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Lexical mediation of phonotactic frequency effects on spoken word recognition: A Granger causality analysis of MRI-constrained MEG/EEG data

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ABSTRACT

Phonotactic frequency effects play a crucial role in a number of debates over language processing and representation. It is unclear however, whether these effects reflect prelexical sensitivity to phonotactic frequency, or lexical "gang effects" in speech perception. In this paper, we use Granger causality analysis of MR-constrained MEG/EEG data to understand how phonotactic frequency influences neural processing dynamics during auditory lexical decision. Effective connectivity analysis showed weaker feedforward influence from brain regions involved in acoustic–phonetic processing (superior temporal gyrus) to lexical areas (supramarginal gyrus) for high phonotactic frequency words, but stronger top-down lexical influence for the same items. Low entropy nonwords (nonwords judged to closely resemble real words) showed a similar pattern of interactions between brain regions involved in lexical and acoustic–phonetic processing. These results contradict the predictions of a feedforward model of phonotactic frequency facilitation, but support the predictions of a lexically mediated account.

Introduction

This paper explores the dynamic relationship between the perception of words and speech sounds. Evidence from a variety of behavioral, BOLD imaging and electrophysiological paradigms demonstrates that spoken word recognition is influenced by phonotactic frequency, a measure of how many words share a specific phoneme or sequence of phonemes in a particular position (cf. Luce & Pisoni, 1998; Pitt & Samuel, 1995; Vitevitch & Luce, 1998a, 1999). Our sensitivity to phonotactic frequency is considered key evidence for understanding both the functional architecture of spoken word recognition processes (Magnuson, McMurray, Tanenhaus, & Aslin, 2003a; McQueen, 2003; McQueen, Jesse, & Norris, 2009; Pitt & McQueen, 1998; Samuel & Pitt, 2003), and the fundamental representational constraints that shape phonology (Albright, 2009; Hay, Pierrehumbert, & Beckman, 2004; Hayes & Wilson, 2008). In this paper, we examine how phonotactic frequency manipulations influence dynamic interactions between brain regions involved in lexical and acoustic–phonetic representation during spoken word recognition.

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Phonotactic frequency effects

The distribution and frequency of linguistic structures affects language processing in many ways. Early psycholinguistic studies found that listeners are sensitive to lexical frequency in spoken word recognition (Pollack, Rubenstein, & Decker, 1959; Savin, 1963). Subsequent work has shown that humans are sensitive to the relative frequency of linguistic units in almost every aspect of language acquisition, perception and production (see review by Ellis, 2002). A second wave of interest in frequency, or more specifically transitional probability, the relative frequency with which one element follows another, occurred following Saffran et al.'s seminal work showing that even brief exposure to manipulations of transitional probability influences the way very young children segment the speech stream (Saffran, 2003; Saffran, Aslin, & Newport, 1996).

Words composed of more frequent phonological constituents generally enjoy a processing advantage (Pitt & Samuel, 1995; Vitevitch & Luce, 1999). Understanding why phonotactic frequency influences processing is important because these biases play a crucial role in competing accounts of language processing and representation. Crucially, they suggest an alternate account of results that have been interpreted as evidence for online top-down lexical influences on speech perception. Elman and McClelland demonstrated that ambiguous word-final fricatives whose interpretation appears to be influenced by lexical context can drive low-level perceptual compensation for coarticulation (Elman & McClelland, 1988). Since the publication of that work, a number of studies have tried to determine whether this phenomenon is due to online top-down lexical influences that perceptually "restore" missing phonemes, or bottom-up perceptual or mapping processes that favor phonotactic patterns that occur in many words (Cairns, Shillcock, Chater, & Levy, 1995; Magnuson, McMurray, Tanenhaus, & Aslin, 2003b; Magnuson et al., 2003a; McQueen, 2003; McQueen et al., 2009; Pitt & McQueen, 1998; Samuel & Pitt, 2003). Phonotactic frequency is a reflection of the structure of the lexicon. The bottom-up account suggests that "lexical influences" on speech perception develop offline as biases that favor the perception or feedforward mapping of more common phonotactic patterns from acoustic–phonetic to lexical representations. This work has shown that the crucial behavioral phenomena are fragile and may influenced by a variety of methodological factors. There is still no consensus about which view is correct.

It is hard to study phonotactic frequency effects independently because they are often masked by the inhibitory effects of phonological neighborhood size (Pisoni, Nusbaum, Luce, & Slowiaczek, 1985), a variable highly correlated with phonotactic frequency (Frauenfelder, Baayen, & Hellwig, 1993). Words composed of more common sublexical constituents that also have large neighborhoods (hereafter referred to as high phonotactic frequency–density) produced slower responses in tasks including shadowing, lexical decision, and speeded same-different judgment, than words with small neighborhoods composed of less frequent elements (Dufour & Frauenfelder, 2010; Vitevitch & Luce, 1998b, 1999; Vitevitch, Luce, Pisoni, & Auer, 1999). Both phonotactic frequency and lexical neighborhood are defined by phonological patterning in the lexicon, and may be considered measures of lexical similarity with phonotactic frequency reflecting partial overlap, and neighborhood size reflecting more complete overlap with words represented in the lexicon. When phonotactic frequency and neighborhood density are varied orthogonally, phonotactic frequency effects are clearer. Words with more common phonotactic components produce better performance in speeded same-different judgments than words with less common components (Luce & Large, 2001). Phonotactic frequency effects are more complex when nonword stimuli are used. High (phonotactic) frequency–density nonwords produce slower lexical decision, but present faster shadowing and speeded same-different judgments, which reverses many of the word findings (Vitevitch & Luce, 1998b, 1999, 2005). Other studies have shown that these results are at least partially attributable to a systematic correlation between neighborhood size and word duration (Lipinski & Gupta, 2005). The one study that deconfounded neighborhood size and phonotactic frequency found no significant effects for either variable in nonword same-different judgment reaction times. A follow up experiment found faster responses for higher phonotactic frequency nonwords, but only when targets were judged to resemble relatively few real words (Luce & Large, 2001).

The dissociation between phonotactic frequency and phonological neighborhood effects has been interpreted in a framework that attributes neighborhood effects to lexical competition and phonotactic frequency effects to sublexical (e.g. phoneme or biphone) phenomena (cf. Luce & Pisoni, 1998; Pylkkänen, Stringfellow, & Marantz, 2002; Vitevitch & Luce, 1998a, 1999; Vitevitch et al., 1999). The literature on lexical frequency effects suggests a number of computationally plausible mechanisms that might be adapted to explain phonotactic frequency effects. These include frequency-sensitive recognition thresholds (Morton, 1969), frequency indexed resting activation levels (Marslen-Wilson, 1990), or frequency-determined priors operating within a Bayesian classifier (Norris & McQueen, 2008).

Another possibility is that phonotactic frequency effects are the result of mapping between acoustic–phonetic representation and lexical representation. Phonotactic frequency could be encoded in the connection weights linking feedforward mapping to lexical representation. This strategy is implemented in some connectionist modeling (Seidenberg & McClelland, 1989), and is consistent with physiological evidence favoring Hebbian learning (Carew, Hawkins, Abrams, & Kandel, 1984; Hebb, 1949). Alternatively, top-down lexical "gang" influences on lower acoustic–phonetic or phonological processing could produce facilitatory effects on word recognition by strengthening lower level speech representations that overlap with more lexical candidates. The benefit to high phonotactic frequency words from the stronger cumulative positive feedback produced by larger cohorts of words with