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Short Communication

The effect of sublexical and lexical frequency on speech production: An fMRI investigation

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ABSTRACT

There is no consensus regarding the fundamental phonetic units that underlie speech production. There is, however, general agreement that the frequency of occurrence of these units is a significant factor. Investigators often use the effects of manipulating frequency to support the importance of particular units. Studies of pseudoword production have been used to show the importance of sublexical units, such as initial syllables, phonemes, and biphones. However, it is not clear that these units play the same role when the production of pseudowords is compared to the production of real words. In this study, participants overtly repeated real and pseudowords that were similar for length, complexity, and initial syllable frequency while undergoing functional magnetic resonance imaging. Compared to real words, production of pseudowords produced greater activation in much of the speech production network, including bilateral inferior frontal cortex, precentral gyri and supplementary motor areas and left superior temporal cortex and anterior insula. Only middle right frontal gyrus showed greater activation for real words than for pseudowords. Compared to a no-speech control condition, production of pseudowords or real words resulted in activation of all of the areas shown to comprise the speech production network. Our data, in conjunction with previous studies, suggest that the unit that is identified as the basic unit of speech production is influenced by the nature of the speech that is being studied, i.e., real words as compared to other real words, pseudowords as compared to other pseudowords, or real words as compared to pseudowords.

1. Introduction

There is no consensus among researchers regarding the units that underlie the phonetic aspects of speech production. Phonemes, syllables, words, and phrases have all been proposed. There is quite good agreement, however, that the frequency of occurrence of the units is an important factor, and, as a result, frequency manipulations have been used as a tool for identifying the basic units of speech production (Bybee, 2002; Bybee & Scheibman, 1999; Dell, Reed, Adams, & Meyer, 2000; Erman & Warren, 2000; Gregory, Raymond, Bell, Fosler-Lussier, & Jurafsky, 1999; Levelt & Wheeldon, 1994; Varley & Whiteside, 2001; Varley, Whiteside, Windsor, & Fisher, 2006; Whiteside & Varley, 1998). This is true both for models of normal speech production and for accounts of disorders of speech production, such as acquired apraxia of speech (AOS), which is considered to be an impairment of the ability to plan and/or program speech movements (e.g., Aichert & Ziegler, 2004; Varley et al., 2006). The speech production model of Levelt, Roelofs, and Meyer (1999) has been used to account for both normal speech production and the underlying pathophysiology of AOS. In this model, the syllable is the basic unit of speech production. A central component of this model is the mental syllabary, which is the store for "whole gestural scores for at least the high-frequency syllables of a given language" (Cholin & Levelt, 2008, p. 2). The syllabary is located at the interface between phonological and phonetic encoding. At this interface, phonological syllables retrieve their "phonetic matches," and these phonetic syllables, which are also referred to as motor programs, guide the speech production process from this point on. Several studies have examined the effect of syllable frequency (Carreiras & Perea, 2004; Cholin, Levelt, & Schiller, 2006; Laganaro & Alario, 2006; Levelt & Wheeldon, 1994). The finding that words and pseudowords that begin with a high-frequency syllable are produced more quickly than those that begin with a low frequency syllable (e.g., Carreiras & Perea, 2004; Levelt & Wheeldon, 1994) has been used to provide support for the syllable as the basic unit of speech production. This facilitative effect of syllable frequency on speech production times has been found for both pseudowords (Carreiras & Perea, 2004; Cholin et al., 2006; Laganaro & Alario, 2006) and real words (Levelt & Wheeldon, 1994; Perea & Carreiras, 1998). Studies of individuals

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with aphasia (an acquired neurogenic language disorder) and AOS have also been used to argue for or against the syllable as a unit of speech production (Aichert & Ziegler, 2004; Varley et al., 2006; Wilshire & Nespoulous, 2003). However, most studies have failed to find a facilitative effect of frequency for syllables other than the initial syllable (Carreiras & Perea, 2004; Cholin et al., 2006, although cf. Levelt & Wheeldon, 1994).

Varley and Whiteside (Varley & Whiteside, 2001; Varley et al., 2006; Whiteside & Varley, 1998) also stress the importance of the frequency of speech and language units for identifying the basic units of speech production. However, they argue that the speech production system is "blind" to the size of the high frequency unit (Varley et al., 2006). According to Varley and Whiteside, movement sequences become chained together if they occur together with some frequency, and these sequences may be as short as a single syllable word or as long as a phrase. Other investigators also have suggested that the unit of speech production is entire words and even multiword utterances for frequently occurring utterances (Bybee, 2002; Bybee & Scheibman, 1999; Erman & Warren, 2000; Gregory et al., 1999). Bybee (2000) found that final /t/ and /d/ were more likely to be deleted in more frequently occurring words than in less frequently occurring words. Bybee and Scheibman (1999) found that the vowel in the word *don't* reduces to a schwa only when it is preceded by the word *I* and followed by the verbs that most frequently followed *I* in the conversational corpus they studied (e.g., *I don't know*). Pluymaekers, Ernestus, and Baayen (2005) found similar effects for Dutch affixes, depending on the frequency of the word to which they were affixed.

Manipulating frequency of the different speech units to be spoken can provide insight into the normal speech production system, thus helping to inform theories of normal speech production and speech production disorders such as AOS. The purpose of this investigation was to compare patterns of brain activation during the repetition of real and pseudowords that had similar initial syllable frequencies. We predicted that if Bybee and other investigators are correct, the syllables of the real words should have become chained together into a phonetic unit as a result of practice, and there should be less activation during repetition of the real words as compared to the pseudowords. There should be greater activation during the repetition of the pseudowords as compared to the real words, since they have not become chained together into a unit as a result of practice. Conversely, if, as Levelt and others have argued, (1) the syllable is the basic unit of speech production; (2) the frequency of the initial syllable affects the ease with which the speaker produces the utterance; and (3) the words and pseudowords have equivalent initial syllable frequencies, then there should be no difference in the amount of brain activation seen during the repetition of the two categories of words.

Fourteen subjects (2 males, 1 left handed) participated in the study. They repeated, aloud, four-syllable real words or pseudowords while undergoing functional magnetic resonance imaging. There was also a no-speech control condition. The pseudowords and the real words had equivalent initial syllable frequencies. Prior to the experiment, the words were rated for articulatory difficulty by 67 native speakers of English and one non-native speaker on a scale of 1–5, with five being most difficult.

2. Results

Subjects practiced repeating the pseudowords prior to scanning, and they repeated the words with 98% accuracy. Errors consisted of sound substitutions. When this occurred, subjects were asked to repeat the word again, correctly. Subjects produced no sound substitution errors that turned the pseudowords into real words. One limitation is that we were not able to record subjects' speech during the scanning. However, these same subjects participated in a subsequent experiment where they repeated these same words, and the subjects were very consistent in their repetition from the first to the second experiment. Therefore, we surmise that they were likely to have produced the words the same way in the scanner.

As compared to the real words, production of the pseudowords showed greater activation in regions of the brain that are part of the speech production network, including regions in which activation is typically greater during more demanding speech tasks. The volumes, centers of mass, and *t* values for these regions are presented in Table 1. The largest volume of activation was in the left anterior insula, followed by the right inferior frontal cortex (Fig. 1). There were also several regions of activation in the right and left supplementary motor areas (SMA, Fig. 2), and bilaterally in the precentral gyrus and inferior frontal cortex. The SMA is divided into SMA proper and pre-SMA (Picard & Strick, 1996). The division is marked by an imaginary perpendicular line crossing the anterior commissure (the Vca line). The area rostral to the Vca line is the pre-SMA, and the area caudal to the Vca is the SMA proper. Fig. 2 shows areas in pre-SMA and SMA where there was greater activation during the production of pseudowords than

Table 1
Nonsense words > real words.

Site	Side	*x*	*y*	*z*	*T* value	Volume (µl)
Precuneus	L	17.3	46.1	46.9	4.2	33
Insula (anterior)	L	37.5	−11.0	10.0	4.1	553
Pre-SMA	L	3.8	−15.4	43.3	4.1	68
Precentral gyrus	L	37.6	12.4	44.4	4.1	43
Superior temporal gyrus	L	50.6	−0.4	−4.1	4.0	16
Claustrum	L	25.9	−8.1	12.3	4.0	15
Inferior frontal gyrus	L	48.9	−8.7	15.5	3.9	30
Superior temporal gyrus	L	49.5	32.0	13.5	3.9	22
Basal ganglia	L	22.4	−4.2	0.0	3.9	19
Superior temporal gyrus	L	59.7	17.0	2	3.8	24
Superior temporal gyrus	L	61.9	4.4	−1.3	3.8	15
Pre-SMA	R	−8.5	−16.6	48.5	4.6	45
Inferior frontal gyrus	R	−42.9	−13.4	12.0	4.2	530
Pre-SMA	R	−6.9	−9.1	59.4	4.2	154
Pre-SMA	R	−3.5	−8.0	48.0	4.1	64
Pre-SMA	R	−1.9	−14.5	55.6	4.1	28
Pre-SMA	R	−1.3	−8.8	45.0	4.1	16
Precentral gyrus/insula	R	−47.4	3.9	47.4	4.0	22
Pre-SMA	R	−1.8	−11.7	63.1	3.9	31

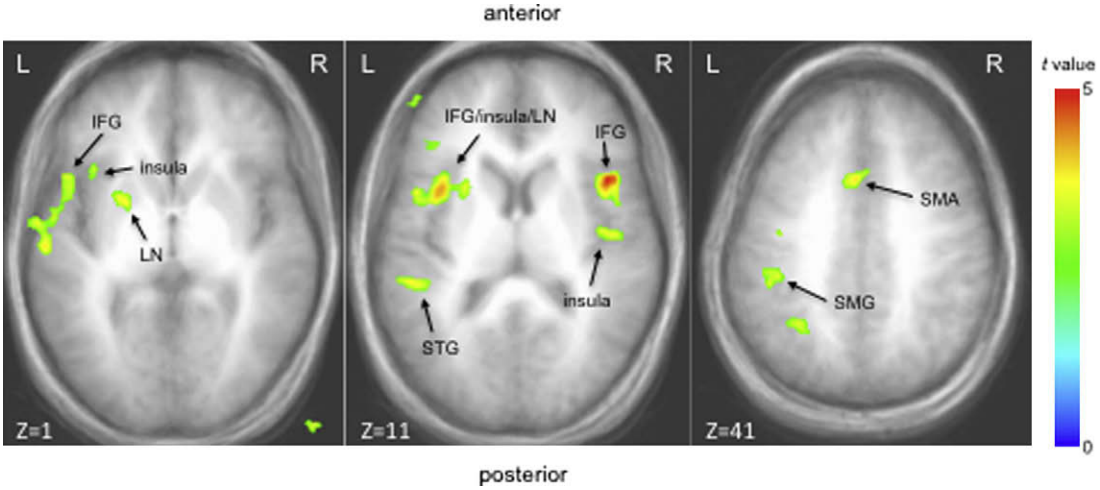

Fig. 1. Greater activation for the production of pseudowords as compared to real words superimposed on the subjects merged anatomies (IFG = inferior frontal gyrus; LN = lentiform nucleus; STG = superior temporal gyrus; SMA = supplementary motor area; SMG = supramarginal gyrus).

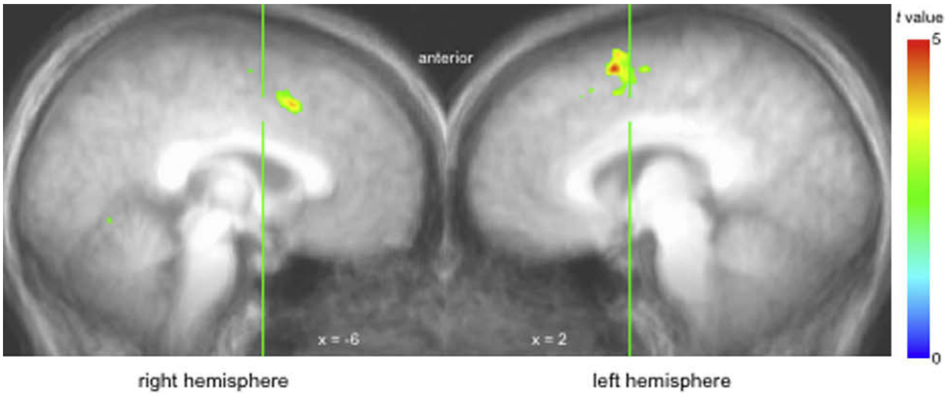

Fig. 2. Greater activation in SMA and pre-SMA for pseudowords as compared to real words.

during the production of real words. The Vca line is indicated as a green line. There was only one small area in the right middle frontal gyrus (-37, -55, 19, $t = 3.32$, p(corrected) $< .006$) that showed greater activation during the production of real words as compared to pseudowords. This is shown in Fig. S1 of the Supplementary material. Fig. 3 shows areas that were more active during the production of pseudowords than during the production of real words superimposed on an inflated brain.

As compared to the no-speech condition, production of both the real and pseudowords produced large bilateral areas of activation in areas known to be involved in speech production, such as the superior temporal gyrus, precentral gyrus, and pre-SMA/SMA, as well as subcortical regions, such as basal ganglia, thalamus, and cerebellum. The Talairach coordinates for the location of the peak intensity values for particular regions of interest are reported in Tables 2 and 3. Fig. S2 (Supplementary material) shows activation for real and pseudowords as compared to no-speech. In general, in comparison to the no-speech control condition, production of pseudowords resulted in larger volumes of activation and larger signal changes than production of real words in a variety of regions including bilateral superior temporal cortex, motor cortex, insula, and basal ganglia. There were two small areas that showed greater activation during the no-speech control condition than in the real word condition. These were in the left anterior cingulate (-12, -33, 30, $t = 3.1$) and at the left temporoparietal junction (-41, 38, 18, $t = 3.2$). There was one small area that showed greater activation during the no-speech control condition as compared to the pseudowords in the left anterior cingulate (-11, -44, 3, $t = 2.7$). Across all comparisons, the data for the two male subjects and the one left handed subject were not different from the other 11 subjects.

3. Discussion

Many investigators have suggested that manipulating the frequency of various aspects of words provides a method for identifying the basic units of speech production. For example, Papoutsi and colleagues (2009) found that production of pseudowords composed of low frequency biphones resulted in larger activation in several brain regions as compared to production of pseudowords composed of high frequency biphones. They suggest that this is because the high frequency biphones are "precompiled and their articulatory codes are retrieved, as suggested by the fact that they are processed faster than the ones with less-frequent components…" (p. 7). However, our data, in conjunction with previous studies, demonstrate that the unit that is identified as the basic unit of speech production is influenced by the experimental comparison. When the production of pseudowords is compared to the production of other pseudowords with different sublexical unit frequencies (e.g., Cholin et al., 2006; Papoutsi et al., 2009; Vitevitch & Luce, 2005) or when the production of real words is compared to the production of other real words with different sublexical unit frequencies (e.g., Levelt & Wheeldon, 1994), then sublexical units, such as initial syllables, phones, and biphones, appear to be the ba-

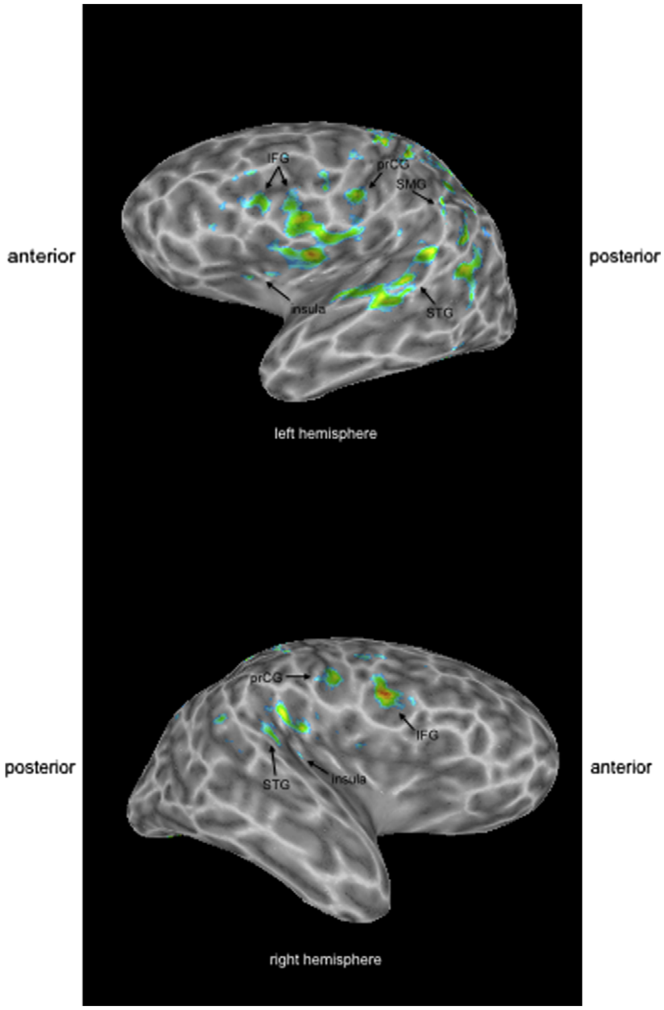

Fig. 3. Greater activation in SMA and pre-SMA for pseudowords as compared to real words superimposed on an inflated brain.

Table 2
Pseudowords > no-speech.

Site	Side	*x*	*y*	*z*	*T* value
Superior temporal gyrus	L	56	16	7	5.5
Precentral gyrus	L	48	10	31	4.9
Putamen	L	26	0	1	4.9
SMA	L	3	−8	58	4.8
Precentral gyrus	L	51	14	11	4.8
Medial frontal gyrus	L	2	−18	47	4.7
Anterior insula	L	39	−14	1	4.5
Inferior frontal gyrus	L	49	−5	14	4.5
Caudate	L	15	−9	12	4.5
Thalamus	L	15	9	9	4.4
Superior parietal lobule	L	26	50	43	3.7
Cerebellum	L	6	39	−5	3.3
Precentral gyrus	R	−50	6	12	5.7
SMA	R	−5	−14	52	5.5
Precentral gyrus	R	−43	5	26	5.4
Medial frontal gyrus	R	−4	−18	47	4.8
Superior temporal gyrus	R	−55	8	2	4.4
Putamen	R	−25	−6	−4	4.2
Anterior insula	R	−35	−21	7	4.0
Thalamus	R	−5	12	9	3.6
Cerebellum	R	−3	54	−14	3.5

Table 3
Real words > no-speech.

Site	Side	*x*	*y*	*z*	*T* value
Superior temporal gyrus	L	58	13	6	5.7
Precentral gyrus	L	44	10	30	5.2
Inferior frontal gyrus	L	43	−2	30	4.4
Cingulate gyrus	L	6	−7	37	3.9
Thalamus	L	7	12	9	3.6
Putamen	L	26	4	2	3.5
Caudate	L	8	−4	5	3.5
Pre-SMA	L	2	−18	48	3.5
Pre-SMA	L	3	−4	53	3.5
Cerebellum	L	1	39	−6	3.3
Posterior insula	L	39	21	7	3.2
Anterior insula	L	39	−19	4	3.2
Precentral gyrus	R	−54	5	10	5.6
Superior temporal gyrus	R	−53	9	2	4.9
Thalamus	R	−4	18	11	4.1
Basal ganglia	R	−24	−7	−2	3.6
SMA	R	−2	−4	53	3.4
Cerebellum	R	−1	41	−5	3.1

sic unit of speech production. However, when the production of pseudowords is compared to the production of real words that are matched for several sublexical unit frequencies (i.e., initial syllable, summed phoneme, and summed biphone probabilities), as in our study, then entire lexical units appear to be the basic unit of speech production.

As noted above, Papoutsi et al. (2009) manipulated the frequency of phonemes and biphones (phonotactic probability) in pseudowords. Phonotactic probability is the frequency with which phonological segments and sequences of segments occur in a particular language (Vitevitch & Luce, 1998, 2005). In a series of studies, Vitevich and Luce found that high phonotactic probability speeded the production of pseudowords, but slowed the production of real words (although cf. Lipinski & Gupta, 2005). Perhaps the effect that we observed was due to differences in the phonotactic probabilities of the real and pseudowords. To test this, phonotactic probabilities were calculated for each word and pseudoword using the online phonotactic probability calculator (Vitevitch & Luce, 2004). A *t*-test revealed no significant differences between summed phoneme ($t(58) = -.209$, $p = .835$) and summed biphone ($t(58) = .513$, $p = .610$) probabilities for real and pseudowords.

Bybee (2002) accounted for the effects of frequency on speech production by an exemplar model that includes the storage of words and frequently occurring sequences of words. The exemplar representation of each token includes the phonetic form. Bybee stated "... phrases such as *I don't know*, *don't you*, and *last year* are stored in the lexicon, and phonetic changes that accrue as their production is automated are registered there" (p. 217). The cognitive advantage here is that highly automated utterances "speed up processing, just as representational strengthening does" (p. 216). In a study of both spoken and written texts, Erman and Warren (2000) found that 55% of these texts consisted of prefabricated utterances. Moreover, they estimated that in a 100 word text, the use of prefabricated utterances would reduce the number of utterance choices that the speaker must make from 55 to 26. Rosenbaum and colleagues (Rosenbaum, Cohen, Jax, Weiss, & van der Wel, 2007) suggested that a motor program can be conceived of as a memory for what has happened. When motor events repeatedly occur together, such as during the production of the concatenated syllables that comprise a word or concatenated words that form a phrase, they are consolidated into a single memory or motor program. However, when there is no existing motor program for an entire lexical unit, as in the production of pseudowords and perhaps very infrequently occurring real words, then the speaker may resort to sublexical units (e.g., Cholin & Levelt, in press; Papoutsi et al., 2009).

Repetition of both real and pseudowords resulted in activation of a network of brain regions that has been shown to be involved in overt speech production (Bohland & Guenther, 2006; Riecker, Brendel, Ziegler, Erb, & Ackermann, 2008; Riecker et al., 2000; Shuster & Lemieux, 2005; Sörös et al., 2006). However, repetition of pseudowords resulted in stronger and larger areas of activation within the network, as we predicted. This includes the four regions in which Papoutsi et al. (2009) found greater activation for their sublexical frequency manipulation of pseudowords, as well as other parts of the speech production network. At our statistical threshold, we observed only one small area that was more active during the production of real words as compared to the production of pseudowords. These data show that the repetition of novel items, even when they have similar sublexical frequencies, places greater demand on much of the speech production network. The majority of studies on practice have shown a decrease in brain activation with practice (Kelly & Garavan, 2005). This decrease has been seen across a variety of cognitive domains including attention (Tomasi, Ernst, Caparelli, & Chang, 2004) and working memory (Landau, Schumacher, Garavan, Druzgal, & D'Esposito, 2004).

Investigators have suggested that word repetition is a post-lexical process that does not involve activation of the semantic system (e.g., Pluymaekers et al., 2005). However, Dell and colleagues (Hanley, Dell, Kay, & Baron, 2004) have proposed a dual route account of the repetition of familiar words. One route is a lexical route and one is a non-lexical route. According to this model, repetition of pseudowords involves the non-lexical route only. Perhaps the real words in our study activated the semantic network, which somehow facilitated their production. However, our finding of only one small area where there was greater activation for repetition of real as compared to pseudowords suggests that real word repetition was not activating lexical/semantic networks to a greater extent than pseudowords.

The increased effort that we observed (as evidenced by increased brain activation) for the production of pseudowords may occur at various points in the repetition task. First, accurate repetition requires accurate perception of the auditory model, and perception of a novel word is more demanding than perception of a familiar word. Perhaps some of the increased activation we observed was a product of the auditory stimulus, rather than the response. However, there was only one small area in the no-speech control condition as compared to the pseudoword condition and two small areas in the no-speech control condition as compared to producing real words. This suggests that the auditory stimulus was effectively subtracted out in the analyses. Moreover, in a study of the perception of real and pseudowords using fMRI, Orfanidou, Marslen-Wilson, and Davis (2006) found that listening to pseudowords generally produced *less* brain activation than listening to real words.

In summary, our data showed that when the frequency of several of the sublexical units was the same (i.e., initial syllable, summed phoneme, and summed biphone probabilities), there was greater demand on the speech production network for the production of novel words than for the production of previously learned words. Our data are more compatible with models of speech production that propose that phonetic information is available at a variety of linguistic levels, including the word and the phrase level.

4. Methods

4.1. Participants

There were 14 participants (2 males, 12 females). Ages ranged from 21;11–36;3 with a mean of 25;7. They were all native speakers of American English with no exposure to Turkish (see below) and had no history of speech, language, or neurological problems. All had normal hearing, as determined by pure tone thresholds, and all were right handed, as determined by the Edinburgh Handedness Inventory (Oldfield, 1971) with the exception of one, who was left handed. The study was approved by the Institutional Review Board at West Virginia University.

4.2. Stimuli

There were 30 four-syllable real words and 30 four-syllable pseudowords. The real words were all nouns. The pseudowords were created by starting with Turkish words of three to four-syllables. English sounds were substituted for any non-English sounds, and syllables were added to three syllable words to make them four-syllable words. All pseudowords obeyed the phonotactic constraints of English. We started with words from a real language, in order to make the pseudowords as natural as possible; however, we wanted to avoid a language that American speakers might be familiar with, such as Spanish. We chose and edited the words so that many were similar to the real English words in syllabic structure (e.g., motorcycle/jelesekle, thermometer/denemeker). After 70 pseudowords were developed, they were recorded by a native English speaker with no knowledge of Turkish. The pseudowords were then played to 18 senior undergraduate students in speech pathology and audiology. Seventeen of the students had no knowledge of Turkish, and one was a native speaker of Turkish. The students were asked to repeat each word aloud and rate the difficulty of production on a Likert scale of 1–5 with one being the word "refrigerator" and five being the phrase "We're real rear wheels." They were also asked to determine whether they recognized the word. The average difficulty rating from the 17 non-native speakers was 2.3, indicating that they found the words relatively easy to produce. Most of the listeners indicated that they did not recognize any of the words. A few listeners indicated that they recognized one or two of the words; however, there was no pattern to the words that listeners claimed to recognize. The native Turkish speaker indicated that she recognized 25 of the 70 words. Thirty of the pseudowords were randomly chosen from those that had a mean difficulty rating of 2.5 or less. These 30 words had a mean difficulty rating of 2.17 (sd = .23).

These 30 pseudowords, along with the 30 real words that were to be used in the study, were played to 20 students in speech-language pathology (SLP) and 30 physical therapy (PT) students. They performed the same judgment task as for the original 70 pseudowords, repeating each word aloud and making judgments regarding difficulty of articulation, as well as whether they recognized the word. All 50 raters recognized the real words. Three thought that they recognized one each of the pseudowords, but it was a different pseudoword for each of the three raters. The mean difficulty of articulation rating by the SLP students (on the five point scale) was 1.13 for the real words (sd = 0.37) and 2.19 for the pseudowords (sd = 0.86). A *t*-test (Meek, Ozgur, & Dunning, 2007) revealed a significant difference in difficulty rating between the two categories ($t(29) = 14.41$, $p = 4.67\text{E}{-15}$). The mean difficulty of articulation rating for the PT students was 1.18 for the real words (sd = .42) and 2.22 for the pseudowords (sd = .95). This difference was also significant ($t(29) = 15.78$, $p = 4.464\text{E}{-16}$). These data show that the raters found these words only slightly more difficult to produce than real words.

The frequency of occurrence of the first syllable of both the real and the pseudowords was determined using the English syllable frequency data from the Celex Lexical Database, Release 2 (1995). A *t*-test ($t = 0.27$, $p = 0.78$) revealed no significant difference in initial syllable frequency between the real and pseudowords. It should be noted that the English Celex database is based on data from written texts. The words were also similar in initial syllable articulatory complexity. For the real words there were 18 CV (consonant–vowel), 6 V, 4 VC, and 2 CVC syllables. For the pseudowords, there were 23 CV, 2 V, 3 VC, and 2 CVC syllables.

There were also 30 pink noise stimuli of the same duration and peak intensity as the words and pseudowords, which served as a no-speech control condition. All of the stimuli (speech and noise) were presented in the same carrier phrase "Say the word ________." The real words, pseudowords, and pink noise were edited so that they had the same peak intensity, and the phrases were edited so that all phrases were 1500 ms in total duration. More details regarding the stimuli and an Appendix listing the words are presented in the Supplementary material.

4.3. Procedure

The imaging was performed on a GE Signa 3 T MR scanner in the Center for Advanced Imaging at West Virginia University. We used a continuous scanning protocol, because we wanted to extend the experimental paradigm to individuals with speech and language disorders who often cannot produce a response in the narrow window of time afforded by a clustered volume acquisition. The functional imaging parameters were as follow: spiral in/out (Glover & Law, 2001); 22 axial slices; TR = 2 s; TE = 35 ms; Flip = 75°; FOV = 240 mm; matrix = 64×64; spatial resolution = $3.75 \times 3.75 \times 5$ mm. We also collected high resolution anatomical images with the following parameters: SPGR; FOV = 250 mm; matrix 256×256; 124 axial whole brain slices; spatial resolution = $.97 \times .97 \times 1.8$ mm.

Prior to being placed in the scanner, participants repeated the pseudowords aloud. If they produced an error, they were asked to repeat the word again until they produced it correctly. Since the words were being presented during continuous scanning (and thus in a noisy background), this permitted some familiarization with the words, but did not provide extensive practice. The experiment was run under the control of the Presentation® software. The stimulus presentation was triggered by a pulse out from the scanner, and Presentation also recorded each pulse (each TR) into a log file, along with a record of the stimuli that were presented. The stimuli were presented in random order over MR compatible earbuds (STAX SRS-005 Earspeaker system; Stax Ltd., Japan) at an intensity level that was adjusted individually for each participant. Noise protective earmuffs were placed over the earbuds. There was a 12 s interstimulus interval. The words were presented in two runs with 15 stimuli from each of the three categories per run (45 stimuli) presented in random order. The participants were instructed to repeat the real words and the pseudowords aloud. They were told that when they heard the noise stimulus, they were to produce no mouth movements in the period after the noise (including swallowing, licking their lips, etc.). This served as the no-speech control condition. The earmuffs fit tightly into the head coil, making it difficult for subjects to move their heads. However, in order to minimize head movement further, a piece of tape was placed across each participant's forehead and attached to either side of the head coil. Participants were told that if they felt a tug on the tape, this meant that they were moving their heads, and they should try to stop.

4.4. Data analysis

Data were analyzed with the Analysis of Functional Neuroimages (AFNI) software (Cox, 1996). After reconstruction, the first five images were discarded from the analysis. Each run was corrected for differences in slice time acquisition, and a measure of percent signal change was computed for each run (as a percent of the mean intensity for a subject's entire brain). The two experimental runs were then concatenated, motion corrected, and blurred using a 6 mm Gaussian filter. These data were entered into a multiple regression analysis using the AFNI program 3dDeconvolve. The stimulus time series (representing the speech motion) was used as a regressor of no interest in the analysis, as described in Birn, Bandettini, Cox, and Shaker (1999) and Shuster and Lemieux (2005). This approach takes advantage of the phase differences between the speech movements and the BOLD response. The speech movements will be completed within a few hundred milliseconds following the stimulus, while the peak of the BOLD response will lag by about 4 s. To model the BOLD response, the stimulus time series was convolved with a gamma variate function (Cohen, 1997). The stimulus time series and the convolved time series then were entered into the regression analysis with the time series representing the speech movements and the convolved time series representing the BOLD response. The data from each subject were then spatially normalized (Talairach & Tournoux, 1988) and entered into a mixed effects analysis of variance (ANOVA). Within the ANOVA, comparisons between conditions were accomplished with *t*-tests. We used the AFNI program AlphaSim to address the issue of multiple comparisons and determined that a cluster size of five voxels in conjunction with a per-voxel probability of $p = .006$ yielded an overall significance level for the volume of $p < .05$. Therefore, the *t* maps from the ANOVA were clustered and thresholded using these values. More details regarding the data analysis are presented in the Supplementary material.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.bandl.2009.06.003.

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