Phonetic Category Structure and Its Influence on Lexical Processing

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1. Introduction

It is generally assumed that the phonetic categories of speech are not indissoluble wholes, but rather can be characterized in terms of a bundle of phonetic or distinctive features. These features may be defined in terms of either acoustic or articulatory attributes of the speech signal. However, it is also the case that at least from an acoustic or perceptual point of view, each of these phonetic features is also defined by a set of acoustic properties. For example, as shown in Figure 1, the phonetic category corresponding to [d] is defined in terms of a set of features and each feature in turn is signaled by a number of acoustic properties. Thus, the phonetic feature [voice], distinguishing voiced and voiceless stop consonants in English, is characterized by a number of attributes including glottal excitation, fundamental frequency, burst amplitude, and vowel length.

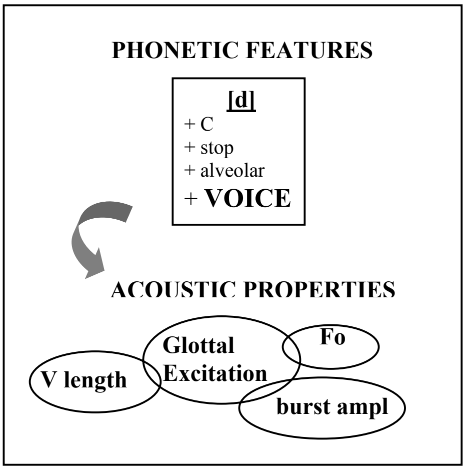

Figure 1. Schematic of relation between phonetic features and acoustic properties

Much past research has focused on identifying these properties and determining what role they play in the perception of speech. There are three defining attributes that may be used to characterize the acoustic properties associated with phonetic features. In particular, the acoustic properties associated with phonetic features are *time varying*, *relative*, and *graded*. Time varying refers to the fact that the acoustic properties of speech are not static attributes, but rather are defined in terms of the nature of spectral/amplitude change across the time domain (Stevens and Blumstein, 1981). For example, rapid change in the short time spectra at the release of a stop consonant serves as a cue to place of articulation in stop consonants (Stevens and Blumstein, 1978; Searle, Jacobson, and Kimberly, 1980; Kewley-Port, 1983; Lahiri, Gewirth, and Blumstein, 1984). Because the acoustic properties of speech are derived with respect to changes in both the spectral and amplitude domains over time, they are relative and not absolute. For example, the acoustic property corresponding to place of articulation in stop consonants is not defined by an absolute value in Hz of the second formant, but rather the amplitude of that formant relative to the other formants in the acoustic spectrum. Finally, and of most importance for the purposes of this chapter, the acoustic properties of speech are graded,

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meaning that an acoustic property associated with a phonetic feature consists not of a single value but of a continuum of values. For example, there is not one voice-onset time value that is associated with a voiceless stop consonant but a range of values that encompass the class of voiceless stop consonants.

That there is a continuum of values that corresponds to acoustic properties is due to a number of factors – all having to do with the consequences of phonetic variability in the speech stream. In particular, speakers are not consistent in their production of speech from utterance to utterance and do not have sufficient articulatory control to produce an utterance the same way every time. Also, co-articulatory effects resulting from phonetic position and phonetic context influence the acoustic-phonetic manifestation of an utterance. For example, the range of voice-onset time values for stop consonants in initial and in intervocalic position is not the same.

The fact that the acoustic properties of speech are graded also has perceptual consequences. Namely, it appears as though the perception of the phonetic categories of speech is also graded. As a consequence, even though the set of values corresponding to a particular phonetic attribute may be categorized as that attribute, some values of the set are better exemplars than others and hence result in stimuli that are better exemplars of the phonetic category than others. For example, there is a range of voice-onset time values corresponding to the voiceless and to the voiced phonetic categories in stop consonants. As Figure 2 shows, if listeners are presented with a voice-onset time continuum and asked to identify the phonetic category of the stimuli, they will show the classic categorical perception function (Liberman, Cooper, Shankweiler and Studdert-Kennedy, 1967). However, if the data are scored not only for phonetic identification but also for reaction time latencies, as shown in Figure 3, the fastest reaction-time latencies occur for the endpoint stimuli. Slower responses emerge for within phonetic category stimuli that are closer to the phonetic boundary, even though these within category stimuli are identified consistently as members of their phonetic category (Andruski, Blumstein and Burton., 1994; Pisoni and Tash, 1974). The slowest reaction time latencies occur for boundary value stimuli. And if subjects are asked to rate the perceptual quality of the stimuli, they will rate the endpoint stimuli as better exemplars of the phonetic category than within phonetic category stimuli, even though all of these stimuli are identified equally as members of the phonetic category (Kessinger and Blumstein, 2003; Miller, 1994; Volaitis and Miller, 1992).

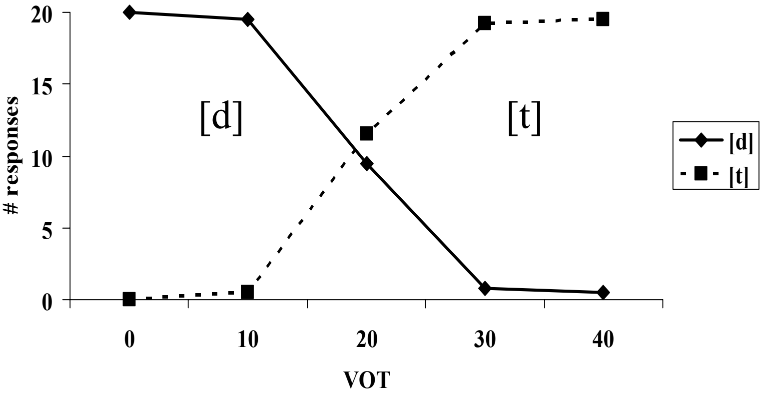

Figure 2. Identification function of a voice-onset time continuum

These results indicate that there is a structure to the phonetic categories of speech and that the perception of phonetic categories is graded (cf. Miller, 1994; Kuhl, 1991; Oden and Massaro, 1978; Samuel, 1982; Massaro, 1994; Iverson and Kuhl, 1995, 1996). The question is whether this acoustic variability that influences the perception of the phonetic categories of speech also influences higher levels of language processing – that is, the mapping of sound structure to the mental lexicon and potentially to the lexical-semantic network itself. It is to this issue to which we turn for the remainder of this chapter.

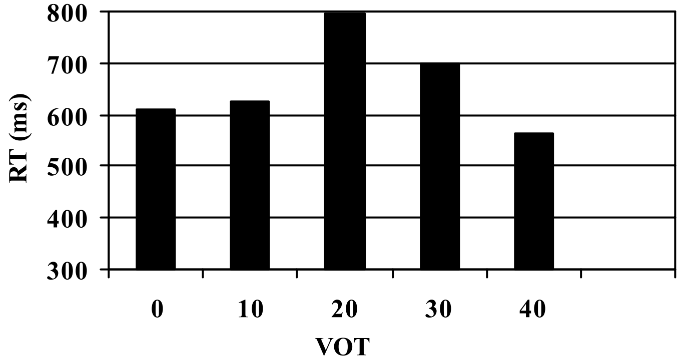

Figure 3. Reaction time latencies for stimuli along the voice-onset time continuum

2. Acoustic-Phonetic Structure and Lexical Access

Speech perception research over the past 40 years has had its primary focus on the nature of the phonetic categories of speech and, as such, emphasis has been placed on phonetic category structure, and how listeners identify and discriminate stimuli in terms of these categories. Yet, the ultimate goal of speech research is to understand how sound structure maps onto meaning. It has generally been assumed that the phonetic categories of speech play a critical role in this mapping. In fact, nearly all lexical processing models include a level of processing in which lexical form is mapped onto or represented in terms of phonetic categories. While such a level or process may be assumed in such models, surprisingly little work has been conducted on the ways that phonetic category structure may influence lexical access.

Earlier research in lexical processing generally assumed that ‘fine’ acoustic differences of phonetic category structure are ‘cleaned’ up in earlier stages of processing and thus have little or no effect on lexical access. And yet, listeners seem to harness the variability in the speech stream and are able to rely on fine acoustic details intrinsic in the variation of speech in the process of word recognition (Warren and Marslen-Wilson, 1987, 1988; Marslen-Wilson, 1978; 1989). In particular, listeners monitor the acoustic signal continuously, not waiting until the end of a segment in order to guide or constrain their lexical choice. Moreover, listeners are sensitive to fine acoustic differences in word recognition. Streeter and Nigro (1979) showed longer lexical decision latencies when stimuli were altered by either removing medial consonant transitions or juxtaposing conflicting transitions. Because this effect emerged for words but not for nonwords, they concluded that processing was slowed during lexical lookup (Pitt and Samuel, 1995, but cf. Whalen, 1991 for an alternative point of view). In a series of studies, Connine and her colleagues explored the mapping processes underlying spoken word recognition. Their results indicated that lexical activation varies as a function of the degree of phonetic-phonological match between a stimulus and a particular lexical representation (Connine, Blasko, and Hall, 1994; Connine, Blasko, and Titone, 1993; Connine, Titone, Deelman and Blasko, 1997; see also Milberg, Blumstein, and Dwortezky, 1988). Additionally, Luce and his colleagues (Luce and Pisoni, 1998) have shown in a series of studies that word recognition is influenced by the phonetic similarity of potential word candidates. In particular, both behavioral and modeling data show that phonetic similarity affects both the accuracy and time required to respond to a particular stimulus input.

Taken together, these results indicate that acoustic-phonetic structure does influence access to lexical form, i.e. the sound shape of the word. However, the sound shape of a word ultimately accesses a lexical semantic network. That is, the words of a language are thought to be organized in a network-like architecture where words that share semantic features or overlap in meaning form a network of connections (Masson, 1995; Plaut and Booth, 2000). Thus, the activation of a lexical form activates not only the semantic representation of the word, but also partially activates words that may be semantically related to it. The question is whether phonetic category structure will also influence access to the lexical-semantic network.

The semantic priming lexical decision paradigm provides a means of exploring this question. In this paradigm, a subject is required to make a lexical decision on presentation of a stimulus. Subjects are faster in making a lexical decision to a word target that is preceded by a word that is semantically related to it, e.g. *cat-dog*, than to a word target that is preceded by a semantically unrelated word, e.g. *ring-dog* or a nonword, e.g. *plub-dog*. This effect is presumably due to the fact that the presentation of the prime word *cat* activates not only the lexical entry for *cat* but also its lexical semantic network. Thus, not only is the meaning of *cat* activated but *dog* which is a part of the lexical semantic network for *cat*, is partially activated as well, resulting in faster reaction-time latencies to semantically related prime-target pairs. If acoustic-phonetic structure influences not only the mapping to lexical form but also to the lexical-semantic network, then the magnitude of semantic priming should be influenced by variations in acoustic-phonetic structure. Thus, there should be significantly less semantic priming for a word such as *dog* if the initial voiceless stop consonant of a prime word such as *cat* is a poorer exemplar of the voiceless phonetic category. To investigate this question, the initial voice-onset time of the voiceless stop consonants of a set of prime word stimuli was shortened by 2/3, creating stimuli which were still perceived as voiceless but which were closer to the phonetic boundary and hence were poorer exemplars of the voiceless phonetic category (Andruski, Blumstein, and Burton, 1994). Additionally, two types of prime stimuli were used. Half were stimuli in which a change in voicing produced a nonword, e.g. *cat* → *gat*, and half were stimuli in which a change in voicing produced a word and hence a voiced lexical competitor, e.g. *time* → *dime*. Table 1 shows examples of the stimuli used in the lexical decision experimental paradigm.

No Competitor			
	Related	Modified	Neutral
PRIME	**CAT**	**C*AT**	**NOSE**
TARGET	**DOG**	**DOG**	**DOG**
Competitor			
PRIME	**TIME**	**T*IME**	**NOSE**
TARGET	**CLOCK**	**CLOCK**	**CLOCK**

Table 1. Examples of stimuli in the lexical decision paradigm

Stimuli were presented auditorily with either a 50 ms or 250 ms ISI between prime-target pairs. The subjects' task was to indicate whether the target stimulus was a word or a nonword. Both measures of accuracy and reaction time were taken. Results for the 50 ms ISI condition are shown in Table 2. Although the acoustically altered prime stimuli showed semantic priming in the lexical decision task, there was a 49 ms reduction in the magnitude of priming compared to the unaltered condition. These results emerged whether the prime stimuli had a lexical competitor or not, although, overall, subjects were slower when the prime stimulus had a voiced competitor. Results from the 250 ms ISI condition showed, however, that these effects are short-lived, emerging at ISI values of 50 ms, but disappearing by ISI values of 250 ms.

	Unaltered	**-2/3 VOT**	**Unrelated**
No competitor	742	796	902
Competitor	806	850	958

Table 2. Results of acoustic-phonetic structure of a prime stimulus on the magnitude of semantic priming

Further research has shown that these findings generalize to acoustic properties other than voicing in initial stop consonants and, as well, to other phonetic positions. Both removing the closure phonation in voiced final stop consonants in prime words and increasing the vowel duration in medial lax vowels in prime words result in reduced semantic priming (Utman, 1997; Utman, Blumstein, and Sullivan, 2002).

Taken together, these results are consistent with the view that acoustic-phonetic structure has a cascading effect on lexical access, influencing not only the mapping from acoustic-phonetic input to lexical form but also activation of the lexical semantic network. They also suggest that activation of the lexicon is graded with the degree of activation a function of the 'goodness' of fit or the prototypicality of an acoustic-phonetic exemplar to its phonetic category.

3. Phonetic Contrast Versus Phonetic Category Goodness Effects

The effects of phonetic category structure on lexical access described above emerged when the VOT of voiceless stop consonants was shortened. This shortening of the VOT not only influenced the phonetic category goodness of the stimulus but it also rendered the initial stop consonant closer to its contrasting voiced counterpart, reducing the acoustic space and hence the phonetic contrast between the voiced and voiceless phonetic categories. It is possible then that the influence of phonetic category structure shown in the Andruski et al. (1994) study reflected increased competition between the voiced and voiceless phonetic categories rather than the phonetic category goodness of the stimulus input. To investigate this possibility it is necessary to identify an acoustic attribute that affects phonetic category goodness while maintaining the contrastive role between phonetic categories. One such attribute is the length of VOT. Increasing the duration of the VOT of an initial voiceless stop consonant relative to an exemplar prototype stimulus affects phonetic category goodness, but it does not reduce the contrastive value of the VOT in cueing the voiced/voiceless phonetic category. If anything, such manipulations increase the acoustic space between voiceless and voiced phonetic categories.

The stimuli used in this study were analogous to those shown in Table 1, however, in the modified condition, the VOT of the initial voiceless stop consonant was increased by 4/3 (Kessinger and Blumstein, 2003). Results are shown in Table 3. The pattern of results is similar to those found when the initial VOT of stop consonants was shortened. Namely, there was a significant reduction of 47 ms in the magnitude of semantic priming when the initial VOT was lengthened by 4/3. In addition, there were slower reaction-time latencies when the prime stimuli had a voiced competitor, although the magnitude of priming was the same whether the prime stimuli had a lexical competitor or not.

	Unaltered	**+4/3 VOT**	**Unrelated**
No competitor	777	819	954
Competitor	819	870	976

Table 3. Results of acoustic-phonetic structure of a prime stimulus on the magnitude of semantic priming

The results of this study show that acoustic-phonetic structure influences lexical access as a function of phonetic category goodness, regardless of whether the poorer exemplar is near or far from a phonetic category boundary. Thus, the reduction in magnitude of semantic priming is not due to an increase in phonetic contrast effects, but rather is due to the 'goodness of fit' or the prototypicality of an acoustic-phonetic exemplar to its phonetic category.

4. Lexical Competition and Phonetic Category Structure

The proposal that the activation of a lexical candidate is graded has important implications for the architecture of the lexical processing system, for it suggests that the phonetic-phonological form of a word not only activates its lexical entry but also partially activates lexical representations that are phonetically and phonologically similar to that entry (McClelland and Elman, 1986; McClelland and Rumelhart, 1986; Dell, 1986; Masson, 1995). In fact, as described earlier, Luce and his colleagues (Luce and Pisoni, 1998) have shown that word recognition is influenced by the phonetic similarity of potential word candidates. These lexical competitors then appear to be partially activated when a phonetically similar word is presented. However, as we reviewed above, phonetic category structure not only has an influence on the activation of the sound shape or lexical form of a word, but it also has an influence on the activation of the lexical semantic network of that word. Thus, as we have described above, acoustically modified prime stimuli such as *t*ime* primes *clock*, but to a lesser degree than an unmodified stimulus such as *time*. Given this notion of graded activation, an acoustically modified prime stimulus in which the VOT is shortened should not only activate its lexical representation but it should also partially activate its lexical competitor and the lexical semantic network of that competitor. Figure 4 shows a schematic representation of this potential effect. In this case, an acoustically modified *t*ime* should activate the lexical representation for *time*, and it should also partially activate *dime* and its lexical semantic network. If this is the case, then *t*ime* should prime *penny* via *dime*.

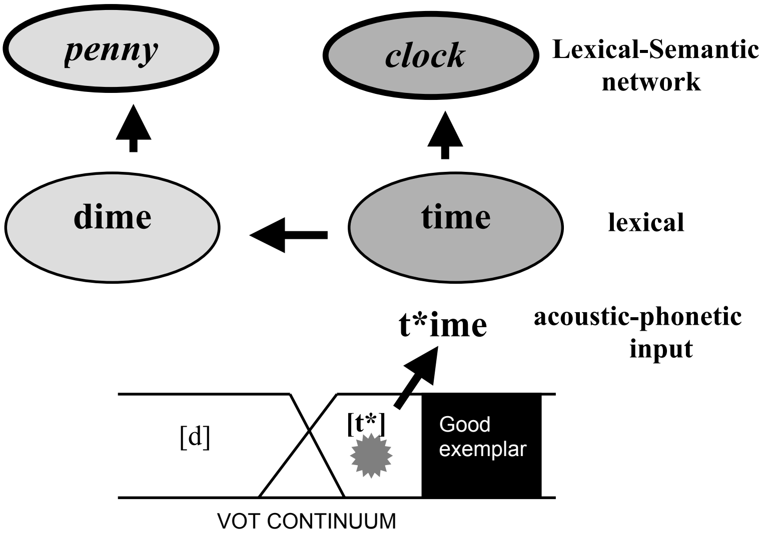

Figure 4. Schematic of mediated priming effect: *t*ime* primes *penny* via *dime*

Table 3 shows the stimuli used to investigate this issue. The design of the experiment (Misiurski, Blumstein, Rissman and Berman, 2003) was similar to that of Andruski et al. (1994) and Kessinger and Blumstein (2003). Subjects heard pairs of stimuli and were required to make a lexical decision on the second stimulus. Results showed reaction-time latencies of 761 ms in the related condition, 818 ms in the competitor condition, and 871 ms in the unrelated condition. Statistical comparisons revealed, as expected, a semantic priming effect (110 ms) for *dime-penny*. Additionally, the acoustically modified voiced lexical competitor for *dime*, i.e. *t*ime*, also primed *penny* (53 ms), although significantly less than that of the semantically related condition.

	Related	Competitor	Unrelated
PRIME	**DIME**	**T*IME**	**NOSE**
TARGET	**PENNY**	**PENNY**	**PENNY**

Table 4. Examples of stimuli used to investigate lexical competition and phonetic category structure

The results of this study indicate that acoustic-phonetic structure not only influences the activation of a lexical entry and its lexical semantic network, but it also partially activates acoustic-phonetic competitors and their associated lexical-semantic networks. Such mediated priming effects in which a prime stimulus such as *t*ime* primes *penny* via the voiced lexical competitor *dime* are consistent with interactive models of lexical processing which allow for graded activation at each level of processing (Marslen-Wilson and Welsh, 1978; Elman and McClelland, 1986; McClelland and Elman, 1986; Marslen-Wilson, 1987; Norris, 1994), and the influence of activation patterns at one level of processing to influence the activation patterns at other levels of processing. The acoustic modification of the stimulus input serves at once to reduce the activation level of the intended lexical target, while, at the same time, increasing the activation of a phonetically similar lexical competitor (McNellis and Blumstein, 2001). The competition between these simultaneously activated lexical candidates results in mutually lower activation levels, an effect that resonates throughout their respective lexical semantic networks.

5. Conclusions

Acoustic variability is a hallmark of speech. Whether that variability is due to articulatory imprecision, coarticulation, or phonetic context effects, it ultimately influences phonetic category structure. Such variability not only affects the perception of the phonetic categories of speech, but also higher levels of language processing including access to lexical form and to the lexical-semantic network. The set of results reviewed above suggest that such detail must be an intrinsic part of models of speech-lexical processing (see McNellis and Blumstein, 2001 for discussion).

Taken together, the patterns of performance observed under conditions of acoustic-phonetic variation are consistent with the view that lexical activation is graded and is influenced by the acoustic-phonetic distance between sound structure input and lexical form. Moreover, these findings indicate that the nature of the acoustic-phonetic input affects not only the activation of lexical form, but also influences the activation of the lexical semantic network itself. Thus, acoustic-phonetic variation of a phonetic category results in differential activation of a lexical candidate and its potential lexical competitors. These activation patterns of the lexical candidate and lexical competitors in turn influence the activation patterns of the associated lexical-semantic network.

Even though the results of this research suggest that acoustic-phonetic structure influences the lexical-semantic network, they do not speak to the nature of the representation of lexical form itself. That is, lexical form could be represented in terms of phonetic segments, which are activated by the acoustic-phonetic input in a graded fashion. Hence, a poorer exemplar of a phonetic category would result in lower activation levels for phonetic segments and these in turn would activate in a graded fashion the lexical representation and its lexical-semantic network. Alternatively, it is possible that lexical form is represented episodically, maintaining the fine details of acoustic-phonetic structure in the lexical representation itself (cf. Goldinger, 1998). In either case, phonetic category structure has a cascading effect on higher levels of language processing influencing not only lexical form but also the lexical-semantic network.

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