, n = 100), a significant correlation was found between accuracy and density for the two-syllable targets ($r = 0.28$, n = 53). (There were not enough three- and four-syllable targets to provide a reliable indication of the relationship for those items.) Both tasks, then, showed a facilitative effect of density.

To summarize the experimental results to date, the density of the phonological neighborhood in which words reside affects the accuracy of speech production in both non-brain-damaged and aphasic speakers. Moreover, the effect of neighborhood density on production is consistently facilitative, in apparent contradiction to the competitive density effect observed in word recognition studies. How can these results be reconciled within a theoretically motivated model of lexical access?

4. Phonological-Lexical Interaction during Production

There are two challenges that confront modelers seeking to explain the beneficial effect of neighborhood density on speech production. The first is to specify how a target's phonological neighbors can exert an influence in a semantically driven task like production. The second is to explain why that influence has the opposite effect to that demonstrated in recognition studies.

Word recognition is a form-driven process; the phonological representation of the target is activated directly by the incoming auditory stimulus. Because neighbors share part of the target's phonology, they too will become partially activated during the recognition process. In contrast, word production is driven by the meaning to be expressed. It is not immediately apparent how this process leads to the activation of formally similar neighbors. Nonetheless, speech production errors suggest that such activation does occur. Form-related word substitutions, such as saying *present* instead of *pressure*, or *button* for *butter,* are a relatively common type of slip in normal speech (Fromkin 1971; Fay and Cutler 1977). These errors, sometimes called *malapropisms*, can also be prevalent in the speech of certain aphasic individuals (e.g. Martin and Saffran 1992; Goldrick and Rapp 2001). The occurrence of malapropisms suggests that neighbors are activated during speech production, at least some of the time.

The question of how the neighbors of a production target can become active requires us to consider, more generally, the nature of lexical access in production. Lexical access is assumed to occur through spreading activation in a network of units representing words, their meanings, and their component sounds. The input to lexical access is an activated representation of the meaning of the word being sought. This might be a single conceptual unit (e.g. Roelofs 1992) or several units corresponding to conceptual or semantic features (e.g. Dell et al. 1997; Rapp and Goldrick 2000). The output of lexical access is an ordered set of units representing the target word's phonological or phonetic segments, or features, along with its nonsegmental properties such as stress (e.g. Roelofs 1997; Levelt, Roelofs, and Meyer 1999). This process of translating the input into the output requires two distinct steps – retrieval of the word representation from semantics (or *lemma access*), and retrieval of the phonological units corresponding to the selected lemma (or *phonological access*) (Fromkin 1971; Garrett 1975; Levelt, Roelofs, and Meyer 1999). The lemma is a lexical representation, typically a single unit,

associated with the word's grammatical properties, which mediates between the semantic input and the phonological output.

Although it is agreed that phonological access follows lemma access, there is controversy regarding the extent to which the two steps are truly separate. According to *discrete-stage* theories (Levelt, Roelofs, and Meyer 1999), lemma access must be completed before phonological access begins. As a result, only the selected lemma undergoes phonological access. *Cascaded* theories (Caramazza 1997; Humphreys et al. 1988), however, relax this constraint. During lemma access, it is generally assumed that both the target lemma and competing semantically related lemmas are activated. A cascaded theory, unlike a discrete theory, would propose that the phonological units of these competing lemmas become active before the lemma access stage settles on the target. *Interactive* theories (Dell et al. 1997; Harley 1993; Stemberger 1985) blur the two stages even more. Like the cascaded theories, interactive theories allow for all activated lemmas, whether targeted or not, to activate their phonological representations. Furthermore, interactive theories allow for active phonological units to feed activation back to the lemma level. Thus, lemma and phonological units continually send activation to one another.

Interactive theories offer a simple mechanism for the activation of a target's neighbors during production. Here we illustrate this mechanism using the two-step interactive-activation model of Dell and colleagues (1997). However, any theory allowing for phonological-lexical interaction would suffice. Figure 1 illustrates the model's lexical network. The network contains separate layers for semantic features, words (lemmas), and phonemes. The connections are excitatory and bi-directional. Top-down connections link semantic features to words, and words to their component phonemes. Bottom-up connections do the reverse, thus providing interactive feedback.

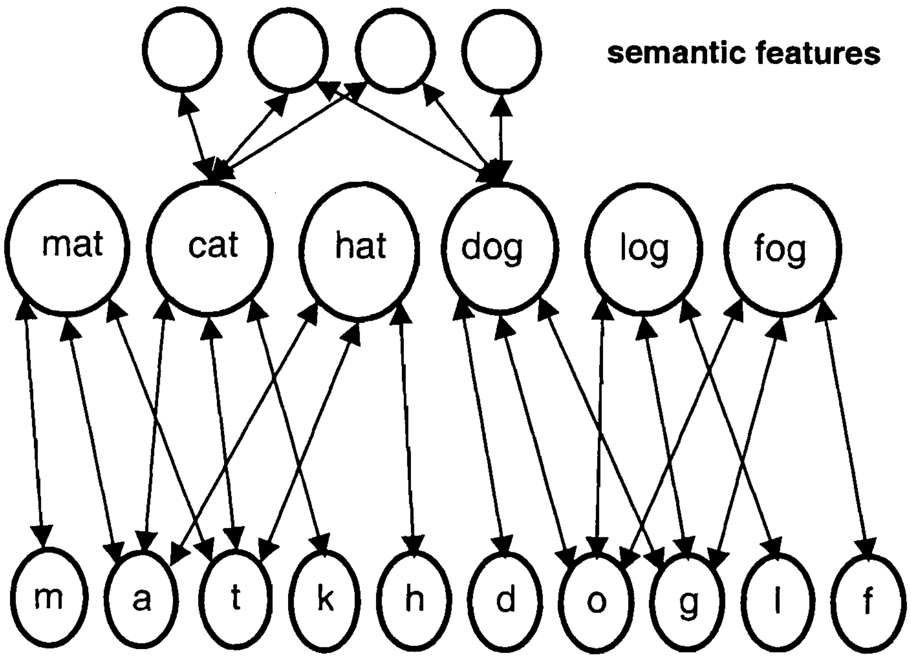

Figure 1. The Architecture of the Two-Step Interactive-Activation Model

Lemma access in the model begins with a jolt of activation to the semantic features of the target, here assumed to be CAT. Activation spreads throughout the network for a fixed number of time steps, according to a noisy linear activation rule:

$$(1)\ A(j,t) = A(j,t\text{-}1)\ (1\text{-}q) + \sum w(i,j)A(i,t\text{-}1) + \text{noise}$$

A(j,t) is the activation of unit j at time step t, q is the rate with which activation decays, and w(i,j) is the connection weight between unit i and unit j. During each time step, each unit's activation level is perturbed by normally distributed noise with a mean of zero and a standard deviation proportional to the unit's activation.

While lemma access is proceeding, the target word unit, in this case CAT, will normally obtain the most activation. However, the

network as a matter of course activates several other word units. Semantically related words such as DOG obtain some activation from shared semantic units. Most importantly for our purposes, formally related neighbors become activated. This is because activation spreads from the target word to its phonemes (/k/, /æ/, /t/) during lemma access – the cascading property of the model – and from those phonemes back to all words that contain them (e.g. MAT) – the interactive property of the model. Word units for neighbors will, naturally, become more active than words that are not related in form to the target.

Lemma access is concluded by a selection process. At a specified time step, the most activated word unit of the appropriate syntactic category is chosen. So, in the case in which the noun CAT is the target, the most activated noun is selected. Most likely, this will be CAT. However, due to the contribution of noise, a semantically related word (DOG), a formally related word or malapropism (MAT), or a mixed semantic-formal word (RAT) could be incorrectly selected instead, provided that it is a noun. If the noise is extreme, an unrelated noun such as LOG might be chosen. Selection is followed by a jolt of activation to the selected word unit. The jolt is controlled by grammatical processes, ensuring that the selected word belongs to the correct syntactic category, and, if a sentence is being produced, that the word is produced at the appropriate time during production of the sentence.

This jolt of activation also marks the beginning of the stage of phonological access. Activation again spreads throughout the network, feeding forward and backward. After a given period of time, the most activated phonemes are, in turn, selected and linked to their respective positions in a phonological frame, a structure that represents the metrical and syllabic properties of the target. Normally, the target phonemes, /k/, /æ/, and /t/, will be most active, but because of the interaction between the phoneme and word layers, the target's neighbors are also activated during phonological access, just as they were during lemma access. Under noisy conditions, this may result in a phonologically similar word being selected instead of the target

(MAT) or, with more extreme disruption, an unrelated word (LOG) or a non-word (DAT).

In contrast to interactive models, discrete-stage and cascaded models of lexical access do not naturally allow for the activation of neighbors. In these models, the phonological properties of the target do eventually become activated – this occurs after lemma access for discrete-stage models, and both during and after lemma access for cascaded models – but lexical units that share these phonological properties are not routinely activated by the production process. How, then, do these models account for the production of phonologically related errors?

If non-interactive models are augmented with an internal monitoring mechanism, a target's neighbors will become active during production (Levelt, Roelofs, and Meyer 1999). Internal monitoring is the checking of planned speech for errors before it is spoken. In the discrete-stage WEAVER++ model of lexical access, this monitoring is assumed to occur through the comprehension system, a system that converges with the production system at the lemma level (Roelofs in press). A phonological representation of the planned utterance is transmitted to the comprehension system, with the result that similar words are activated through normal word-recognition mechanisms. For example, if CAT is the target word for production, the monitoring of its phonological representation results in a reactivation of the lemma for CAT, along with some activation of neighboring lemmas such as CAP or CAN. The activation of neighbors by monitoring gives non-interactive models a mechanism for malapropism errors to occur (Levelt, Roelofs, and Meyer 1999). If phonological access is incomplete (for example, only the first two sounds of CAT are retrieved), monitoring this incomplete representation will lead to neighboring lemmas that may be as active as the targeted lemma. If one of them is in the target grammatical category (e.g. the noun CAP), it may be selected, leading to a malapropism.[3]

Thus far, we have considered how neighbors could become activated during production. Phonological-lexical feedback in interactive models directly leads to the activation of neighbors during both lemma and phonological access. In discrete-stage models, internal monitoring through the comprehension system allows for the activation of neighbors after the creation of a target's phonological representation. The next issue that must be considered is that of how the activation of neighbors could benefit production. In the following section, we use the two-step interactive-activation model to explore the consequences of neighborhood structure in an interactive model. We will show that, although there are some competitive effects from activated neighbors, this model predicts that denser neighborhoods are associated with greater accuracy in both lemma and phonological access.

5. Effects of Neighborhood Density in an Interactive Model

The effects of neighborhood density on speech production were examined by manipulating the characteristics of the lexicon in the two-step interactive-activation model (Gordon and Dell 2001). This model employs very simple lexicons of single-syllable, consonant-vowel-consonant (CVC) words and was originally constructed to simulate error patterns shown by normal speakers. Dell and colleagues (1997) set up the model by selecting parameters so that the model's behavior matched the pattern of errors produced by normal speakers during a picture-naming test, the Philadelphia Naming Test (Roach et al. 1996). The critical error categories in this test were: correct responses (CAT), semantic errors (e.g. DOG), formal errors or malapropisms (e.g. MAT), mixed semantic-formal errors (e.g. RAT), unrelated word errors (e.g. LOG), and non-words (e.g. DAT). Most of the model's responses (97%) were correct, the remaining responses consisting primarily of semantic errors (2%) and mixed errors (1%).

By altering two of the model's parameters, Dell et al. (1997) were also able to simulate patterns of errors made by aphasic subjects on the same test. In the normal model, all of the weights (w(i,j)), had been set to the same value, 0.1, and the decay rate was 0.5 per time step. To produce aphasic deficits, the model was "lesioned" by either reducing the connection weights or increasing the decay rate. Both forms of lesioning increased error rates by reducing the activation of network units, which caused the noise to have more of an impact. However, the two types of lesions resulted in different error patterns. Weight lesions increased the chance of non-word and unrelated-word errors because these errors reflect circumstances in which activation at one processing level is inconsistent with other levels. If weights are low, information about what is activated at one level cannot be effectively sent to other network levels. Decay lesions, in contrast, increased the occurrence of related word errors, either semantic, mixed, or formal errors. In this case, the connection weights are still strong, so activation still spreads effectively between layers. Thus, errors tend to be more closely related to the target, either in form, meaning, or both. By varying these two parameters, Dell and colleagues found that they could set up the model to mimic the picture-naming error patterns of each of 21 aphasic patients with a fair degree of success. In essence, each patient could be characterized by the model in terms of his/her lesioned weight and decay values. These values, in turn, were used to predict other aspects of the patients' speaking behavior (see Dell et al. 1997 for details).

The same principles were applied here. We examined the effect of neighborhood density on the model's accuracy using both a normal version of the model, and versions designed to reflect aphasic lesions (Gordon and Dell 2001). We started with a simple lexicon consisting of a target, CAT, two phonological neighbors, HAT and MAT, one semantically related word, DOG, and two unrelated words, LOG and FOG (refer back to Figure 1). This was designated the *dense* neighborhood. A *sparse* neighborhood was created by eliminating one of the target's neighbors (HAT), and an *empty* neighborhood was created by removing both of them.[4]

5.1. Simulation using normal parameters

To explore the effect of neighborhoods, we first examined the model's performance with the dense, sparse, and empty neighborhoods using normal weight (0.1) and decay (0.5) parameters[5]. The

model attempted to produce the target 100,000 times. Accuracy and error rates are shown in Table 1. Although the accuracy was generally very high, more errors were produced as the neighborhood became sparser, in keeping with the facilitative effects of density shown for normal speakers. The facilitative effect is apparent not only in the overall accuracy rates (the proportion of cases in which the model's final output is correct), but also in the rates of lemma and phonological accuracy (see Table 1). Lemma accuracy is the proportion of cases in which the target lemma was selected, regardless of whether it was then encoded correctly. Phonological accuracy is the proportion of correct lemmas that were also phonologically encoded correctly, in essence, factoring the effects of lemma accuracy out of the overall accuracy rate.

Table 1. Effects of Neighborhood Density on the Normal Model.

Neighborhood			
Measure	Dense	Sparse	Empty
Overall Accuracy (%)	97.8	97.6	96.9
Lemma Accuracy (%)	97.9	97.8	97.6
Phonological Accuracy (%)	99.9	99.8	99.3
Correct (out of 100,000)	97,799	97,607	96,932
Semantic Errors	2113	2215	2415
Formal Errors	3	0	0
Unrelated Errors	0	0	0
Non-word Errors	85	178	653

The bottom part of Table 1 presents the raw frequencies of each error type as a function of neighborhood density. The facilitative effect of density is clearly seen in the lower numbers of both semantic and non-word errors, as neighborhood density increases. The only error type that increases with increasing density is formal errors, although these are extremely rare with normal parameters in the model (and in normal speakers performing a picture-naming task).

5.2. Simulations using lesioned parameters

If the facilitative effect of neighborhood density depends on the interactive nature of the model, then alterations to the model that disrupt the flow of activation should reduce the role of density. Two types of lesions, previously found to accurately represent a majority of lexical access deficits in fluent aphasia (Dell et al. 1997), were also implemented in this study. Reducing the strength of connection weights, which disrupts the ability of the model to spread activation from one layer of nodes to the next, was predicted to result in a diminished density effect. On the other hand, increasing the rate of decay of activation, although expected to increase error rates overall, should not affect the facilitative effect of density.

Each type of lesion was simulated at three different levels of severity, but for the sake of simplicity, only one is reproduced here (for more details, see Gordon and Dell 2001). The decay lesion was implemented by increasing the decay rate parameter from $q = 0.5$ to $q = 0.9$; the weight lesion was implemented by decreasing the connection weight parameter from $p = 0.1$ to $p = 0.0033$. The overall accuracy of production was approximately equivalent for each lesion type, representing a moderate-to-severe lexical access deficit.

Results for the decay-lesioned model are shown in Table 2. As predicted, a clear effect of neighborhood density is evident in the rates of overall accuracy, as well as lemma and phonological accuracy; all three rates are reduced as neighborhood density is decreased. The raw frequencies of each error type, provided in the lower half of the graph, show that, as density decreases, all error types increase except formal errors, which decrease because there are fewer opportunities for such errors.

Table 3 illustrates the results for the weight-lesioned model. Here, the effect of neighborhood density is obviously reduced, as predicted. In fact, overall accuracy and lemma accuracy rates *rise* slightly as

density is decreased, suggesting a slight competitive effect. The raw frequency counts for each error type show that, as in the normal and decay-lesioned models, the numbers of semantic and non-word errors increase with decreasing density and, as in the decay-lesioned model, the number of unrelated errors increases as well. However, the differences are not as great here as in the other two models, and are therefore overwhelmed by the reduction in formal errors that necessarily occurs with fewer neighbors. Thus, when target activation is low enough, and the spread of activation between levels is disrupted, the increased opportunity for error provided by a larger neighborhood creates a competitive environment.

Table 2. Effects of Neighborhood Density on the Decay-Lesioned Model.

Measure	Neighborhood Dense	Sparse	Empty
Overall Accuracy (%)	47.8	40.2	25.4
Lemma Accuracy (%)	66.6	66.0	65.0
Phonological Accuracy (%)	71.7	60.9	39.1
Correct (out of 10,000)	4779	4019	2542
Semantic Errors	1553	1956	2426
Formal Errors	1654	599	0
Unrelated Errors	457	677	865
Non-word Errors	1557	2749	4167

5.3. The role of neighbors in production and comprehension

Why do additional neighbors increase the accuracy of the model? We know that phonological-lexical feedback leads to the activation of neighboring words. By itself, though, that does not explain the greater accuracy. Neighbors are activated during word recognition, and one would not expect them to contribute to more accurate recognition, but rather the contrary.

Table 3. Effects of Neighborhood Density on the Weight-Lesioned Model.

Measure	Neighborhood Dense	Sparse	Empty
Overall Accuracy (%)	33.7	35.1	36.4
Lemma Accuracy (%)	62.5	65.6	68.7
Phonological Accuracy (%)	54.0	53.4	52.9
Correct (out of 10,000)	3373	3507	3636
Semantic Errors	816	886	980
Formal Errors	1267	649	0
Unrelated Errors	828	905	1004
Non-word Errors	3716	4053	4380

To show this, we did a simple simulation of word recognition using the same interactive activation model. We made only two changes, reflecting the change from production to a word recognition task: (1) Instead of semantic input, the input was phonological. Each of the target phonemes, /k/, /æ/, and /t/, received a jolt of activation analogous to the jolts given to semantic units during production. (2) The most activated word node after the given number of time steps was chosen as the recognized word. Everything else – connection weights, decay rate, noise parameters, number of time steps allowed for spreading activation – was the same as in the production simulations. Again, the correct target was CAT. Testing the same three neighborhood densities, we found, as expected, that neighbors are highly detrimental to recognition. Accuracy was 100%, 82%, and 58% for the empty, sparse, and dense neighborhoods, respectively. All errors consisted of selecting a phonological neighbor instead of the target.

The recognition simulation demonstrates that the interactive spread of activation is not, by itself, responsible for the production model's facilitative effects of density. Exactly the same interactive model, when used for recognition, creates an inhibitory effect of density. Clearly, it is the combination of interaction and the *task* of production that leads to the beneficial influence of neighbors.

Neighbors promote accurate production in the model because they enhance the activation of the target word, but do not enhance the activation of its principal semantic competitors. Because production is a semantically driven task, semantic features are activated first, and semantically related words therefore receive more spreading activation throughout the entire process of lexical access than do other non-target words in the lexicon. Thus, a production target's main competitors are semantically related rather than phonologically related words. This explains the prevalence of semantically related errors in normal speakers. The primary challenge of the production task, then, is to ensure that the target's activation (CAT) exceeds the activation of competing semantic neighbors (DOG).

When the target has phonological neighbors (MAT and HAT), these become activated and, in turn, send activation back to the target, *via* their shared phoneme units (/æ/ and /t/). Thus, in a dense neighborhood, the target and its neighbors all have higher activations than they would in a sparse neighborhood. Consequently, the greater activation of CAT caused by MAT and HAT promotes the selection of CAT over DOG, which does not benefit from the activation of MAT and HAT. It is true that MAT and HAT also receive more activation, but these phonological neighbors are not serious contenders in the contest. (Note that when the facilitation provided by neighbors is reduced, as in the weight-lesioned model, the formal neighbors *do* become serious contenders.) In this way, the phonological neighbors reinforce the activation of the target relative to its semantic competition.

The benefit to the model's production from neighbors occurs both during lemma and phonological access. Both CAT and its phonemes benefit from interaction with neighbors. During lemma access, neighbors keep CAT's lemma activation above that of DOG. As a result, semantic errors are less likely in dense neighborhoods. For example, in Table 1, there were 302 fewer semantic errors in the dense neighborhood than in the empty one. During phonological access, the neighbors contribute directly to the activation of the target's phonemes. This contribution primarily prevents non-word errors, as these are the most common errors of phonological access. Compare the 653 non-word errors produced in the empty neighborhood to only 85 in the dense neighborhood.

In summary, production and comprehension differ in their response to neighborhood density in the model because production and comprehension tasks create different competitive environments. When the task dictates that phonological neighbors are serious competitors, a densely populated phonological neighborhood is detrimental to fast and accurate retrieval. When the task dictates that other words are the main competitors, neighborhood density promotes accurate retrieval of the target.

5.4. Predictions for aphasic error patterns

Our analysis of the model makes specific predictions regarding the effects of neighborhood density on speech production in aphasia. If the mechanism by which density exerts a facilitative influence is accurately represented, then the effect of neighborhood density on aphasic error patterns will differ depending on the underlying lexical access impairment. Specifically, aphasic subjects with decay-rate lesions should show density effects similar to those shown by normal subjects, whereas aphasic subjects with connection-weight lesions should show attenuated, if not absent, neighborhood effects. Moreover, neighbors should generally help prevent aphasic errors that occur at lemma access such as semantic errors, as well as phonological errors such as non-words.

As a preliminary investigation of these hypotheses, the aphasic subjects examined by Gordon (2002) were classified as either "decay-lesioned" or "weight-lesioned" (for details of the classification procedure, see Dell et al. 1997). Item-level correlations between

neighborhood density and the picture-naming response proportions were calculated for each subject group separately (see Table 4). Contrary to predictions, both weight-lesioned and decay-lesioned subjects showed significant positive correlations between overall accuracy and density (using 2-, 3-, and 4-syllable items, the items most sensitive to density effects in Gordon's study). However, the expected reduction of the neighborhood effect for weight-lesioned subjects *was* observed in the correlations of density with semantic errors and non-word errors. The incidence of semantic errors was significantly negatively correlated with neighborhood density for the decay-lesioned subjects, but not the weight-lesioned subjects. Similarly, the incidence of non-word errors, representing phonological encoding accuracy, was significantly negatively correlated with density only for the decay-lesioned subjects. Admittedly, the correlations and the differences between them were small. Nevertheless, the results are suggestive of a difference between aphasic subjects that accords with predictions of the model. Most importantly, the correlations show that larger neighborhoods are associated with fewer semantic (lemma access) errors as well as fewer errors of phonological encoding.

Table 4. Correlations of Neighborhood Density with Incidence of Correct Responses, Semantic Errors, and Non-word Errors.

Subject Group		
Response	Decay-Lesioned	Weight-Lesioned
Correct Responses	0.30*	0.27*
Semantic and Mixed Errors	- 0.27*	- 0.09
Non-word Errors	- 0.29*	- 0.22

* indicates significantly different from 0

6. Conclusions and Caveats

We have argued that lexical-phonological interaction can explain the beneficial effects of neighbors on production, and investigated the properties of a particular interactive model. Insofar as this kind of interaction has independent motivation from other production facts, it is a viable explanation for the neighborhood effect. Indeed, lexical-phonological feedback has been implicated in speech-error phenomena such as the existence of a syntactic category constraint on malapropisms (e.g. Harley and MacAndrew 2001) and the tendency for semantic errors to exhibit formal relations (the *mixed error effect*, Martin et al. 1996). Recently, interactive models have been offered to explain how these phenomena are disrupted or preserved in aphasia (Dell et al. 1997; Gordon 2002; Rapp and Goldrick 2000). Moreover, interaction provides a mechanism for the tendency for phonological errors to create words over non-words (the *lexical-bias effect*, Baars, Motley, and MacKay 1975; Dell 1986, 1990; Nooteboom in press). This evidence has not been viewed as providing a definitive case for interaction, however. These error effects could arise, instead, from a suitably configured internal monitoring system (e.g. Levelt, Roelofs, and Meyer 1999; Roelofs in press). The existence of these non-interactive accounts for error effects leads to the final issue that we confront in this chapter. Is there truly a need to posit interaction to account for neighborhood effects?

Our claim is that interaction leads to the activation of a target's phonological neighbors and offers a mechanism to explain why this interaction is beneficial in production. In a discrete model such as that of Levelt and colleagues (1999), the assumption that planned speech is monitored by the comprehension system also provides for the activation of the target's neighbors. It is unclear, though, how this process could increase the speed or accuracy of either lemma or phonological access in this model. The activation of neighbors makes them available as possible errors if they are selected instead of the target. However, their activation would not contribute to the activation of the target without adding assumptions to the model. Thus, the comprehension monitor, which offers a discrete model a way to deal

with interactive error effects, does not explain the neighborhood density effect.

There is, however, another way that neighbors could contribute positively to production in a discrete model. A word with many neighbors will tend to have sublexical units that are frequent. In the model of Levelt et al. (1999), for example, the phonetic syllable units are assumed to be sensitive to their frequency of usage. To the extent that words from dense neighborhoods tend to have frequent syllables, words with those syllables would be encoded faster in the model. At this point in time, the available data cannot definitively rule out the alternative sublexical frequency explanation. However, two sources of evidence are potentially problematic for this alternative.

First, there is the finding by Vitevitch (2002) that the neighborhood density facilitation of picture-naming latencies was preserved even when positional phoneme frequencies and biphone frequencies were equated between sparse and dense targets. The suggestion is that what matters is the lexical representations of neighbors themselves rather than the consequences of density for sublexical frequency. However, it still could be the case that the frequency of larger sublexical units, such as phonetic syllables, is confounded with density in the study.

The other relevant finding is Gordon and Dell's (2001) report that the rate of aphasic semantic errors was negatively associated with neighborhood density. So, neighbors were protective against semantic errors as well as phonological errors, a result that was predicted by the simulations using the interactive model (Tables 1 to 3). The alternative explanation based on sublexical frequency could explain faster or more accurate word-form encoding, but not more accurate discrimination at the lemma level between a target and its semantic competitors. Again, though, there is good reason to withhold judgment. The relevant correlations were weak and the study has yet to be replicated.

In summary, a word's phonological neighbors have complex influences on the processing of that word. Whether neighbors are competitive or cooperative depends on the task: Neighbors are costly in recognition but beneficial in production. Lexical-phonological interaction provides a simple and motivated explanation for the benefits of neighbors in production and the evidence, although preliminary, is consistent with that explanation.

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Notes

1. Frequency-weighted neighborhood densities were calculated by summing the log frequencies of all of the neighbors of a given target word.
2. Phonotactic probability was calculated by two measures: the sum of the positional segment probabilities of the phonemes in a word (i.e. how frequently each phoneme occurs in that word position), and the sum of the probabilities of each sequential pair of phonemes.
3. Although internal monitoring provides a mechanism for discrete-stage models to produce malapropisms, such a mechanism is not incompatible with other models. In fact, the evidence that internal monitoring occurs is quite strong (see Levelt, Roelofs, and Meyer 1999 for review) and hence any complete account of production would include this kind of monitoring.
4. The model's neighbors differed from the target at the initial position. This is arbitrary. The same results would occur if they differed at other positions because the implemented model encodes the phonemes of a single-syllable word in parallel.
5. Other parameters were the same as in Dell et al. 1997: Intrinsic noise SD = .01; Noise slope parameter = 0.16; n = 8 time steps for lemma access, and n = 8 for phonological access; semantic jolt = 100, divided over 10 feature units; word jolt = 100 to selected word.

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