

Phonological Neighborhood Effects in Spoken Word Production: An fMRI Study

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Abstract

■ The current study examined the neural systems underlying lexically conditioned phonetic variation in spoken word production. Participants were asked to read aloud singly presented words, which either had a voiced minimal pair (MP) neighbor (e.g., *cape*) or lacked a minimal pair (NMP) neighbor (e.g., *cake*). The voiced neighbor never appeared in the stimulus set. Behavioral results showed longer voice-onset time for MP target words, replicating earlier behavioral results [Baese-Berk, M., & Goldrick, M. Mechanisms of interaction in speech production. *Language and Cognitive Processes*, 24, 527–554, 2009]. fMRI results revealed

reduced activation for MP words compared to NMP words in a network including left posterior superior temporal gyrus, the supramarginal gyrus, inferior frontal gyrus, and precentral gyrus. These findings support cascade models of spoken word production and show that neural activation at the lexical level modulates activation in those brain regions involved in lexical selection, phonological planning, and, ultimately, motor plans for production. The facilitatory effects for words with MP neighbors suggest that competition effects reflect the overlap inherent in the phonological representation of the target word and its MP neighbor. ■

INTRODUCTION

Speaking and understanding require that multiple sources of information be integrated in the service of communicating meaning. Most current models of the functional architecture of language propose that in accessing the words of a language, there are multiple stages of processing, each of which requires mapping from one level of representation to another. For example, in spoken word production, a word is selected from among all of the words in the mental lexicon to express a particular concept; this representation is mapped on to the sound shape of the word specifying its phonological form; and this abstract phonological representation, in turn, is mapped on to articulatory implementation processes which provide detailed information to the articulators about the ultimate phonetic realization of the word.

Current models also assume that at each level of processing, not only is there automatic activation of the target word but also partial activation of other related representations that share structural properties with the word candidate (Gaskell & Marslen-Wilson, 1999; Dell, 1986). These representations compete with each other and the best fitting candidate is ultimately selected from the set of activated representations. The ultimate selection of a target from this set of activated presentations is typically called competition. In some cases, selection among multiple activated representations leads to interference, resulting in increased

processing difficulty (as shown behaviorally by longer processing times). In other cases, it results in facilitation, ending in enhanced processing (as shown by decreased processing times). For example, lexical decision latencies are slower for words that have many phonologically similar words or neighbors compared to words that have few phonologically similar neighbors (Luce & Pisoni, 1998), whereas naming latencies for pictures of words are faster for words that have many phonologically similar neighbors than for words with few neighbors (Vitevitch, 2002).

Recent research has suggested that the activation of multiple representations has consequences throughout the language processing system. In particular, information from one stage of processing cascades and influences other stages of processing downstream from it (see Goldrick, 2006, for a recent review). Thus, the selection of the phonological representation of a word is modulated by the number of words in the lexicon that share sound properties with it (Dell & Gordon, 2003), and this has a cascading effect on its articulatory implementation (Baese-Berk & Goldrick, 2009; Goldrick & Blumstein, 2006). For example, as described above, reaction-time latencies for naming pictures of words which have many phonological neighbors are faster than those for naming words which have few phonological neighbors (Vitevitch, 2002; but cf. Luce & Pisoni, 1998). Neighborhood density effects also influence acoustic–phonetic patterns of speech output. Words with many phonological neighbors are produced with a larger vowel space than words from sparse neighborhoods (Scarborough, in press; Munson, 2007; Munson & Solomon,

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2004; Wright, 2004). In a recent study, Baese-Berk and Goldrick (2009) also showed lexically conditioned phonetic variation for “local” effects of neighbors, namely, the effects of a phonologically contrasting minimal pair (MP) lexical neighbor. In particular, the voice-onset time (VOT) productions of words with initial voiceless stop consonants are longer in words that have a contrasting initial voiced stop (*tart* with a contrasting voiced lexical item *dart*) than in words that do not have a contrasting initial voiced stop (e.g., *tar* does not have a voiced competitor *dar*).

This influence of lexical neighbors on articulatory processes reflects the cascading effects of lexical activation and selection processes on plans for articulation. Thus, the activation level of a target word is influenced by the phonological properties of the word’s neighborhood. A lexical candidate from a dense neighborhood requires greater activation to override the activation of contrasting lexical items relative to a lexical candidate from a sparse neighborhood. Similarly, a lexical candidate will require greater activation if it must override a contrasting MP neighbor. In both cases, this increased activation cascades throughout the system and influences processes downstream from lexical access—including the articulatory implementation of the lexical candidate itself. As a consequence, productions are “hyperarticulated.” For example, vowels in words will be produced with wider vowel spaces and the VOT of voiceless stop consonants will be longer.

The finding that spoken word production is influenced by the number of potentially activated, and thus, contrasting phonological lexical competitors raises the question of the neural substrates of this effect. It is the goal of the current study to examine the neural systems underlying this “lexically conditioned phonetic variation” (Baese-Berk & Goldrick, 2009) and to determine whether modulatory effects arising from the activation of phonologically similar words in the lexicon cascade throughout the spoken word production processing stream.

Recent studies exploring the neural systems underlying phonological/lexical competition in auditory word recognition show that posterior areas, including the left supramarginal gyrus (SMG), and frontal areas, including the inferior frontal gyrus (IFG), are modulated by lexical competition (Righi, Blumstein, Mertus, & Worden, 2010; Prabhakaran, Blumstein, Myers, Hutchison, & Britton, 2006). Okada and Hickok (2006) also showed activation in the bilateral superior temporal gyrus (STG) in a study exploring neural activation patterns for high-density compared to low-density words (although their analyses were restricted to the temporal lobes). Taken together, these findings suggest that the IFG, posterior STG, and SMG are part of a network involved in accessing and maintaining the sound shape of a word from the mental lexicon (posterior STG, SMG) and, ultimately, selecting the word from among activated representations (IFG). Previous work by Gold and Buckner (2002) is consistent with this view. They showed coactivation of the SMG with frontal areas when subjects performed a controlled phonological task.

Less research has been conducted exploring the neural systems underlying the influence of phonologically related words (such as lexical neighbors) in spoken word production. One study (Schnur et al., 2009) using a blocked naming paradigm failed to show any neural areas sensitive to the presence of phonologically similar words. However, using a picture–word interference paradigm in which subjects were asked to name a picture with a written distractor presented within the target picture, De Zubicaray, McMahon, Eastburn, & Wilson (2002) showed sensitivity to the presence of phonologically/orthographically related competitors in the left posterior STG (see also de Zubicaray & McMahon, 2009) and a range of areas in the right hemisphere, including the inferior temporal gyrus, inferior parietal lobule (IPL), superior and middle frontal gyrus, and postcentral gyrus. In a later study, Abel et al. (2009) also used a picture–word interference paradigm, but subjects were asked to name a picture presented 200 msec after the presentation of an auditory distractor. Results showed a broad network activated in the context of phonological distractors which shared the two initial phonemes of the stimulus to be named. This network encompassed posterior areas, including the SMG and STG, and frontal areas, including the IFG (BA 44) and the postcentral gyrus. These areas mirror those identified by Indefrey and Levelt (2004) as underlying the components involved in word production.

In the studies discussed above, both the target stimulus and its phonological neighbor are a part of the stimulus set. Thus, the speaker must select and produce the target word in the context of a strongly activated phonological competitor. What is less clear is whether competition effects will also emerge when the competitor is inherent in the structure of the mental lexicon itself but not present in the stimulus array. More specifically, how does the existence of a phonologically similar neighbor in the lexicon affect the neural substrates underlying phonological processing in spoken word production?

The goal of the current study is to further investigate the influence of phonological neighbors in word production by examining the neural systems underlying lexically conditioned phonetic variation. Participants will be required to read singly presented words which either have or do not have MP neighbors (e.g., *cape* with a voiced MP *gape* vs. *cake* which does not have a voiced MP). Thus, the target words in the MP competitor condition will be maximally similar to their MP competitor, sharing all phonemes except for the initial consonant. In contrast to previous fMRI word production studies, the competitor will never appear in the stimulus set. Thus, any effects of competition will arise implicitly from the phonological similarity of words in the mental lexicon and not from competition effects induced by the overt presence of a competitor in the stimulus array.

A reading task was selected rather than an auditory repetition task for several reasons. First, we wanted to avoid the possibility that subjects’ productions would be shaped

by the acoustic properties of the words to be repeated. Recent behavioral research has shown phonetic convergence between speakers in conversation (Pardo, 2006). In addition, we wanted to assure that any speech output patterns were not influenced by potential misperceptions of the test stimuli.

We hypothesize that the effects of phonological competition on spoken word production will recruit a similar network to that shown for phonological competition in auditory word recognition. In particular, we expect activation in the SMG/posterior STG consistent with the view that these areas are involved in accessing and maintaining the lexical (sound shape) form of a word from the mental lexicon (Righi et al., 2010; Prabhakaran et al., 2006; Indefrey & Levelt, 2004; Paulesu, Frith, & Frackowiak, 1993). Activation of the SMG should be modulated by the extent to which there are words in the lexicon which share their sound shape with the lexical candidate.

Based on recent findings that the IFG is recruited in auditory word recognition when words share phonological onsets (Righi et al., 2010), we also expect activation in the IFG (and, in particular, BA 45/44) because this area is recruited when a lexical candidate is selected from among a set of multiple activated representations. Such findings would support the claim that there is a common neural substrate for resolving competition at multiple levels of the language processing system (semantic and phonological) in both language production as well as comprehension, and thus, that the IFG plays a domain-general role in cognitive control (cf. Badre & Wagner, 2007; Snyder, Feigenson, & Thompson-Schill, 2007; Thompson-Schill, D'Esposito, & Kan, 1999; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997).

Of interest is whether in addition to the modulatory effects of phonological competition on the SMG and IFG there will be similar effects in regions involved in the planning of the motor gestures necessary for word production. In particular, the finding that regions such as the precentral gyrus are modulated by phonological competition would be consistent with those models of spoken word production in which access of a word has a cascading effect on the processes downstream from it (Baese-Berk & Goldrick, 2009; Goldrick & Blumstein, 2006). In this case, the selection of a word that has a competitor will affect not only its access and selection but also its motor plans for production of that word.

In sum, in the current experiment, participants were visually presented with one word at a time in the scanner, and they read each word aloud. A sparse sampling design allowed for their productions to be recorded in relative silence. These recordings were analyzed off-line to measure the VOT of the initial voiceless stop consonants of the test stimuli.

METHODS

Participants

Eighteen subjects (2 men) participated in the MR portion of this study and all received payment for their involve-

ment. Their ages ranged from 19 to 31 years with a mean age of 25 years. All participants were native English speakers, were right-handed, as determined by the Oldfield Handedness Inventory (Oldfield, 1971), reported normal hearing and had no known history of neurological disorders. Each subject was screened for MR safety before being placed in the scanner and gave written informed consent in accordance with the guidelines established and approved by the Human Subjects Committee of Brown University.

Stimuli

Stimuli consisted of a subset of the stimuli from Baese-Berk and Goldrick (2009) (see Table 1). All of the 12 pairs of /k/ target stimuli, 18 out of 19 /t/ pairs (the pair *tyke/tithe* was eliminated), and 60 filler words (from the original 128 fillers) were selected from their study and combined into one list for use in the current study. Target pairs were all monosyllabic words that shared both the same initial voiceless stop consonant and vowel. Each MP word, having a voiced neighbor with a voiced initial consonant (e.g., *tart* with a voiced neighbor *dart*), was paired with a nonminimal pair (NMP) word, which lacked such a neighbor (e.g., *tar*). The /t, k/ target words were chosen because they showed the greatest mean VOT difference between MP and NMP target words in the Baese-Berk and Goldrick data. The test words differed as well by lexical density with MP words having more phonological neighbors (28.7) compared to NMP words (21.3) (Irvine Phonotactic Online Dictionary; www.iphod.com). Thus, MP words displayed greater local competition than NMP words by having a competing word which shares all attributes but initial stop consonant voicing and they had greater global competition having had more words overall that share phonological properties with the target word. All pairs were matched across a number of parameters including sum segmental probability, sum biphone probability, and phoneme length (for details, see Baese-Berk & Goldrick, 2009). Additionally, the form-level properties of the coda were controlled across the stimulus pairs. The length and phonological frequency (phonotactic probability) of the codas were taken into account; these did not significantly differ across the two sets. All words were low frequency (less than 20 per million) and were matched for frequency.

In addition to the target stimuli, the list of /t/ and /k/ filler words used by Baese-Berk and Goldrick were combined and reused in this study (see Table 2). Filler words were included to ensure that subjects did not become either implicitly or explicitly aware that half of the experimental stimuli had MP word rhymes and also to provide a richer phonological set of stimuli for them to produce. The filler words were selected such that 24 of the fillers had initial stop consonants evenly distributed across the stop consonants which were not targets in the experiment (i.e., [p b d g]). The remaining fillers were selected so that they

Table 1. Mean VOT across All Subjects of Each Item Used in the fMRI Analysis

<i>MP Stimuli</i>	<i>Average (msec)</i>	<i>Standard Error</i>	<i>NMP Stimuli</i>	<i>Average (msec)</i>	<i>Standard Error</i>	<i>MP–NMP</i>	<i>Number of Subjects Who Showed an MP > NMP Effect for That Pair</i>
tab	104.7	7.4	tat	90.7	7.0	14.0	11
tan	98.6	4.4	tag	88.8	3.9	9.9	10
tank	101.7	10.0	tap	89.8	8.4	11.9	9
teal	110.0	5.6	teat	89.2	5.3	20.8	13
teem	102.3	5.4	teethe	88.7	4.7	13.7	13
tick	96.1	11.6	tiff	84.0	7.3	12.1	10
tuck	80.4	8.2	tuft	68.2	5.6	12.2	9
ted	99.0	6.2	tempt	88.3	5.9	10.6	15
tense	109.4	11.6	tenth	95.8	12.1	13.5	8
tart	120.9	12.4	tar	110.8	7.2	10.1	5
taunt	96.7	6.0	torch	82.7	5.7	14.0	12
tore	106.8	6.5	taut	87.1	5.7	19.7	12
torque	108.4	12.5	torn	96.5	11.5	11.9	8
tomb	110.3	8.5	tooth	91.9	7.1	18.3	11
tame	97.5	6.8	taint	89.0	6.5	8.5	15
tile	96.3	5.4	tights	83.1	6.4	13.3	14
toe	107.4	6.9	toast	88.7	5.6	18.8	14
tote	103.4	13.9	toad	97.3	14.4	6.1	6
cob	108.1	8.5	cog	100.2	9.2	7.9	12
cod	94.8	5.9	cop	82.8	5.7	11.9	12
kilt	93.7	8.8	kin	82.6	7.4	11.1	4
kit	79.0	*	kiln	77.7	*	1.3	1
core	122.3	8.6	corn	108.1	7.7	14.2	14
cuss	101.8	7.6	cub	93.1	7.8	8.8	11
cuff	95.8	11.5	cud	89.3	10.6	6.4	6
curl	116.1	8.3	curb	105.7	9.1	10.4	11
coo	116.6	6.6	coot	97.1	6.2	19.4	12
cab	121.4	8.9	cad	108.5	7.4	12.8	8
cape	91.1	11.4	cake	79.3	8.9	11.9	9
code	92.2	7.0	comb	90.2	9.3	2.0	7
Mean	102.8			90.8		12.0	

An asterisk (*) indicates that there was only one observation for this stimulus, hence, no standard error could be computed.

were distributed across the consonants of English and included fricatives, affricates, nasals, and glides. Finally, only filler words were selected, which did not form an MP or rhyme with the target word stimuli.

Task

Subjects were asked to read each stimulus aloud as it appeared on a screen. Stimuli were presented via an LCD

Table 2. The List of Filler Words Used in the Experiment

bait	dump	jail	pond
bale	fierce	joke	rate
bear	fish	just	ripe
badge	fool	lamp	round
bike	fun	lane	sage
boss	gang	lint	self
charge	geese	look	share
chase	ghost	male	shirt
chip	gown	mint	they
church	guide	moth	vain
dance	gum	pack	vast
date	hand	peach	wait
deep	hedge	pest	west
dice	hole	pink	zip
duke	hunt	poise	zone

projector, which displayed stimuli on a back-projection screen in the scanner room. Subjects viewed this screen using the head coil mirror. Each trial consisted of the presentation of a word (black 24pt MS San Serif font on a white background) in the center of the screen for 2000 msec. Behavioral pilot work indicated that subjects could easily read and produce the stimuli for recording within the 2-sec interval provided.

Presentation of stimuli was controlled by a laptop (IBM Thinkpad) running the BLISS software suite (Mertus, 2002). Subjects' responses to the stimuli were recorded using the built-in patient microphone of the Avotec SS-3100 Silent Scan audio system and an Edirol R-09 24bit Digital Recorder. Stimuli were recorded as 24-bit uncompressed WAV files sampled at 44.1 kHz, and then down-sampled, using BLISS, to 16-bit WAV before subsequent acoustic analysis.

Subjects participated in six experimental runs of an event-related design, each consisting of 60 stimulus presentations. The 120 stimuli were divided into two lists and each list was repeated three times, with stimuli in a pseudorandom order. Each run consisted of 6 /k/ MP, 6 /k/ NMP, 9 /t/ MP, and 9 /t/ NMP target stimuli and 30 fillers. Prior to running the six experimental runs, participants performed a short practice run during EPI data collection (30 practice trials consisting of 7 MP and 7 NMP pairs and 16 fillers) so that they could accustom themselves to the timing of the stimuli and the scanner environment.

Image Acquisition

Both anatomical and functional images were acquired using a 3-T TIM Trio scanner (Siemens Medical Systems, Erlangen,

Germany). High-resolution 3-D T1-weighted anatomical images were acquired for anatomical coregistration (TR = 1900 msec, TE = 4.15 msec, TI = 1100 msec, 1 mm³ isotropic voxels, 256 × 256 matrix). Each functional volume consisted of sixteen 5-mm-thick echo-planar (EPI) axial slices with a 3-mm isotropic in-plane resolution, and slices were acquired in an ascending, interleaved order. Functional volumes were aligned to image the peri-sylvian cortex (TR = 3 sec, TE = 30 msec, flip angle = 90°, FOV = 192 mm³, 64 × 64 matrix).

The 16 slices in the EPI scan were acquired in the first 1000 msec of each 3000 msec TR, followed by 2000 msec of silence in which a stimulus was displayed and the subject's response was recorded. Stimuli presentation was jittered such that each stimulus was distributed across three trial onset asynchrony (TOA) bins (TOA = 3, 6, and 9 sec). To account for T1 saturation effects, each of the six EPI runs were preceded by two "dummy" volumes; these two volumes were discarded during analysis. In addition, five more volumes were added to the end of each EPI run to account for the decay in the hemodynamic response following the final stimulus. A total of 127 EPI volumes were acquired for each of the six runs.

RESULTS

Behavioral Results

For each MP and NMP stimulus, VOT of the initial voiceless stop consonant was measured by hand using the BLISS software program developed at Brown University (Mertus, 2002). To this end, the time (msec) from the onset of the burst to the onset of the vowel was determined. Stimuli were excluded from analysis if the subject read the test stimulus incorrectly or if it was impossible to determine the burst onset from background noise. A total of 9.2% of the total productions were not included in the analysis. Analysis of the pattern of errors revealed no difference between MP and NMP words, either in the incorrect productions of words (average number across the subjects was 0.41 for MP words and 0.53 for NMP words) or in the inability to measure VOT (average number across the subjects was 3.5 MP words and 3.9 for NMP words).

The results of the acoustic analysis revealed that, as predicted, the MP condition showed longer VOTs than the NMP condition (96.2 vs. 94.1 msec). Although the effect is smaller than the 4.5-msec effect shown by Baese-Berk and Goldrick (2009), it was, nonetheless, significant. Wilcoxon matched-pair signed-rank tests revealed a significant difference between the VOT of the MP and NMP conditions effect by participant ($W = -145, p < .0016$) and by item ($W = 197, p < .0434$).

Because the magnitude of the VOT effect was small and only occurred in some of the stimuli for some of the subjects, only those trials containing stimulus pairs showing a VOT difference greater than 1.0 msec across the three paired tokens were used in the fMRI analysis. This subset

of stimulus pairs was still matched for sum segmental probability, sum biphone probability, and phoneme length. The remaining trials were modeled separately during deconvolution analysis (see MR Analysis: Statistical Analysis, below). Overall, stimuli were included in the analysis from all of the target pairs; however, for any given pair, there were different numbers of subjects contributing to that value in the MR analysis. Table 1 lists the target pairs, the differences in VOT between them, and the number of subjects whose data are included for that pair. Overall, the mean VOT of the MP stimuli included was 12 msec longer than that of the included NMP stimuli.

MR Analysis

Imaging data were analyzed using the AFNI software package (Cox & Hyde, 1997; Cox, 1996) on a cluster of 18 Apple dual processor G5 XServe servers. The runs were concatenated and the EPI images were then corrected for head motion after aligning all the collected volumes with the fourth volume (Cox & Jesmanowicz, 1999), transformed to the Talairach–Tournoux space, resampled to 3-mm isotropic voxels, and smoothed with a 6-mm full-width half-maximum Gaussian kernel. All subsequent analyses involving the EPI data were restricted to those voxels imaged for all the subjects and found inside the brain.

For one subject, the data for only four trials were completed due to technical difficulties; as a result, there were only two repetitions of each stimulus for that subject.

Statistical Analysis

Experimental stimuli not used in the fMRI analysis were placed in a separate “bad stimulus” vector. These included stimuli for which a subject made an error as well as for stimulus pairs in which a subject made three errors on one member of the pair. Moreover, those stimulus pairs for which the computed VOT difference between the MP and NMP stimuli pairs was less than 1.0 msec were placed in separate “bad MP” and “bad NMP” vectors. Thus, the good MP and good NMP vectors referenced only those trials where MP and NMP pairs showed a mean VOT difference of 1 msec or more for a given subject. A total of 1509 out of the original 3240 productions were included in the final analysis of the data.

To estimate the hemodynamic response of each stimulus condition (good MP, good NMP, filler, bad MP, bad NMP, bad stimuli), a deconvolution analysis was performed on the functional data using AFNI. Time-series files, which contained the time points at which stimuli were presented, were created for each condition. These were convolved with a gamma function to obtain the idealized hemodynamic response for each condition.

Multiple linear regressions were performed with AFNI's 3dDeconvolve program using the gamma function convolved time-series files for each stimuli condition. In addition,

the six parameters that were output by the motion correction process were also included as nuisance regressors. The 3dDeconvolve analysis returned by-voxel fit coefficients for each condition, which were used to calculate the percent signal change for each of the stimuli conditions for each subject. The data were then submitted to a mixed-factor ANOVA with subjects as a random factor and stimulus conditions as a fixed factor, and a planned comparison was made between the good MP and the good NMP stimuli (good MP – good NMP).

Monte Carlo simulations were performed to determine the number of contiguous voxels needed to achieve a correct significance level of $p < .05$. The simulations were run for 10,000 iterations on a small-volume mask of the brain (Forman et al., 1995). This mask consisted of bilateral areas previously implicated in language function including the IFG, SMG, MFG, AG, and STG. In addition to these areas, the mask also included other bilateral areas such as the TTG, cingulate gyrus, precuneus, IPL, precentral gyrus, insula, and posterior cingulate. At a voxel-level threshold of $p < .05$, a cluster size of 80 contiguous voxels achieved a corrected significance of $p < .05$. The maximum intensity point of the activated clusters was used to identify the location of the activated anatomical regions and the proportion of voxels within a particular cluster that fell within different anatomical regions using the N27 atlas (Eickhoff et al., 2005).

fMRI Results

A summary of all the significant (cluster-threshold $p < .05$) clusters activated in the good MP versus good NMP comparison is shown in Table 3. Four clusters emerged in this comparison; three of which showed greater activation for the NMP stimuli condition (Figure 1).

The NMP stimuli condition showed greater activation than the MP condition in the left SMG, left inferior gyrus (IFG), and left precentral gyrus. The largest cluster (193 voxels) was in the SMG (59%) and extended into the STG (21%) and IPL (8%). The second largest cluster, 103 voxels in size, was found in the left IFG. The majority of this cluster fell in the left pars triangularis (49% of BA 45), and extended into the pars orbitalis (16% of BA 47), pars opercularis (6% of BA 44), and insula. Finally, an 88-voxel cluster was found in the left precentral gyrus, which extended into the left postcentral gyrus. Only one cluster, 289 voxels in size, showed greater activation for the MP condition compared to the NMP condition. This medial cluster was located in the left precuneus and extended bilaterally into the right precuneus and both the left and right calcarine gyrus.

As noted in the Methods section, the test words were distinguished by both local competition (MP words had a voiced lexical competitor and NMP words did not) and global competition (MP words had a higher lexical density than NMP words). In order to determine whether similar activation patterns would emerge solely due to local competition effects, we redid the cluster analysis as described

Table 3. Clusters Thresholded at a Cluster-level Threshold of $p < .05$ with a Minimum of 80 Contiguous Voxels, and at a Voxel-level Threshold of $p < .05$, $t = 2.110$

Cortical Region	Brodmann Area	Cluster Size	t Stat (p)	Talairach Coordinates		
				x	y	z
<i>NMP > MP</i>						
Left supramarginal gyrus	40, 22	193	4.331 (.00045)	-53	-41	24
Left inferior frontal gyrus	44, 45, 47, 13	103	4.738 (.00019)	-53	14	6
Left precentral gyrus	6, 2	88	4.323 (.00046)	-53	-2	27
<i>MP > NMP</i>						
Left precuneus	31, 23	289	5.142 (.000082)	-2	-59	18

The coordinates indicate the voxel with the largest intensity for that cluster. The t stat column gives the t statistic at that maximum intensity point, and the corresponding voxel-level p value. The Brodmann's areas for anatomical regions where the clusters overlap are also given. The Eickhoff and Zilles Atlas (N27) was used to identify cortical regions.

above, controlling for global lexical density. To this end, we excluded five word pairs which differed in lexical density (Ted–tempt; tense–tenth; tile–tights; toe–toast; kit–kiln). Even with this reduced number of observations, results replicated the previous analysis; significant clusters emerged in the SMG and the precentral gyrus, showing greater activation for the NMP compared to the MP words. A 63-voxel subthreshold cluster in the IFG also emerged (equivalent to $p < .15$, corrected threshold).

DISCUSSION

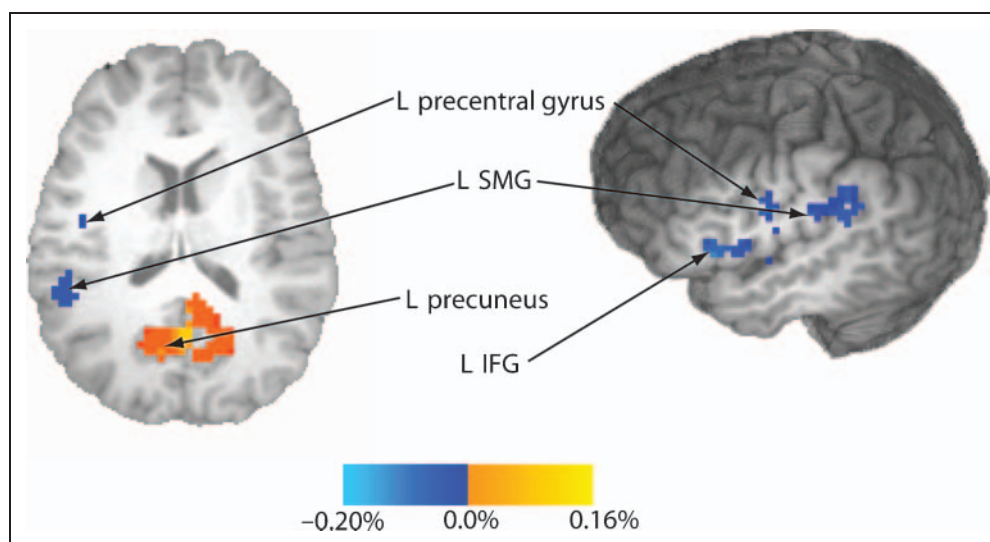
The results of the current study show that lexically conditioned phonetic variation in spoken word production activates a network that includes the left posterior STG, the SMG, the IFG, and the precentral gyrus. In particular, the production of initial voiceless stop consonants is longer

for words that have a voiced MP than for words that do not (cf. Baese-Berk & Goldrick, 2009). The modulation of activation throughout the frontal–parietal network is consistent with a cascade model of language production, where lexically driven differences in the activation of phonological representations modulate subsequent articulatory processing (Baese-Berk & Goldrick, 2009; Goldrick & Blumstein, 2006).

The Frontal–Parietal Network

Activation of the SMG extending into the posterior STG is consistent, with recent work showing activation in these areas in the perception of the phonological sound shape of words (Hickok & Poeppel, 2000; Paulesu et al., 1993) and in the perception of auditorily presented words under conditions of phonological competition (Righi et al., 2010; Prabhakaran et al., 2006). Of importance, the current study

Figure 1. Clusters significant at a voxel threshold $p < .05$ for the MP–NMP comparison. Activations are presented as percent signal changes. With the exception of the precuneus cluster, all clusters showed greater activation for the NMP condition. On the left, the axial slice ($z = 17$) shows a large medial cluster in the precuneus (289 voxels). On the right, the sagittal slice at $x = 43$ shows three clusters in the left SMG (193 voxels), left IFG (103 voxels), and left precentral gyrus (88 voxels).



shows that this area is recruited in spoken word production as well (cf. Indefrey & Levelt, 2004). Thus, this area appears to be modality independent and to be involved in accessing the sound shape of words from the mental lexicon for both auditory word recognition and for spoken word production.

Information from the SMG cascades to frontal areas including the IFG and the precentral gyrus for selecting the word from among the competing set of potential word candidates, for phonological planning processes, and, ultimately, for articulatory implementation. The literature has suggested that the IFG is involved not only in the selection of a word from among a set of competing alternatives (Righi et al., 2010; Thompson-Schill et al., 1997) but also in phonological planning (Guenther, 2006; Huang, Varr, & Cao, 2001; Bookheimer, Zeffiro, Blaxton, Gaillard, & Theodore, 1995) and in grapheme–phoneme conversion (Indefrey & Levelt, 2004; Fiez, Balota, Raichle, & Petersen, 1999; Pugh et al., 1996). The modulation of activation in the IFG is consistent with these results. Whether there is a functional division of the IFG, as has been suggested in the literature (Burton, 2001; Poldrack et al., 1999; Fiez, 1997; Buckner, Raichle, & Petersen, 1995), with selection processes recruiting BA 45 and phonological planning processes recruiting BA 44, cannot be determined from the current data because the IFG cluster that emerged encompassed both of these areas.

Nonetheless, what this study does show is that the IFG is recruited when contrasting phonological neighbors become active. The competition induced by the contrasting elements of the target and its MP neighbor (e.g., /t/ vs. /d/ for target *tart* and MP neighbor *dart*) influences both selection and, ultimately, phonological planning stages for spoken word production. In all previous studies showing modulatory effects of the IFG as a function of phonological competition (Abel et al., 2009; de Zubicaray & McMahon, 2009; de Zubicaray, McMahon, Eastburn, & Wilson, 2002), the competitor has been directly present in the stimulus array. The subject thus had to select the correct target from among other stimuli which directly and overtly competed with it. In contrast, the current study provides evidence that the competitor effect is determined by the phonological properties of the lexicon and *not* by the extent of competition present in the stimulus array. Participants had to read singly presented words; the competitor of the target, the voiced MP, never appeared in the experiment. Thus, the competition effects that emerged were implicit; they reflected the representational properties inherent in the mental lexicon and the extent to which a particular lexical candidate shared phonological properties with other words in the lexicon.

That there was a *reduction* in activation in the IFG for MP target words compared to nonminimal target words also indicates that selection processes in the IFG may reflect facilitatory as well as interference effects. As we discuss below (see The Nature of Modulatory Effects), the facilitatory effects of MP words in spoken word production reflect

the overlap in phonological properties of the activated target and its MP neighbor. In either case, the IFG is recruited when multiple representations are activated and a candidate word must be selected from among these multiple representations.

In addition to competition effects emerging in the IFG, modulatory effects also emerged in the ventral precentral gyrus extending into the postcentral gyrus. This modulation of activation in the precentral gyrus as a function of the lexical properties of words (i.e., whether or not a target stimulus had a MP) suggests that information flow from those areas involved in lexical processing (SMG) and lexical selection (IFG) is retained and cascades to those areas involved in articulatory planning and articulatory implementation (precentral gyrus). Thus, these results suggest that spoken word production recruits a neural system in which the extent of neural activation at the lexical level modulates activation in those neural areas involved in postlexical processes including articulatory implementation.

The Nature of Modulatory Effects

Competition effects in the literature typically result in increased activation. Such results have been shown in auditory word recognition not only in the context of semantic competition (Bilenko, Grindrod, & Blumstein, 2008; Thompson-Schill et al., 1999) but also in the context of phonological competition. In particular, increased activation has been shown in auditory word recognition when accessing words that share phonological onsets (Righi et al., 2010) and for words which have many phonological neighbors compared to those that have a few (Prabhakaran et al., 2006). Consistent with these findings, Abel et al. (2009) showed increased activation in naming the picture of a word with an auditory distractor presented 200 msec prior to the target that shared the initial consonant and vowel with the target.

In contrast to increased neural activation, the current study, as well as several other studies (de Zubicaray & McMahon, 2009; Bles & Jansma, 2008; de Zubicaray et al., 2002), has shown reduced neural activation under conditions of phonological competition. As noted in the Introduction, a similar contrast has been found behaviorally; interference from neighbors is found in speech perception tasks versus facilitation of processing by neighbors in production. Dell and Gordon (2003) attribute these contrasting patterns to the differential demands of perception and production. In perception, phonologically related words are strongly activated by the incoming acoustic signal; the listener's task is made more difficult by the presence of many phonologically related words. In contrast, production is driven by meaning. Because the primary competitors for selection are semantically related words, phonologically related words do not substantially interfere with target encoding. In this context, target selection can benefit from

the boost it receives from the structure it shares with phonologically related words. Thus, the reduction in activation shown in the current study for target words which had an MP is likely due to the overlap between the phonological representation of the target word and its MP neighbor. In particular, MPs share all phonological properties of the word except for the voicing of the initial consonant. This large overlap in the number of sound segments that the competitor shares with the target word primes or facilitates the production of the target word by increasing the activation of these shared segments in relation to the other sound segments in the lexicon and by facilitating those processes involved in both planning and implementing articulatory routines. Hence, fewer neural resources are required to access the sound shape of the target stimulus, leading to reduced neural activation (cf. also de Zubicaray & McMahon, 2009).

In our study, facilitatory effects emerged not only in terms of the neural response but also behaviorally. We compared the naming latencies for the target words with and without MPs measuring from the onset of the visually presented target. Results showed a trend ($p < .09$) for faster naming latencies for MP targets (509 msec) compared to NMP targets (516 msec). Similar patterns were found in examining naming latencies for the subset of words used in the fMRI analyses taken from The English Lexicon Project (Balota et al., 2007; <http://lexicon.wustl.edu/default.asp>) (three pairs were excluded because one or both of the items were not in the database). MP words had a naming latency of 616 msec, whereas NMP words had a naming latency of 628 msec.

The Functional Architecture of Spoken Word Production

Taken together, the results of this study provide additional support for those models of spoken word production in which the extent of activation resulting from competition at the lexical phonological level affects the activation of phonetic representations and, ultimately, articulatory processes (Baese-Berk & Goldrick, 2009; Goldrick & Blumstein, 2006). The present pattern of results suggests that modulatory effects conditioned by the presence of phonological competition emerge in the SMG and cascade to frontal areas including the IFG and precentral gyrus. The effects of competition then are not simply resolved once the target word is selected or even planned for articulation. Rather, competition effects continue throughout the neural network, leaving their signature in those areas involved not just in lexical access and the resolution of competition and selection but also in phonetic processes in production.

These findings are consistent with other behavioral studies of speech production that have documented lexical influences on speech articulation. Studies of speech errors have shown that “traces” of the phonetic properties of the

target are present in both acoustic (Goldrick & Blumstein, 2006) and articulatory measures (McMillan, Corey, & Lickley, 2009). Critically, these phonetic traces are sensitive to the lexical properties of the produced utterance (e.g., whether the utterance results in a word or nonword). This is consistent with the presence of cascading activation from lexical phonological to phonetic processes.

The results reported here augment these behavioral findings by demonstrating that brain areas involved in phonetic processing are influenced by lexical properties. This modulation of phonetic processing by lexical properties is consistent with theories of spoken word production that allow lexically driven activation to cascade to phonetic processes. Functional theories postulating a discrete relationship between lexical and phonetic processes (e.g., Levelt, Roelofs, & Meyer, 1999) cannot account for such effects.

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