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VOWEL TARGETING AND PERCEPTION IN APRAXIA OF SPEECH

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VOWEL TARGETING AND PERCEPTION IN APRAXIA OF SPEECH

by

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DEDICATION

To Sarah Butler Jacks, whose love and encouragement
were essential to the completion of this work.

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VOWEL TARGETING AND PERCEPTION IN APRAXIA OF SPEECH

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Vowel production and perception were examined as a window on speech motor control processes in five adults with acquired apraxia of speech (AOS) and five non-brain-damaged (NBD) control participants. Articulatory targeting for vowels was assessed acoustically for the three front vowels [ɪ], [ɛ], and [æ] in four stimulus conditions varying in word length. Vowels were produced in a normal, unconstrained context and in two bite block conditions, where the mouth opening was controlled by placing a small or large piece of plastic between the teeth. Vowel perception for front vowels was tested using standard categorical tests of identification and same-different discrimination. Processing of vowel information also was assessed in tests of rhyme generation and judgment. Acoustic analysis of apraxic vowel production revealed formant frequencies within normal ranges. Introduction of the bite block constraint destabilized vowel targeting for both apraxic and normal participants, resulting in greater targeting error and reduced distinctiveness between adjacent vowels in the vowel space. Vowel formants in multisyllabic words varied from those produced in monosyllables for both groups, although these deviations were perceived as normal variation by listeners. Although apraxic vowel formants generally conformed to normal ranges, perceptual goodness ratings indicated poorer perceived quality of apraxic vowels compared to NBD controls, and measures of vowel targeting accuracy and vowel distinctiveness also were consistently inferior for apraxic speakers. Perceptual testing revealed normal vowel discrimination in all AOS participants, while four of five apraxic listeners had inconsistent ability to identify vowels. Comparison of production and perception measures indicated no significant relationship between abilities in the two domains for AOS or NBD participants. Distinctiveness of produced vowels was significantly related to clinical measures of speech deficits in apraxia, while perceptual deficits were correlated with auditory comprehension scores. Findings suggest that vowel production in AOS is characteristic of a motor targeting deficit, although variability of vowel formants has a minor effect on the overall communicative impairment in people with the disorder. The lack of correspondence between production and perception abilities indicates that perceptual processing is not a major factor in the motor targeting abilities of individual with AOS.

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CHAPTER 1
INTRODUCTION

Apraxia of speech (AOS) is a neurogenic disorder of speech motor control that affects the ability to specify kinematic parameters of speech movements in the absence of neuromuscular weakness. Impaired spatial and temporal targeting in AOS results in distorted consonant and vowel production, irregular patterns of rhythm and stress, and effortful and groping attempts to produce speech. AOS frequently is accompanied by aphasic (i.e. linguistic) impairments including agrammatism and anomia, as well as varying degrees of sensory processing deficits for tactile, kinesthetic, proprioceptive, and auditory information. Lack of consensus on the critical behavioral characteristics of the disorder and the terminology used to describe apraxia of speech (e.g. aphemia, anarthria, apraxic dysarthria, minor Broca's syndrome, motor aphasia) has led to confusion in the development of a coherent theoretic framework to describe the disorder, in dissemination of research pertaining to the disorder, and in the development of efficacious treatment approaches for AOS.

Many important questions about apraxia of speech are undecided, including the presence of concomitant behavioral deficits and theoretical accounts of the speech motor control deficit. Differing theoretical vantage points primarily hinge on the questions of which behavioral deficits are central to the disorder and what are the mechanisms from which they arise. For example, some theorists suggest that irregular movement patterns are the central defining characteristics of AOS and that associated features such as perceptual deficits result from independently impaired processing systems not crucial to the planning of movements (Ballard, Granier, & Robin, 2000; Ballard, Robin, & Folkins, 2003). Other theories consider sensory factors to be more integral to the planning of speech movements (e.g. Guenther, Ghosh, & Tourville, in press; Code, 1998; van der Merwe, 1997; Ziegler, 2003). In speakers with AOS, deficits in auditory perception, tactile-kinesthetic perception, and inability to compensate for articulatory perturbations (i.e. bite-block speaking conditions) may reflect speech motor control systems that are unable to utilize sensory information in the development and/or modification of motor plans for articulatory gestures.

Vowel production errors in AOS are of interest because they reflect impaired spatial targeting ability (Kent & Rosenbek, 1983). The frequency of vowel errors in AOS is disputed, however, with broad phonemic analyses indicating that consonant production is more susceptible to error than vowel production (Canter, Trost, & Burns, 1985; LaPointe & Johns, 1975; Monoi, Fukusako, Itoh, & Sasanuma, 1983; Trost & Canter, 1974), while narrow phonetic analyses suggest that consonants and vowels are equally impaired (Haley, Bays, & Ohde, 2001; Odell, McNeil, Rosenbek, & Hunter, 1991). Ability to compensate for articulatory perturbances during vowel production is also an open question, with studies showing that speakers with aphasia and apraxia have difficulty with bite block speaking conditions (Sussman, Marquardt, Hutchinson, & MacNeilage, 1986) or that they perform as well as non-brain-damaged control participants (Baum, 1999; Baum, Kim, & Katz, 1997). The role of sensory deficits in AOS has been infrequently examined, with results showing that many, but not all, individuals with the disorder have difficulty perceiving auditory stimuli (Aten, Johns, & Darley, 1971) and processing tactile, kinesthetic, and proprioceptive information (Rosenbek, Wertz, & Darley, 1973).

One explanation for the variability in research findings in the three domains of interest in this study (viz. vowel targeting, compensatory vowel production, perceptual abilities) is that participants identified on the basis of traditional classification criteria represent a heterogeneous group of disorders. AOS results from neural lesions to the left hemisphere, with traditional accounts suggesting a left “Broca’s area” lesion (Broca, 1861/1977) and other reports showing lesions in parietal cortex (Square-Storer & Apeldoorn, 1991; Square, Darley, & Sommers, 1982), subcortical structures (Kertesz, 1984; Marquardt & Sussman, 1984), and anterior insula (Dronkers, 1996). In any given sample of individuals identified as apraxic, variation between participants likely will occur in the site of neurological lesion, the extent to which spatial targeting of articulators is affected in vowel production, ability to compensate for perturbed speaking conditions, and presence of auditory perceptual deficits. The possibility remains, however, that the frequent occurrence of sensory deficits in adults with AOS is not coincidental, but reflects a speech motor control system that depends upon connected sensory processing networks to enable the production of articulate speech.

The purpose of this investigation is to explore mechanisms of speech motor control in adults with apraxia of speech using vowels as a window on a) articulatory targeting adequacy, b) compensatory articulatory abilities under novel articulatory constraints, and c) integrity of auditory and phonetic processing mechanisms. In particular, acoustic parameters of vowel production will be assessed in normal and bite block conditions to determine articulatory targeting adequacy and compensatory articulation abilities in adults with the disorder. Categorical discrimination of vowels (e.g. identification and discrimination) and rhyme processing will be tested to assess the integrity of auditory and phonetic processing systems.

The following chapters will review relevant literature pertaining to description of the disorder, including behavioral characteristics and etiological findings in apraxia of speech and the behaviors of particular interest in this study, namely vowel production, compensatory articulation in bite-block speech, and perceptual abilities in AOS.

CHAPTER 2: LITERATURE REVIEW

Chapter 2.1

Definition of the disorder

Apraxia of speech (AOS) has been described for more than a century, using a large group of diagnostic labels (see Darley, 1968 and Johns & LaPointe, 1976 for a review of the terminological history). The contemporary definition of AOS is as a phonetic-motoric disorder that impairs the translation of a phonologic frame into spatial and temporal kinematic parameters corresponding to intended speech movements (McNeil, Robin, & Schmidt, 1997). Impaired articulatory targeting in AOS results in speech production characterized by segmental and prosodic distortions and that is often perceived by listeners as “effortful”. Most definitions of AOS specify that impaired articulation is not attributable to neuromuscular impairment or sensory or linguistic processing deficits (Aten et al., 1971; Darley, 1968; McNeil et al., 1997). Nevertheless, the disorder usually is accompanied by varying degrees of impaired language and sensory abilities, including agrammatism, anomia, mild auditory comprehension deficits, and auditory or kinesthetic imperception.

Chapter 2.2

Theoretical framework

The basic problem in apraxia of speech is to understand the nature of the speech processing system, the subsystems involved in this process, and how breakdown in the system results in the wide array of behavioral symptoms characteristic of the disorder.

Apraxia of speech often is characterized as an impairment in the ability to move downstream from phonologic specifications of speech sounds to abstract speech goals (i.e. motor planning) and from abstract speech goals to muscle-specific positioning and timing parameters (i.e. motor programming). This description, however, does not take into account the influence of sensory processes in the control of speech movements. High frequency of sensory deficits in adults with apraxia of speech suggests that sensory processing may be a critical factor in the control of speech movements in AOS.

Theoretical models vary in the importance given to sensory processes for control of speech production. In open-loop control models (i.e. feedforward), articulatory parameters for a given speech sound are considered to be relatively invariant across multiple productions and thus sensory feedback is not needed to modify speech movements. In contrast, closed-loop models (i.e. feedback) use sensory information extensively to modify articulatory movements in order to meet expected auditory perceptual goals. Open-loop control systems are useful for accounting for the rapid progression of highly accurate articulatory movements in frequently used and practiced speech patterns, although they do not address how adjustments are made in response to articulatory constraints (i.e. bite blocks). Closed-loop models explain how sensory information can be used to modulate articulatory parameters to correct for unusual speaking conditions, but the processing time requirements involved in closed-loop control suggest that this mode cannot account for the rapidity of articulatory movement in typical speech production.

The DIVA model of speech processing (Directions into Velocities of Articulators; Guenther, 1995; Guenther et al. in press; Guenther, Hampson, & Johnson, 1998) includes integrated feedforward and feedback control mechanisms to accommodate distinct production modes needed for typical speech and for unusual or unpracticed conditions. This model will be used as a provisional theoretical framework, as it is a neurally plausible, well specified, theoretically sound, and experimentally tested theory for speech motor control.

The DIVA model (figure 2.2.1) is an adaptive neural network system that uses functionally specific groupings of neural units to represent different information types (e.g. auditory states, phonemic categories, articulatory parameters). Synaptic connections between functional groupings are used to map behaviorally-related patterns of activation from one level of processing (i.e. speech sound map) to another (i.e. articulatory parameters). The various processing maps and the connections between them are formed and modified in an emergent process during a simulated developmental babbling phase. During this process, the system "learns" the correspondences between related states of activation in the different processing maps. Following training, the model is used to simulate the derivation of appropriate articulatory configurations for target speech sounds on the basis of the learned connections.

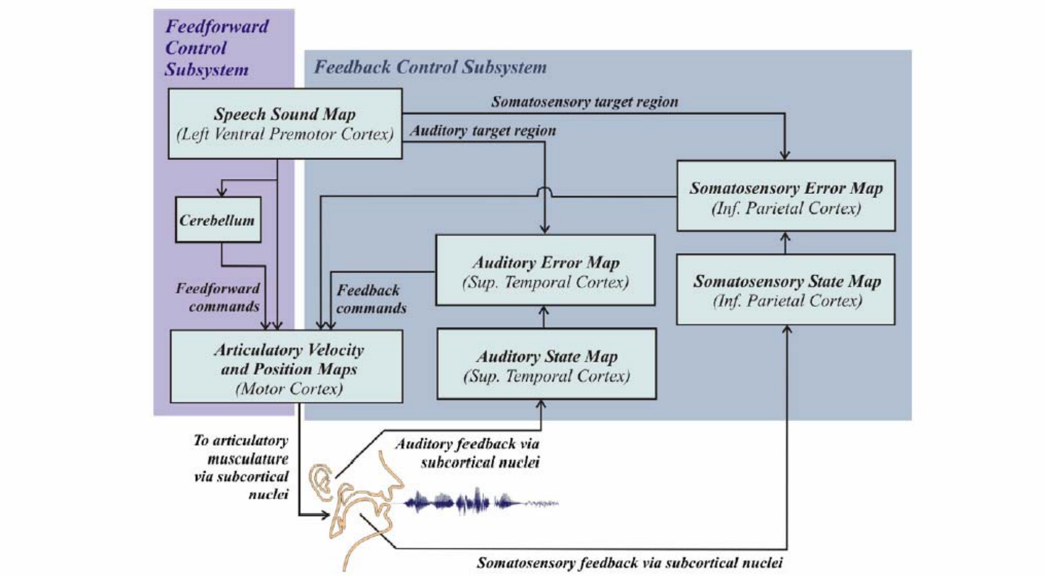

Figure 2.2.1. Schematic of the DIVA (Directions into Velocities of Articulators) speech processing model (Guenther et al., in press). Reprinted from Brain and Language, volume in press available online 22 July 2005, Guenther, Ghosh, & Tourville, Neural modeling and imaging of the cortical interactions underlying syllable production, pp. 1-22, Copyright (2005), with permission from Elsevier

The feedforward system in the DIVA model refers to learned correspondences between higher-level speech sound representations (i.e. phonemes) and articulatory parameters. The feedback system refers to the processes that modify learned motor commands on the basis of auditory or somatosensory input. The feedback schema presented here can be conceptualized as a means for "predictive simulation" (Lindblom, Lubker, & Gay, 1979), enabling a speaker to make appropriate modifications for unusual constraints (i.e. bite blocks) prior to initiating speech or during ongoing production.

Theoretical accounts of speech motor control must account for both speech production and perception phenomena in normal speakers and in those with neurological impairment. It is not possible to state with certainty whether apraxia of speech is a disorder affecting motoric targeting to the exclusion of sensory or linguistic systems or whether these systems play an integral role in the control of speech movements. The present work adheres to a definition and theoretical framework for AOS that implicates impaired motor targeting for speech movements, without excluding the possibility that representational structures tied closely to perception and language are intimately involved in the regulation of speech movements. The following description of the behavioral characteristics and etiology of AOS will reflect this viewpoint.

Chapter 2.3
Characteristics of AOS

Several behavioral characteristics of AOS have been agreed upon by most researchers, including the presence of 1) apparent “motoric” features, 2) high frequency of articulatory errors, and 3) prosodic abnormality. Other commonly associated features include frequent co-occurrence of nonspeech oral apraxia, expressive aphasia, receptive aphasia, and sensory impairment. Associated behaviors are used by some as exclusionary factors to select groups of speakers with so-called “pure” apraxia of speech, while others include broader groups with more diverse behavioral deficit profiles.

Apparent “motoric” features of AOS

In most descriptions of AOS, perceived effortfulness, articulatory groping, and general visible and audible struggle behavior during speech production are among the first characteristics listed (e.g. Darley, Aronson, & Brown, 1975; Wertz, LaPointe, & Rosenbek, 1984) although recent researchers have suggested that phonemic paraphasic individuals may experience as great an “effort” in speaking (McNeil et al., 1997). The subjective description of speech as effortful-sounding appeals nevertheless to the notion of AOS as a disorder of motor programming; speakers appear to have limited control over their articulatory performance despite their best efforts.

Speech variability, or inconsistency of speech production, is another commonly-cited characteristic of apraxic speech typically associated with motor programming deficits (Kent & Rosenbek, 1983). However, definitions of the concept differ across studies and leaving unresolved the question of what is meant by variability. The notion of speech variability may derive from observations that speakers with AOS are sometimes able to produce a given word accurately and at other times not. Task conditions have been shown to affect phonemic accuracy in speakers with apraxia but not those with dysarthria, with better performance for real vs. nonsense words and for spontaneous production vs. imitation or reading (Johns & Darley, 1970). Although task manipulations can be seen to cause differential performance by apraxic speakers, these effects are in fact quite predictable.

Alternatively, variability has been assessed by comparing errors produced in multiple productions of the same words or utterances under identical task conditions. Miller (1992) found that apraxic speakers were variable in multiple productions of single words, with consistency ratings ranging from 6% to 58%. Speakers with phonemic paraphasia performed similarly to apraxic speakers, with a range of 0 to 48% consistency. In contrast, dysarthric speakers were generally highly consistent, with 50% to 99% consistency.

These studies show that speakers with AOS produce patterns of error that vary both across and within task conditions. Since AOS is defined as a disorder of speech motor control, particularly affecting spatial and temporal targeting, it is important to consider variability of speech movements and the resulting acoustic patterns. Kinematic and acoustic studies have shown that speakers with apraxia are able to produce articulatory patterns that approximate desired spatial and temporal targets, but that they do not do so with precision, i.e. they do not consistently achieve targets on multiple attempts. Kinematic findings of articulatory variability have been reported for lip, jaw, and velar movement, showing that speakers with apraxia are able to move articulatory structures with the same ranges of amplitude and velocity as normal speakers, but that on repeated trials they do not produce consistent patterns of articulatory movement (e.g. Itoh & Sasanuma, 1984; McNeil & Adams, 1991; McNeil, Caligiuri, & Rosenbek, 1989; Robin, Bean, & Folkins, 1989).

Acoustic analyses in AOS suggest variability in both temporal and spatial patterns of speech production. Voice onset time (VOT) analysis, for example, indicates that speakers with AOS initiate voicing in consonant production in a similar range as normal speakers, but that they do not clearly differentiate VOT in voiced and voiceless sounds (Itoh & Sasanuma, 1984; Kent & Rosenbek, 1983). A similar pattern of reduced acoustic differentiation has been found in apraxic fricative production, indicating imprecise spatial targeting (Haley, Ohde, & Wertz, 2000). Speakers with AOS and aphasia producing multiple repetitions of [s] and [ʃ] in word context had measurements of the first spectral moment within generally normal ranges, but most did not consistently produce the two fricative types as clearly distinct sounds.

The rationale for considering error variability to be an indicator of motor control impairment is that stored patterns of movements for articulatory gestures are dissolved or damaged, resulting in poorly organized attempts to complete speech goals. Instrumental analyses of speech production show that ranges of movement amplitudes and velocities of apraxic speakers are similar to normal speakers, unlike dysarthric speakers whose movements are reduced. However, individuals with AOS have difficulty in consistently meeting spatial and temporal targets, resulting in poorly differentiated speech movements with resulting acoustic patterns that are perceived by listeners as articulatory errors. Interpretation of speech variability findings is notably dependent on how variability is defined. However, instrumental analysis of variability in speech production is an important tool useful for quantifying deficits in spatial and temporal targeting in speakers with apraxia of speech.

Articulatory errors in AOS

By definition, AOS is a disorder of speech production, thus description of the types of articulation errors experienced by speakers is critical to understanding the nature of the disorder. Articulatory errors in AOS result from inefficient assignment of articulatory parameters for speech sounds, leading to temporal and spatial distortion of speech movements often perceived as sound substitutions (e.g. Kent & Rosenbek, 1983; McNeil et al., 1997). Consonant errors traditionally have been the most salient feature of speech disturbance in AOS, although impaired motor targeting in principle affects spatial positioning for vowel production as well as articulatory timing needed for appropriate patterns of rhythmicity and stress. Historically, consonant errors were taken to be more susceptible to error than vowels due to relatively greater articulatory complexity. However, early studies relied heavily on broad, phonemic analyses of speech production, and as more fine-grained analysis procedures became more prevalent (i.e. narrow transcription, acoustic analysis), the disparity between error occurrence in consonants and vowels diminished. The following review primarily will address patterns of consonant error reported in speakers with AOS, and vowel errors will be reviewed in detail in a later section.

Substitution errors are the most commonly reported error type in most early studies of apraxia of speech, likely due to the use of broad-based phonemic transcription analyses of speech. For example, Johns and Darley (1970) reported that substitution errors and distortion errors comprised 32% and 10% of errors in speakers with AOS respectively, in contrast to dysarthric speakers, whose errors were predominantly distortions. Analysis by different classes of sound showed that a) place of articulation errors are more common than errors of manner or voicing (e.g. Darley et al., 1975; Wertz et al., 1984), b) consonant clusters are more often in error than consonant singletons (e.g. Canter et al., 1985; LaPointe & Johns, 1975; Trost & Canter, 1974), and c) consonant errors are more common than vowel errors (Canter et al., 1985; Darley et al., 1975; LaPointe & Johns, 1975; Monoi et al., 1983; Trost & Canter, 1974). Analysis of errors by length of utterance indicated that speakers produce more speech errors as the length of the targeted production increased (Dabul, 1979; Darley et al., 1975). Although these studies focused on phonemic analysis of speech production, findings generally were interpreted to indicate that motorically more complex speech sounds (e.g. clusters vs. singletons, consonants vs. vowels) were more susceptible to error than less complex sounds.

While many early researchers routinely referred to AOS as a disorder of motor programming, the methods of analysis lent themselves to an interpretation that articulation errors in AOS had a basis in phonological selection, implying a linguistic deficit in a motor control disorder. Kent and Rosenbek (1983) noted that application of phonological analyses in AOS "runs a risk of confusing methods of analysis with the results of that analysis". In other words, by applying phonemic transcription methods to behavioral data that include sub-phonemic errors (i.e. distortions), the disorder may be interpreted as one of phonological selection when other analysis methods might prove otherwise. Indeed, applying acoustic analysis to speech production in AOS, Kent and Rosenbek found evidence of distortions not previously reported, especially in errors of temporal variation (e.g. consonant and vowel prolongation, voice onset timing). In some cases, articulatory distortions of vowels were so extreme that they might be perceived as substitutions by listeners. Narrow transcription analyses of consonant and vowel production by Odell and colleagues confirmed this finding, with distortions and distorted substitutions found to be the predominant error type in speakers with AOS (Odell, McNeil, Rosenbek, & Hunter, 1990, 1991).

Articulatory errors are an important component of the speech disorder in AOS, reflecting difficulty in spatial and temporal targeting ability and representing the primary feature that affects the ability to communicate effectively. Prosodic abnormality affects the naturalness of speech production more than communicative content, but may nonetheless be a key indicator of speech motor control in AOS, particularly for temporal parameters of speech production.

Prosodic abnormality in AOS

Individuals with AOS have speech patterns characterized by slow rate, equal-stressed syllables, and generally lacking in natural flow and rhythm due to initiation difficulty, repetitions, and revisions (Odell & Shriberg, 2001). Prosodic abnormalities are considered to be a primary feature of the disorder by some researchers (e.g. McNeil et al., 1997), while others suggest that they serve as compensation for speech motor control deficits (Darley et al., 1975).

Perceptual study of prosodic abnormality has shown that adults with AOS have slowed rate of speech, characterized by perceived increased duration of articulation and pauses in the majority of utterances (Odell & Shriberg, 2001). Acoustic studies of apraxic speech confirm the perceptual findings, indicating increased segment and inter-segment durations (Kent & Rosenbek, 1982, 1983), particularly pronounced as the length of utterance increases (e.g. Strand & McNeil, 1996). Slow rate characteristics may result from speakers' inability to move articulatory structures at appropriate velocities (i.e. primary result of motor programming disorder) or alternatively, from the knowledge that rapid articulation results in speech errors and a compensatory slowed rate minimizes articulatory breakdown.

"Phrasing errors", as defined by Odell and Shriberg (2001), include repetition or revision of sounds, syllables, and words, resulting in speech with an unnatural rhythmic flow. Findings of repetition errors have varied in several perceptual studies of prosody (e.g. Odell et al., 1991; Odell & Shriberg, 2001) likely due to differences in stimulus materials. Repetitions were rarely noted for speakers with AOS performing the standard increasing word length task from the Apraxia Battery for Adults (e.g. Dabul, 2000; used by Odell et al., 1991; e.g. thick, thicken, thickening). In spontaneous conversation, however, Odell and Shriberg reported 45% of utterances contained repetitions or revisions of sounds, syllables, or words. Repetitions and revisions apparently are not primary characteristics of the motor control disorder in AOS, but serve as compensation by speakers to modify inadequately articulated utterances. Increased phrasing errors in conversation relative to word repetition suggest that cognitive and linguistic processing demands also influence the speaker's ability to produce fluent speech.

Equal stress in multiple-syllable words is also a commonly-occurring feature in speakers with AOS. Perceived equal stress results from undifferentiated patterns of timing and intensity in stressed and unstressed syllables. Kent and Rosenbek (1982) reported excessively lengthened vowels in unstressed syllables of apraxic speakers. Individuals with AOS also show minimal variation of intensity in words over the course of a phrase compared to normal speakers (Kent & Rosenbek, 1983). Odell and colleagues (1991) reported syllable stress errors in 43% and 46% of disyllables and trisyllables, respectively, and in 15% of spontaneous speech utterances (Odell & Shriberg, 2001).

Equal-stressed syllables may be an inherent feature of the motor control disorder in AOS, reflecting an inability to set appropriate vocal intensity parameters for separate syllables. Alternatively, speakers with AOS may be able to program the movements needed for segmental detail or for prosodic contours but not both at the same time, an explanation consistent with limited processing capacity accounts of AOS (e.g. Kent & McNeil, 1987). If speakers have conscious or subconscious knowledge that preserving segmental details is more critical to communicating their message than preserving a natural prosodic contour, then the latter might be sacrificed. In this situation, an equal-stressed production pattern can be said to be a secondary, though not necessarily compensatory, effect of the motor programming deficit.

Although researchers differ on whether prosodic abnormalities in AOS are a direct or indirect consequence of motor control deficits, there appears to be consensus that they do not result from a linguistic cause (e.g. impaired linguistic stress assignment). In contrast, prosodic deficits in children with a developmental form of apraxia (viz. childhood apraxia of speech) likely result from failed development of appropriate stress rules (Odell & Shriberg, 2001). Regardless of whether prosodic errors are a primary feature of disordered motor control, prosodic abnormality remains an important marker for AOS and some researchers have suggested that it may be the only characteristic that reliably differentiates speakers with AOS from those with phonemic paraphasia (McNeil et al., 1997).

Associated characteristics of AOS

The behavioral characteristics reviewed are believed to be core features that reflect the motor programming disorder in AOS. Participants with co-occurring language or sensory impairment should have these core features in common. In speakers with so-called "pure" apraxia of speech (e.g. McNeil et al., 1997; Square, Darley, & Sommers, 1981), the core features are present to the exclusion of frequently associated characteristics. The practice of excluding apraxic speakers on the basis of concomitant deficits has the potential to help researchers understand impaired speech motor control processes in the absence of unrelated factors but has the limitation of not describing speech motor control in a broader sense that includes potential links between perceptual, linguistic, and motor control systems. The following review of associated characteristics in AOS includes features that are 1) often present but not necessary for AOS diagnosis (e.g. nonspeech apraxia), 2) nearly always present in speakers with AOS and on occasion used to exclude participants (e.g. expressive aphasia), 3) nearly always used as exclusionary factors (e.g. receptive language impairment), and 4) may co-occur in a percentage of speakers but are not central to the disorder (e.g. auditory perception deficits, oral tactile-kinesthetic deficits).

Nonspeech oral apraxia

Nonspeech oral apraxia is an impairment of volitional movement for nonspeech behaviors that involve speech structures (e.g. sticking out the tongue, licking lips, whistling, showing teeth, coughing, etc.). Nonspeech oral apraxia occurs more often in participants with AOS than those with other neurologic communication disorders, but apraxia of speech need not be accompanied by oral apraxia. DeRenzi and colleagues (DeRenzi, Pieczuro, & Vignolo, 1966) found a high correlation between oral apraxia scores and "phonemic-articulatory" deficit, but a third of participants with no oral apraxia were moderately or severely impaired in articulation.

More sensitive tasks of nonspeech oral movement include physiologic measures of isometric force and static position control (e.g. McNeil, Weismer, Adams, & Mulligan, 1990) and visuomotor tracking, where articulatory movement modulates a visually-presented target (Clark and Robin, 1998). McNeil et al. found that adults with AOS were more variable than non-brain-damaged (NBD) participants in their ability to exert a targeted amount of force using the upper lip, lower lip, tongue, jaw, and finger and to maintain a static position with the upper and lower lips and the finger. Clark and Robin found that adults with AOS, when asked to track a moving visual target using the jaw, are either able to match the temporal and positional parameters of the target or to match the overall shape of the moving target, but not both. These studies employing sensitive physiologic measures of oral movements suggest that nonspeech oral apraxia may be more prevalent in adults with AOS than indicated by previous studies of clinical measures of oral apraxia.

Expressive aphasia

The terms nonfluent aphasia, anterior aphasia, motor aphasia, and 'minor' Broca's aphasia have been used to label a disorder with characteristics in keeping with descriptions of AOS (e.g. Blumstein, Cooper, Zurif, & Caramazza, 1977; Mohr, 1976, 1980; Ryalls, 1981, 1986). The use of the term "nonfluent aphasia" can be particularly confusing, because the descriptor "nonfluent" appropriately applies both to speakers with Broca's aphasia and those with apraxia of speech. In Broca's aphasia, the most prominent language impairment is the loss of grammatical form, resulting in verbal expression that sounds telegraphic, or nonfluent due to the absence of function words. Broca's aphasics sound particularly "nonfluent" when contrasted with speakers with Wernicke's aphasia, whose language is characterized as fluent, with generally intact grammatical form but lacking coherent semantic content. In many speakers with AOS, speech may contain disfluencies in the form of sound, syllable, and word repetitions or revisions (e.g. Odell et al., 1991, Odell & Shriberg, 2001) also resulting in speech that appears "nonfluent" although not necessarily ungrammatical. Add to this the fact that most speakers with AOS have concomitant aphasia, and it is not surprising that terminological confusion has plagued researchers and clinicians regarding this disorder.

In recent years, excluding apraxic speakers with concomitant aphasia from studies has become common practice, enabling researchers to better understand the motor speech disorder while minimizing potential confounds of language deficits. Generally the most important exclusionary characteristic for AOS is agrammatism. Kent and Rosenbek (1983) required ratings of grammatical form and phrase length to be "towards normal", i.e. ratings of 6 or 7 on the Boston Diagnostic Aphasia Examination. In addition to agrammatism, Strand and McNeil (1996) excluded participants with significant paraphasic errors, believed to be a differentiating characteristic between AOS and conduction aphasia (e.g. McNeil et al., 1997).

The study of apraxia in its "pure" form is a useful pursuit insofar as it reduces the influence of confounding factors in research studies. The "extremely infrequently occurring" nature of the "pure" disorder (McNeil et al., 1997) suggests that results from these studies may not generalize well to the population of adults with AOS. Inclusion of "pure" apraxia groups has been used by Square and colleagues in studies of speech and auditory processing characteristics in apraxic individuals with no signs of aphasic impairment (Square et al., 1981; Square et al., 1982; Square-Storer, Darley, & Sommers, 1988; Square-Storer & Apeldoorn, 1991). An alternative method has been used by Haley and colleagues (e.g. Haley, Ohde, & Wertz, 2000, 2001; Haley, Wertz, & Ohde, 1998) by including participant groups with aphasia and co-existing aphasia as well as nonapraxic aphasic groups. This approach has the benefit of allowing researchers to study a greater number of individuals with the disorder, although the variability of their aphasic characteristics is greater. Interpretation of results of mixed apraxic-aphasic participants is potentially more complex than in studies of "pure" groups, with particular findings attributable either to speech motor control system deficits or linguistic processing deficits. However, since linguistic processing cannot be entirely ruled out as a contributory factor in speech motor control, the use of mixed groups may be instructive in developing a broader understanding of inter-related processing systems.

Receptive aphasia

Excluding participants with significant auditory comprehension deficits from studies of AOS also is common and is less contentious than excluding speakers with expressive aphasia. One of Broca's observations of Leborgne was that "he understood everything that was said to him; in fact his hearing was excellent" (Broca, 1861/1977). Researchers have acknowledged the likely presence of varying degrees of comprehension deficit in AOS, especially for lengthy, complex, or abstract information, but the belief that receptive language is generally intact is non-controversial.

Other factors in AOS

Normal performance on auditory comprehension tasks from an aphasia battery is sufficient to indicate that a person generally understands what is said to them, but does not suggest that sensory or linguistic processing mechanisms are completely intact. Auditory, perceptual, and linguistic abilities potentially have important roles in speech motor control, although it is not known to what extent impairment in these domains impacts the ability to plan, monitor, or modify speech movements in persons with AOS.

Several studies have found sensory processing deficits in speakers with AOS, including impairment of auditory (e.g. Aten et al., 1971; Baum, 2002) and orosensory perception (Rosenbek et al., 1973). Many speakers with AOS are unable to compensate for perturbed speaking conditions (e.g. speaking with a block between the teeth), suggesting that proprioception, i.e. knowledge of articulatory position, is involved at some level of articulatory targeting (e.g. Sussman et al., 1986). Speakers with AOS also have been found to have difficulty making rhyme judgments, a task that requires high level processing and manipulation of phonological information (Waters, Rochon, & Caplan, 1992; see also Blumstein et al., 2000; Cermak, Stiassny, & Uhly, 1984; Gordon & Baum, 1994 for studies of rhyme in aphasia).

Many speakers with AOS appear to have normal sensory and linguistic processing abilities, suggesting that deficits in these areas, when they do occur, are concomitant and not central features of the disorder. These skill domains rarely are examined in studies of AOS, however, and when tested they are not usually tested in depth. For example, most studies of auditory perception in AOS have involved broad phonemic discriminability testing (e.g. are /i/ and /a/ the same or different) in lieu of standard categorical perception methods often used in studies of normal perception. Higher rates of perceptual deficit may be detected in AOS when more sensitive tests of perceptual abilities are employed. The topics of auditory perception, compensatory articulation, and rhyme processing will be addressed in greater detail later in the paper, as they represent topics of focus in this study.

Summary of characteristics

Apraxia of speech is characterized by frequent articulatory errors, resulting from imprecise spatial and temporal targeting of speech movements. Articulatory errors are best described as distortions or distorted substitutions; instrumental analysis of speech production often reveals inaccurate and unstable patterns of movement reflecting the motor disorder. The status of variability in AOS depends upon how it is defined; while acoustic and kinematic analyses reveal significant variability of articulatory gestures, the types of errors and their prevalence in different phonetic contexts is predictable. Apparent effortfulness of speech and visible and audible groping behaviors are salient characteristics of speakers with AOS, although the subjective quality of effort and struggle make their occurrence likely in other disorders, including aphasia. Broca's aphasia commonly co-occurs with apraxia but represents a distinct disorder characterized by grammatical deficits. Some researchers exclude participants with coexisting Broca's aphasia to study AOS in its "pure" form, while others study broader groups with both AOS and various types of aphasia. Auditory comprehension is generally intact in speakers with AOS, even those with some degree of expressive aphasia. Other associated characteristics include nonspeech oral apraxia, auditory perceptual impairment, and tactile-kinesthetic deficits. These features are infrequently studied in AOS and researchers differ on whether they are core to the motor speech disorder. Further study of associated characteristics is needed to better understand the potential role of sensory systems in the planning of speech movements.

Chapter 2.4

Lesion studies of AOS

Apraxia of speech is caused in most cases by vascular lesions (i.e. stroke) of the left cerebral hemisphere (Duffy, 1995). Beyond this general statement, considerable variance exists in neuropathological accounts of the disorder, owing largely to inconsistencies in terminology and definition of the disorder in the historical literature, theoretical bias, and period differences in medical technology. The majority of clinicoanatomic research in AOS has focused on center-lesion theories, i.e. where is the critical brain area whose damage results in apraxia. Various accounts suggest that AOS results either from damage to cerebral cortex, especially frontal lesions (e.g. Johns & Lapointe, 1976; Luria, 1966), damage to subcortical structures (e.g. Kertesz, 1984, 1985; Marquardt & Sussman, 1984; Peach & Tonkovich, 2004), or damage to the anterior insula (Dronkers, 1996; Gorno-Tempini et al., 2004; Nagao, Takeda, Komori, Isozaki, &

Hirai, 1999). Alternatively, proponents of disconnection syndromes (e.g. Buckingham, 1979; Geschwind, 1975) suggest that apraxia results from the isolation of neural regions critical for speech control from regions responsible for other functions by infarctions of intervening pathways. The recent proliferation of structural lesion studies in apraxia has fueled the debate suggesting various neural control centers for speech motor control (e.g. cortical, insular, subcortical), but the emerging use of functional neuroimaging also suggests that apraxia may result from the isolation, and not necessarily destruction, of cortical regions responsible for speech motor control (Hillis et al., 2004). In the following section, evidence will be reviewed suggesting focal lesions of cortex, insula, and subcortical structures, as well as potential functional or disconnection neural accounts for apraxia of speech.

Cortical lesions in apraxia

The belief that apraxia of speech results from left frontal cortical lesions, particularly to Broca's area, traces to Broca's original autopsy studies of Leborgne and Lelong. Although Leborgne's lesions were quite extensive, Broca inferred that the lesion responsible for the "aphemic" (i.e. apraxic) deficit originated in the left posterior frontal third convolution (i.e. Broca's area; henceforth referred to as LF3) (Broca, 1861/1977, Mohr, 1976). Broca's second aphemic patient Lelong had a more circumscribed lesion of the same region, thus confirming the original report suggesting a connection with a motor speech deficit and LF3 (Ryalls & Lecours, 1996).

In the absence of brain imaging technologies, early researchers relied on theoretical inference to determine the critical site of neural damage for individuals with AOS. For example, Broca's conclusion that LF3 was the locus of the original damage (and not LF2, insular cortex, or lenticular nucleus, also damaged) was inferred from the fact that Leborgne did not experience limb hemiparesis until later in the course of his disease and that LF3 was the geometric center of the full lesion at autopsy. Jackson (1893/1915) and Nathan (1947) used an "evolutionary" argument to rule out the role of subcortical structures in AOS. Namely, since speech and cerebral cortex are relatively recent evolutionary advancements, articulate speech was assumed to be controlled by cortical structures. Other scientists argued that various subtypes of apraxia of speech may occur based on the relative involvement of areas believed to affect motor planning (frontal cortex) or sensory processing (temporo-parietal cortex) (Liepmann, 1900, 1905, 1906/1988; Luria, 1966). Despite some variations in theories, the preponderance of evidence indicated that AOS was caused by a cortical lesion in the posterior frontal cortex, generally in the area of LF3.

Use of electroencephalography (EEG) improved researchers' ability to localize site of lesion in large numbers of live stroke patients, although this method has limited resolution and is not able to directly assess depth of lesion. Wertz, Rosenbek, and Deal (1970) determined the approximate site of lesion for 22 adults with pure AOS and 114 with coexisting aphasia and AOS. However, the study was limited in precision, demonstrating only whether lesions were localized to LF3, or to other unspecified areas; the findings suggested that only 22% of pure apraxic speakers and 41% of aphasic apraxics have LF3 lesions. This study suggested that the neuropathology of AOS might be more complicated than previously believed.

The invention of computerized transverse axial tomography (i.e. CAT, or CT; Ambrose and Hounsfield, 1973) revolutionized the clinicoanatomical study of apraxia and other neurogenic communication disorders, enabling researchers to visualize with fairly high spatial resolution the brain infarcts associated with behavioral deficits. Early CT studies of large numbers of aphasic/apraxic individuals helped dispel the myth that the broad Broca's aphasia syndrome (i.e. agrammatism + anomia + AOS) is caused by a small, focal lesion to LF3, i.e. Broca's area, while suggesting that this is the likely site of damage for formerly aphasic patients with residual apraxia of speech (Mohr, 1976, 1980). These studies also showed that subcortical structures underlying Broca's area were often damaged, although it was suggested that the cortical lesion was responsible for the apraxic deficit.

Subcortical lesions in AOS

Neuroanatomical studies of AOS and apraxia-like speech disorders focused on cortical regions as critical sites of lesion for the better part of the 20th century, despite the contentions of several notable scientists that underlying subcortical structures were of equal importance. Pierre Marie, for example, believed that what he termed anarthria was caused by damage to the lenticular zone (viz. Marie's quadrilateral; Lecours & Lhermitte, 1976) and that Broca's area played no role in the disorder (Marie, 1906, as cited by Benson, 1979). Dejerine, while disagreeing with Marie on the terminology for the disorder, agreed at least for a time that "pure motor aphasia" is caused by subcortical white matter lesions and does not require a cortical lesion (Dejerine, 1901, as cited by Lecours & Lhermitte, 1976).

In the early 1980s, subcortical structures received renewed attention as potential sites of lesion in AOS, with several case studies indicating that cortical infarction was not necessary to cause the disorder. Square and colleagues (1982) reported on four speakers with pure AOS with widely varying sites of lesion; one of whom had a deep temporal lesion with caudate nucleus involvement. Square and Mlcoch (1983) followed with a case study of a speaker with pure AOS and a lesion confined to the basal ganglia, particularly affecting the caudate nucleus. The speech symptoms of the participants with only subcortical lesions were consistent with classical descriptions of apraxia, including frequent substitution and distortion errors and articulatory groping, but were distinct in the high frequency of vowel errors, hyper- and hypo-nasalization, and in the general perception of abnormal prosody. In a later study, Square-Storer and Apeldoorn (1991) compared the speech of two speakers with basal ganglia lesions to that of one speaker with a parietal lesion, again finding that speakers with basal ganglia damage have abnormal prosody and slow rate, while the speaker with cortical damage did not show these characteristics. Together, these studies show that non-aphasic apraxia of speech can be caused by lesions to various neural regions, although behavioral characteristics may vary based on lesion site, including abnormal prosody and rate in speakers with primarily subcortical lesions.

Other studies provided evidence for the potential role of subcortical structures in causing apraxia of speech. In a study of 15 participants diagnosed as Broca's aphasic with verbal apraxia, Marquardt and Sussman (1984) reported only nine with cortical involvement, with sites of lesion ranging from the frontal lobe to anterior parietal and temporal lobes. Although the cortical site of lesion varied across speakers, all 15 had subcortical damage, suggesting that subcortical involvement may be a crucial factor resulting in apraxia of speech.

Two recent small-sample studies also have reported speakers with AOS with damage limited to the basal ganglia (Jacks, Marquardt, & Cannito, 2004; Peach & Tonkovich, 2004). Peach and Tonkovich (2004) reported phonemic characteristics of a male with a circumscribed lesion to the basal ganglia and frontal white matter. This individual presented with AOS characterized by labored speech output and frequent substitutions[1]. Similar to previous studies (e.g. Johns & Darley, 1970), the participant had more consonant errors in initial position than in medial or final positions, but no difference in error frequency was shown due to phoneme type (e.g. cluster, fricative, stop, etc.). The speaker also presented with some expressive aphasia, but ratings of anomia and agrammatism were at least two points higher than articulatory agility on the BDAE rating scale (total of 7 point). Melodic line and phrase length were also unimpaired, suggesting that articulatory agility was the primary disordered feature in this individual.

Jacks, Marquardt, and Cannito (2004) studied speech and language characteristics in two paired case studies of apraxic speakers with subcortical only lesions compared to those with cortical plus subcortical lesions. Articulatory agility was impaired for all speakers, with ratings of 3 or 4 on the BDAE scale (i.e. sometimes clumsy or effortful, or worse). The speakers with subcortical only lesions had generally intact grammatical form, similar to the Peach and Tonkovich (2004) case study, while those with cortical + subcortical lesions were more agrammatic.

Site of neurological lesion varies across individuals with AOS, with corresponding variation in particular behavioral profile. Evidence suggests, however, that cortical lesions alone do not cause apraxia of speech, and that basal ganglia lesions in particular may serve an important role in disordered speech motor control in AOS.

[1] Analysis was by broad phonemic transcription, therefore possible distortions were classified as substitutions.

Insular lesions in AOS

Another possible site of lesion for AOS is the anterior insular cortex (e.g. Bennett & Netsell, 1999; Dronkers, 1996). Historically, the insular lobe has been mentioned as an area of importance to speech motor control, particularly by researchers who have suggested that the anterior insula should be included with LF3 as a critical site of damage in Broca's aphasia (e.g. Mazzocchi & Vignolo, 1979; von Mayendorf, 1911, cited by Brown, 1975). Insular cortex was also included as part of Marie's "quadrilatere" along with the lenticular nucleus and as part of the anterior language zone responsible for motor aphasia by Bernheim and Dejerine (Bernheim, 1906; Dejerine, 1914; Marie, 1906; all cited by Mazzocchi & Vignolo, 1979).

Recent work by Dronkers and colleagues provided persuasive evidence that AOS is caused by damage to the anterior insula based on a series of anatomical lesion studies. Most often cited is Dronkers' (1996) paper reporting a 100% double dissociation between individuals with apraxia and non-apraxic aphasics. Although lesion sites varied across individuals, 100% of 25 speakers with AOS had damage to a particular area of the anterior insula (viz. tertiary gyrus brevis), while 0% of 19 non-apraxic aphasics had damage to this area.

Further evidence suggesting the importance of the anterior insula for speech articulation in general and in AOS has included case studies of AOS (e.g. Nagao et al., 1999), functional imaging studies of articulation in normal speakers (Wise, Green, Büchel, & Scott, 1999), a lesion study in a progressive form of aphasia with AOS (Gorno-Tempini et al., 2004), as well as theoretical papers suggesting the mechanism by which the anterior insula contributes to speech motor control (Ackermann & Riecker, 2004; Bennett & Netsell, 1999). The anterior insula account of AOS is attractive given the recent clinical evidence as well as historical accounts of case studies that implicate insular cortex among other areas of neural damage (e.g. Broca, 1861/1977, Lecours & Lhermitte, 1976).

A number of exceptions have been published, however, indicating that the insular lesions may not explain all cases of AOS. For example, Jones, Peach, and Schneck

(2003) reported on 11 individuals with AOS, only 3 of whom had damage to the insula. Sites of lesion varied widely in this study and included frontal, temporal, and parietal cortex as well as basal ganglia damage. The following year, Peach and Tonkovich (2004) studied a single participant with AOS whose lesion was limited to the basal ganglia and frontal white matter, sparing the insular cortex and other regions often associated with AOS (e.g. LF3).

Although the evidence supporting a critical link between anterior insula damage and AOS is striking, the exceptions suggest the need to explore alternative explanations for the disorder. In particular, the studies reviewed thus far focus on a localizationalist perspective, i.e. attempting to identify the critical region where articulatory control "lives" and whose damage results in articulatory impairment. A number of scientists have suggested that neural control of behavior in general and of articulation in particular relies on the cooperative function of several neural processing networks (e.g. Buckingham, 1979; Penfield & Roberts, 1959; Schiff, Alexander, Naeser, & Galaburda, 1983). Even admitting a general principle of localization of function, e.g. precentral gyrus responsibility for muscle innervation, the organization of complex behavior likely requires the integration of several different processing systems that might be disrupted.

A recent study examined the question of the neural basis of AOS by studying both structural lesions as well as "functional lesions", i.e. neural regions shown to be inactive even though they are structurally sound. Hillis and colleagues (2004) used perfusion-weighted imaging (PWI), a process that identifies areas of reduced blood flow (i.e. hypoperfusion), to assess the functional status of regions of interest in stroke patients with and without AOS. Findings indicated first, that structural lesions of the left anterior insula were present in only approximately a third of participants with AOS, and second, that hypoperfusion of the anterior insula was not associated with apraxia. The most striking result of the study was that AOS was associated with damage to or hypoperfusion of LF3, i.e. Broca's area. In short, the study suggests that the insular lesion thought by many to be a critical site of injury for AOS is in fact artifactual. Hillis and colleagues argue that the insula is often damaged in strokes resulting in apraxia because of structural location and that damage often results in reduced activation of areas necessary for articulatory control, specifically Broca's area.

The relationship between specific neural regions and behavioral characteristics is a complex one. Damage to frontal cortex, specifically the left frontal third convolution, for many years was believed to be responsible for Broca's aphasia and the commonly associated apraxia of speech. Evidence of co-occurring regions of infarction, including the anterior insula and basal ganglia, was interpreted to be coincidental and not necessarily linked to the articulatory disorder. The introduction of imaging technologies of increasingly greater resolution led to studies suggesting very particular sites of lesion for AOS, especially for insular cortex. The development of still more advanced neuroimaging methods has resulted in research suggesting that Broca's area is the critical neural site for articulatory control but that infarct to a wide variety of structures may be responsible for reduced activation in this area and to corresponding behavioral deficits characteristic of AOS. Further research using different methodologies is clearly needed to elucidate the issue of neural control of articulation in typical speakers as well as individuals with AOS. We can conclude at present that no one critical site of lesion can account for every instance of AOS or for every characteristic of the disorder. The great variety in behavioral profiles in individuals with the disorder reflects the lack of a single lesion profile and the inherent individual differences in functional reorganization following neurological damage.

CHAPTER 3
CHARACTERISTICS OF INTEREST

The objective of this study is to explore mechanisms of speech motor control in apraxia of speech vis-à-vis spatial targeting of vowels under normal and bite block conditions, auditory perception of vowel information, and phonological processing of vowels in a rhyming paradigm. Vowels are an apt target for investigation of speech motor control mechanisms on several grounds. First, errors in vowel production may reflect a general spatial targeting impairment (Kent & Rosenbek, 1983). Acoustic parameters of vowel production are easily measured to provide an index of articulatory accuracy and precision. Perturbed speaking conditions (i.e. bite block) have been used to explore preplanning and feedback control mechanisms for vowel production both in normal and impaired speakers (e.g. Lindblom & Sundberg, 1971; Sussman et al., 1986). Synthetic vowels may be created to test the integrity of auditory and phonetic processing, allowing direct comparisons of production and perception abilities for the same behavioral target. Phonological processing of vowel information also can be assessed using rhyme tasks to determine ability to compare features of multiple speech sound units. Finally, vowels have been shown to be a critical factor in speech intelligibility for individuals with speech motor control disorders (Turner, Tjaden, & Weismer, 1995; Weismer, Jeng, Laures, Kent, & Kent, 2001), suggesting that vowel production may be an important focus for understanding communicative deficits in AOS.

Isolated studies have found deficits in vowel production, compensatory articulation abilities, and auditory and phonological processing in apraxia of speech. However, the research record is limited and contradictory with respect to many of these findings. While vowel errors have been reported in speakers with AOS, their importance has been downplayed due to reported infrequency relative to consonant errors (e.g. Canter et al., 1985; LaPointe & Johns, 1975; Monoi et al., 1983; Trost & Canter, 1974, although cf. Haley et al., 2000; Odell et al., 1991). Studies of compensatory articulation in bite-block speech are similarly mixed, with some researchers suggesting that varying ability to compensate is related to site of neural lesion (Sussman et al., 1986) while others have reported compensatory abilities similar to normal speakers (Baum, 1999; Baum et al., 1997). Auditory-perceptual ability has been addressed by several researchers, with some asserting categorically that AOS is a production disorder in the absence of perceptual deficit (e.g. Wepman & Van Pelt, 1955), others reporting perceptual deficits in a subset of speakers with AOS (Aten et al., 1971) or nonfluent aphasia (Blumstein et al., 1977; Blumstein, Tartter, Nigro, & Statlender, 1984), and others finding that nonfluent aphasics have greater perceptual deficits than other brain-damaged speakers groups (Baum, 2002). Vowel perception, while studied in some detail in normal listeners (e.g. Hoemeke & Diehl, 1994) and in aphasic adults (e.g. Keller, Rothenberger, & Göpfert, 1982), has not been investigated in apraxia of speech. Rhyme processing also has been examined to a limited extent in apraxic and aphasic individuals (e.g. Blumstein et al., 2000; Cermak et al., 1984; Gordon & Baum, 1994; Waters et al., 1992). The targets of investigation in this study, namely vowel production, compensatory abilities in vowel production, vowel perception, and rhyme processing have not been examined together in any one group of participants with apraxia of speech. Nevertheless, these areas have been studied in sufficient detail to warrant further study.

The following sections provide a review of the literature on the behaviors of interest. First, vowel production studies in AOS, including both perceptual and acoustic analyses will be reviewed. Second, sensory and linguistic influences in AOS will be addressed, including studies of compensatory speech production (i.e. bite block studies), auditory perception, and rhyme processing. Studies from the non-brain-damaged literature and disorders related to AOS will be included as needed to provide perspective on studies of individuals with AOS, especially when specific studies with apraxic individuals are limited.

Chapter 3.1

Vowel production in AOS

Vowel errors often have been reported in studies of acquired apraxia of speech, although most researchers have found that they occur less often than consonant errors

(Canter et al., 1985; LaPointe & Johns, 1975; Monoi et al., 1983; Trost & Canter, 1974). Infrequency of vowel errors relative to consonants supports the theoretical position that phonetically complex targets are more susceptible to error for speakers with AOS (i.e. consonants are more complex than vowels, therefore consonants are more susceptible to error). Vowel errors may be under-reported, however, because variations in vowel targeting are not perceived as errors unless they are so deviant as to fall into an entirely different phonemic category (Kent & Rosenbek, 1983). More recent studies using narrow transcription procedures have revealed greater frequency of vowel errors in AOS than previously believed (e.g. Haley et al., 2001; Odell et al., 1991). Acoustic analysis of vowel production can be used to characterize the presumed spatial targeting deficit in AOS with even greater specificity (Haley, Ohde, & Wertz, 2001).

In the following section, findings of vowel errors will be reviewed in detail, including perceptual studies of AOS using both broad and narrow transcription methodologies, as well as acoustic studies of vowel production in speakers with AOS and in other populations with probable apraxia (e.g. nonfluent aphasics, Broca's aphasics).

Vowel errors in AOS

Several early studies of phonetic characteristics of apraxia of speech suggested that consonants are more susceptible to error than vowels. For example, Trost and Canter (1974) found that three of ten speakers with AOS produced no vowel errors whatsoever, with an additional five speakers with vowel accuracy of 88% or greater. Similarly, LaPointe and Johns (1975) reported average vowel accuracy of 86% in 13 speakers with AOS, in contrast to 74% consonant accuracy.

Two other studies showed that vowel errors represent a smaller proportion of overall errors than consonants. Monoi et al. (1983) found that consonant errors comprised 92% of speech errors in three speakers with signs of AOS (i.e. less than 8% of errors were vowel errors) in contrast to speakers with conduction aphasia who had similar proportions of vowel and consonant errors. Canter and colleagues (1985) also found that vowel errors were relatively infrequent, representing approximately 10% of all speech production errors.

The relative infrequency of vowel errors in speakers with apraxia has been interpreted as a manifestation of a more general phenomenon of increased difficulty with increased motoric complexity of the behavior (e.g. Darley, 1982). Higher rates of error for consonant clusters than singletons supported this view (LaPointe & Johns, 1975; Trost & Canter, 1974). However, the perceived lack of vowel errors in AOS has been overstated. Individual data from studies from several studies show that at least the most severely impaired participants present with significant vowel errors. For example, Trost and Canter (1974) reported that two participants out of 10 accounted for most of the vowel errors in the study. Similarly, LaPointe and Johns (1975) reported vowel errors of 25% or higher for 3 of 13 participants. While broad transcription analysis of speech production may be adequate to detect vowel errors in severely impaired speakers, more detailed methods of speech analysis such as narrow transcription and acoustic analysis enable researchers to capture more subtle vowel variations in less severely impaired speakers.

Odell and colleagues used narrow transcription analyses to study vowel production in words of increasing length in speakers with AOS (Odell et al., 1991). Findings revealed patterns of production errors at variance with previous studies, with vowel errors occurring with approximately the same frequency as consonant errors (viz. 49% vowel errors vs. 46% consonant errors). In contrast with previous studies, Odell et al. found that distortions and distorted substitutions were the most common error types, rather than outright substitution errors. Distortions primarily consisted of prolongation errors, which represented 74% of vowel distortions. This study highlights the importance of methodological differences in phonetic descriptions of apraxic speech.

Recent studies by Haley and colleagues examining perceptual analyses of speech in speakers with AOS illustrate the same principle, namely that differences in measurement technique impact significantly on the results achieved (Haley, Bays, & Ohde, 2001; Haley et al., 2000). These studies examined production of single-word monosyllables by 10 speakers with apraxia and concomitant aphasia, using phonetic analyses of gloss transcriptions (Haley et al., 2000) and narrow transcription of errors

(Haley, Bays, & Ohde, 2001). The analyses in the 2000 study, analogous to broad transcriptions of errors, indicated a 10% error rate for vowels, similar to early studies using broad transcription of apraxic speech (Canter et al., 1985; LaPointe & Johns, 1975; Trost & Canter, 1974). Consonant error rate was 12%, which is lower than previous studies. Vowel height errors were the most frequent for all speaker groups, representing 5% of errors by AOS speakers.

Narrow transcription analyses of the same data (Haley, Bays, & Ohde, 2001) revealed a vowel error rate of 35% and a consonant error rate of 34%. Vowel errors consisted of equal proportions of substitutions and distortions (e.g. 40%); among distortions, prolongations were the most common subtype (32% of all distortions). The high rate of vowel errors and high frequency of prolongation errors are consistent with Odell et al.'s findings, providing further support for the use of narrow transcription in the analysis of apraxic speech.

Narrow transcription studies have shown that speakers with AOS make a variety of vowel errors, many of which may be attributed to articulatory timing deficits (e.g. prolongations) rather than spatial targeting (e.g. distortions of vowel raising, lowering, fronting, or backing). Vowel substitutions also are common and may reflect either phonological selection errors or extreme errors of articulatory positioning.

Acoustic studies of vowel production

Acoustic analysis has been used as an objective means to assess timing characteristics (e.g. consonant/vowel duration) and to infer articulatory position during speech production in both impaired and non-brain-damaged populations. Acoustic studies of vowel production in AOS are limited (e.g. Haley, Ohde, & Wertz, 2001; Kent & Rosenbek, 1983), although some studies have included speakers with "motor" aphasia (e.g. Ryalls, 1981, 1982) or "anterior" aphasia (Ryalls, 1986). Like the transcriptional studies, acoustic studies of AOS and nonfluent aphasia present a mixed set of results with respect to durational and spectral measures of vowel production, making uncertain the proposition that vowel characteristics are a sensitive index of speech motor control in AOS. However, review of these studies will show that some of the disparity between studies may be related to differences in individual participant characteristics as well as experimental characteristics.

Durational patterns of vowel production in apraxia of speech

Results of duration and durational variability differ considerably across studies. Several studies have found increased duration of utterances (Collins, Rosenbek, & Wertz, 1983; Dressler, Buder, Cannito, Marquardt, & Strauss, 2000; Kent & Rosenbek, 1983; Ryalls, 1981; 1982**)** and increased durational variability in speakers with AOS relative to non-brain-damaged (NBD) controls (Ryalls, 1986), while others have found duration comparable to normal comparison groups (Mathes, unpublished data; Ryalls, 1986).

The disparity between studies in durational findings can be explained at least in part by differences in task demands. For example, Kent and Rosenbek (1983) found consistently higher duration in seven apraxic speakers compared to control participants at the sentence level and for syllables, vowel and consonant segments, and transitions when speaking multisyllabic words or phrases. In contrast, consonant and vowel segment duration were comparable between the apraxic speakers and the control group when producing monosyllabic words. The pattern of aberrant durational measures in multisyllabic utterances and normal-appearing measures in monosyllables is repeated in the literature.

For example, Ryalls (1981) found that vowel and overall utterance durations were consistently longer for 11 French-speaking motor aphasics relative to 11 NBD control speakers for production of multisyllabic words and phrases. Dressler and colleagues (2000) also found longer duration as well as greater variability of word and intersyllabic interval duration in multisyllabic words produced by nonfluent aphasic speakers compared to NBD control speakers. In contrast, Ryalls (1986) found no significant differences in vowel duration of monosyllabic /hVd/ words between English-speaking "anterior" aphasics and control participants. Similar results were found in unpublished data from an acoustic study of monosyllabic /hVC/ words in AOS speakers (Mathes, 2005). AOS speakers had lower mean durations and coefficients of variation for duration than speakers in a normative study (normal data from the North Texas vowel database; Katz & Assmann, 2005).

Speakers with AOS present with relatively normal durational patterns of speech when asked to produce monosyllabic words in isolation. When producing multisyllabic words and/or phrases, AOS speakers have higher average duration and variability across productions relative to NBD controls. While these differences across task are reflective of the high rate of prolongation errors in words of increasing length reported by Odell and colleagues (1991), the present study primarily is interested in spatial targeting errors and variability. The following section will explore acoustic evidence of spatial targeting deficits vis-à-vis spectral patterns of vowel production.

Spectral patterns of vowel production in AOS

Spectral measures of vowel production in speakers with AOS typically indicate normal average values and/or ranges of vowel formants (Haley, Ohde, & Wertz, 2001; Kent & Rosenbek, 1983; Mathes, 2005; Ryalls, 1986). However, reduced differentiation of vowel formants, i.e. vowel centralization has also been reported in speakers with AOS, especially in multisyllabic productions (Kent & Rosenbek, 1983; Ryalls, 1981). In general, formant variability tends to be increased in AOS groups relative to NBD controls (Kent & Rosenbek, 1983; Ryalls, 1981; Ryalls, 1986), although normal speakers and non-apraxic aphasic speakers also can be quite variable in the ranges of formant frequencies (Haley, Ohde, & Wertz, 2001). Furthermore, recent work has indicated apparently well-differentiated formants in speakers with AOS and low within-participant formant variability on repeated productions, despite high group variability of formants (Mathes, 2005).

Kent and Rosenbek (1983) plotted the vowel space of six speakers with AOS, showing that first and second formants generally fall within the ranges expected for normal speakers. Some acoustic overlap in vowel categories was noted, particularly for the front vowels /i/, /ɪ/, and /æ/, and one speaker produced /u/ with formants clearly in the range of the high front vowel /i/ (i.e. acoustic evidence of vowel substitution). The context in which the plotted vowels were produced is not clear, as Kent and Rosenbek included monosyllabic and polysyllabic words, phrases, and sentences as stimuli. Qualitative formant description of individual polysyllabic words indicated lack of formant differentiation between syllables with a general pattern of vowel centralization. Although speakers with AOS were able to produce formants within the normal range, they did not always make different vowels distinctively while producing connected speech.

Ryalls' studies of vowel production in French- and English- speaking motor aphasics (1981, 1986) also found vowel formants comparable to normal speakers. In the study of French-speaking participants, average F1 and F2 values for five vowels were similar for the aphasic and normal group, although analysis of variance revealed significant differences for both F1 and F2 (Ryalls, 1981). Post-hoc analysis revealed that these differences are primarily accounted for by differences in the vowels /i/ and /a/ (i.e. two of the five vowels). Inspection of the formant means revealed more differentiation in F1 for the aphasic group than the normal group. Formant variability (i.e. standard deviation) of F1 was higher for the AOS group for 4 of 5 vowels, but the difference was statistically significant for only one of the comparisons. Variability of F2 was higher in all vowels, with statistical significance for two of five comparisons. While some differences were present between the aphasic and normal groups, these differences do not appear to reflect a clear pattern of vowel impairment in the aphasic group.

In the study of English-speaking participants, Ryalls (1986) found no significant F1 or F2 differences between motor aphasic and normal groups producing vowels in /hVd/ context. Group variability of F1 and F2 was approximately twice as high for the aphasic group compared to the normal group. Since this study included multiple productions of each vowel, within-subject formant variability also was analyzed. Aphasic speakers had significantly higher within-participant variability of F1 for all vowels, but F2 variability was higher for only two of nine vowels assessed. While previous studies examined group variability, this study importantly showed that speakers with apraxia may show greater variability in their repeated productions of the same words.

A recent study of Haley and colleagues (Haley, Ohde, & Wertz, 2001) examined the acoustic vowel space of “hid” and “head” produced by aphasics with and without apraxia and a normal control group. Although no quantitative analyses were presented, F1xF2 vowel space plots showed similar patterns for the aphasic groups with and without apraxia, with approximately half of each group producing distinct bimodal distributions for /ɪ/ and /ɛ/ and the remaining participants showing either a small collapsed vowel space or widely varying formants for both vowels not showing a clear pattern of distinction between the two categories. At least two participants with apraxia showed a pattern of two distinct categories with occasional substitutions, i.e. productions with vowel formants clearly falling within the range of the other vowel.

While considerable vowel category overlap was found in the group with apraxia, it is notable that at least two of ten NBD speakers presented with a similar pattern. Furthermore, it is important that the vowels considered in this study frequently overlap in speakers with Southern American English dialects (Bailey, 1991; Pollock & Berni, 2001). When individual vowel plots from this study were inspected in detail, the only apraxic speakers lacking clear bimodal distributions of /ɪ/ and /ɛ/ happen to be the five speakers who are speakers of Southern American English (e.g. speakers A-AOS 1, 2, 3, 7, and 9; Haley, Ohde, & Wertz, 2001, p. 1111). The two normal speakers with collapsed /ɪ/ and /ɛ/ categories were also Southern American English speakers, although three other normal Southern speakers had clearly distinguished vowel categories. This study exemplifies the notion that, at least in monosyllabic words, vowel formants of speakers with apraxia may differ very little from what is expected in normal speakers.

One further example of this principle is drawn from the recent study of apraxic vowel production, including repeated production of six vowels in /hVC/ context (Mathes, 2005). As shown in figure 3.1.1, the average formant values of the apraxic speakers vary from the values of normal speakers, although they are still within the expected range of formants (comparison data from Katz & Assmann, 2005). Group variability, as shown by error bars, is greater for the apraxic speakers compared to that of normal comparison groups, especially for the vowels [i], [a], and [u].

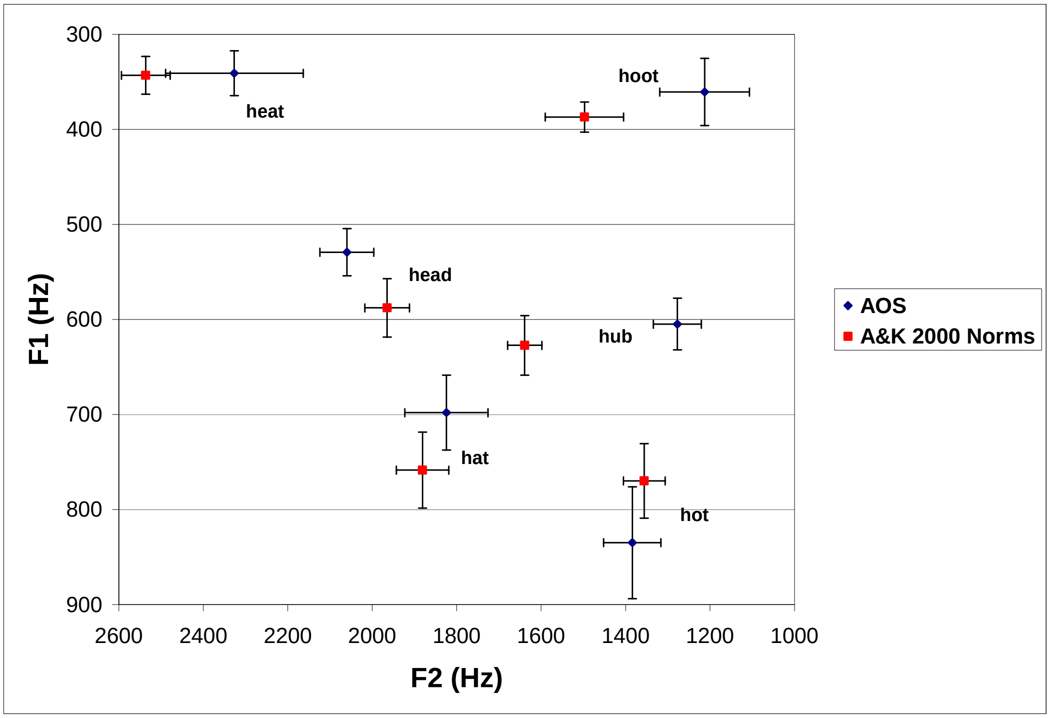

Figure 3.1.1. F1 x F2 vowel space in a group of seven apraxic speakers. Normative comparison is made to male and female adults from Katz & Assmann (2005). Average F1 and F2 values for vowels from the words "heat", "head", "hat", "hot", "hub", and "hoot" are displayed, with error bars representing the group standard deviation of formant values.

Individual data from this study reveal a slightly different picture (figure 3.1.2). Although average formant values differ between participants, the vowel space of each individual is well differentiated, with each vowel's average formant values separated in acoustic space. Within-participant variability on repeated productions, shown by error bars in figure 3.2, varies by participant but indicates little or no overlap between formant values of different vowel categories. These data suggest that vowel production in single words for speakers with apraxia is functional for communication, insofar as vowel formants are sufficiently distinctive for listeners to perceive the intended vowel. However, formant variability in speakers with AOS appears greater than would be expected in normal speakers, suggesting a mild vowel impairment that might be more evident under more taxing speaking conditions.

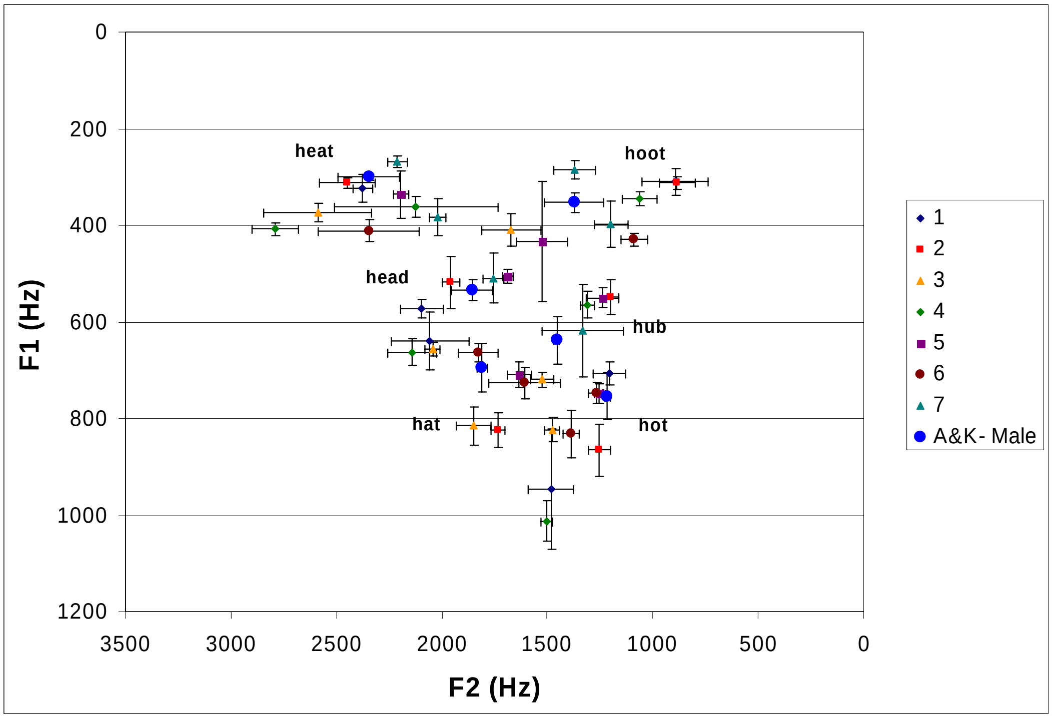

Figure 3.1.2. Individual F1 x F2 vowel space data from seven apraxic speakers. Normative comparison is made to male speakers from Katz and Assmann (2005). Average F1 and F2 values for vowels from the words “heat”, “head”, “hat”, “hot”, “hub”, and “hoot” are displayed, with error bars representing the standard deviation of formant values from repeated productions of words.

Transcriptional and acoustic studies of AOS reveal an incomplete story with respect to the presence of vowel impairment in speakers with the disorder. The null hypothesis, that vowel production in AOS is not an area of significant difficulty, remains viable. However, a number of studies have demonstrated the presence of vowel errors in at least some speakers with AOS. These disparate findings derive from several sources, including variation in participant characteristics (e.g. disorder severity, dialectal variation) as well as experimental characteristics (e.g. stimulus complexity, method of analysis). Detailed analyses of vowel production, including narrow transcription and acoustic analyses, enable detection of small deviations in vowel production even in mildly impaired speakers. If the speech stimuli to be produced are not sufficiently complex to disrupt the accurate and stable production of vowels, then even the most detailed analysis procedure will be unable to reveal a vowel impairment.

It is notable that in the studies showing mostly normal vowel production in AOS, the materials used were relatively simple. In most of the transcriptional studies, word stimuli were exclusively monosyllables (e.g. Canter et al., 1985; Haley et al., 2000; Haley et al., 2001; LaPointe & Johns, 1975; Trost & Canter, 1974; cf. Monoi et al., 1983 and Odell et al., 1991). In the acoustic studies that found irregularities of vowel positioning or timing, the production stimuli included both words and sentences (e.g. Kent & Rosenbek, 1983; Ryalls, 1981). In contrast, in the recent studies that have shown accurate and stable vowel production, stimuli included vowels produced in hVC context (Haley et al., 2001; Mathes, 2005).

Assessment of vowel production in phonetic environments of varying complexity has not been systematically explored, and is a potentially valuable avenue to discover the level of breakdown in speakers who experience little difficulty with short and simple sequences.

Chapter 3.2

Sensory influences in AOS

Involvement of the sensory system in speech motor control has been a question of interest both for scientists studying normal speech production as well as those investigating disorders of speech motor control. Online revision of movement behavior based on sensory input has been well established, with research including studies of articulatory modification based on intrusive articulatory conditions (e.g. artificial palate; Baum & McFarland, 1997) and altered auditory feedback (Houde & Jordan, 1998, 2002). Reports of immediate compensation for unusual speaking conditions (i.e. bite block speech) entailed the development of a “predictive simulation” theory of speech motor control (Gay, Lindblom, & Lubker, 1981; Lindblom et al., 1979; Lindblom & Sundberg, 1971). In predictive simulation, sensory input of initial speaking conditions is used to modify motor plans such that intended auditory-acoustic targets are produced immediately despite the articulatory perturbation of a bite block.

In the study of apraxia of speech, sensory factors have received only sporadic attention, likely because the disorder appears to affect production primarily. Early scientists distinguished AOS and its predecessors as a disorder in which patients could understand what was said to them but could not produce articulate speech. Wepman and Van Pelt (1955) developed a theory of neurogenic communication disorders based on clinical experiences, emphasizing the importance of distinguishing between disorders of language formulation (i.e. aphasia) and transmission (i.e. apraxia or sensory imperception). Disorders of transmission, including apraxia of speech, were claimed to be modality-bound, and thus motor performance could not be directly affected by sensory factors. In a significant revision of this theory, Wepman and associates acknowledged the importance of sensory feedback in the planning of actions (Wepman, Jones, Bock, & Van Pelt, 1960).

Few studies have examined sensory factors in AOS, although several notable exceptions suggest that further attention to the issue is warranted. For example, several authors have examined compensatory articulation under perturbed speaking conditions in Broca's or nonfluent aphasic speakers (Sussman et al., 1986, Baum et al., 1997; Baum, 1999). Oral tactile-kinesthetic sensation has been studied in one study of participants with AOS (Rosenbek et al., 1973), auditory perceptual skills in AOS have been examined in several other studies (Aten et al., 1971; Square et al., 1981; Square-Storer et al., 1988), and at least one study explored rhyming abilities in AOS (Waters et al., 1992). These studies will be reviewed to assess the potential role of sensory and linguistic factors, including, oral sensation, compensatory articulation, auditory perception, and rhyming ability in the control of speech movement in people with AOS.

Orosensory abilities in AOS

The role of oro-sensory impairment in speakers with apraxia of speech has been less studied than auditory perception, a surprising fact given that research of normal speech motor control has indicated the importance of tactile sensation for planning speech movements (e.g. Lindblom & Sundberg, 1971). While tactile-kinesthetic feedback also has been implicated as an important factor for therapy of AOS (e.g. Bose, Square, Schlosser, & van Lieshout, 2001), direct study of impaired oral sensation in AOS has been neglected since Rosenbek et al. (1973) explored the issue.

Rosenbek and colleagues (1973) used three tests of oral sensation in 30 participants with AOS and varying degrees of aphasia, 10 non-apraxic aphasic participants, and 30 NBD adults. In all tests, participants were required to discriminate whether two oral stimuli were the same or different, and in all tests, participants with AOS performed significantly more poorly than aphasia-only and NBD participants. In an oral-form identification task, speakers with AOS made approximately twice as many errors as aphasic-only and NBD participants, having greater difficulty determining whether two geometrical shapes placed in the mouth were the same or different. In a two-point discrimination task, participants with AOS could detect that they were being stimulated at two different points, but the distance between the two points had to be about twice as large for them to discriminate as for aphasic-only and NBD participants. In the third task, "mandibular kinesthesia", participants with AOS made more errors in determining whether their jaw was lowered to two different, or to two identical distances. Rosenbek and colleagues also found that not all participants with AOS had difficulty with oral sensation tasks, but that severity of the disorder was related to oral sensory impairment.

The issue of oro-sensory impairment has not been addressed in speakers with AOS since Rosenbek et al. (1973), although several researchers have taken up the study of compensation for perturbed speaking conditions, i.e. bite-block speech (Baum, 1999; Baum et al., 1997; Sussman et al., 1986). The phenomenon of "immediate compensation" in normal participants speaking with a bite block between the teeth (e.g. Lindblom et al., 1979; Lindblom & Sundberg, 1971) has important implications for the study of speech motor control disorders. The correlation between impaired oral kinesthesia and apraxia severity suggests that ability to sense articulatory structures is related to ability to control those articulators for speech. In the case of bite block speech, speakers who have difficulty sensing the initial articulatory conditions may also have problems modifying articulatory parameters to produce the intended auditory-acoustic target. While the link between oral sensation and compensatory articulation has not been directly tested, at least one study has shown that Broca's aphasics have difficulty compensating for bite block speaking conditions.

Compensatory articulation in AOS

The phenomenon of "immediate compensation" in normal participants speaking with a bite block between the teeth (e.g. Lindblom et al., 1979; Lindblom & Sundberg, 1971) has important implications for the study of speech motor control disorders. Sussman and colleagues (1986) studied bite block compensation in 13 individuals with Broca's aphasia, with varying degrees of oral and verbal apraxia. Speakers had particular difficulty producing the vowel /i/ with a large (20 mm) bite block placed between the teeth, as determined by large differences between F1 and F2 values achieved during normal production and with the bite block. In particular, F1 values were generally higher in the bite block condition, on average 54.8 Hz higher, than in normal conditions, and F2 was lower by 146 Hz. Degree of acoustic deviation was significantly correlated with ratings of oral apraxia (not verbal apraxia) and overall aphasia severity from the BDAE. Sussman et al. also reported some correspondences between lesion data and bite block performance, suggesting that damage to Broca's area and underlying structures is responsible for poor compensatory articulation. As with most clinicoanatomic analyses, there were notable exceptions, with one individual with damage to Broca's area (i.e. LF3) and intact bite block performance and one with a very small temporoparietal lesion and impaired bite block speech.

One limitation of the Sussman et al. (1986) study was the lack of a control group, although the purpose was not to determine whether compensatory articulation in aphasics was similar to that in normal speakers, but instead to study differences in performance on the basis of lesion site. Baum and colleagues (1997) studied bite block speech of several groups, including speakers with fluent aphasia, nonfluent aphasia, and NBD controls. Speakers produced two high vowels and two low vowels in normal conditions, in a compensatory bite block condition (i.e. large bite block for high vowels, small bite block for low vowels) and a noncompensatory condition (i.e. bite blocks approximated the target jaw position for a given vowel). In contrast to Sussman and colleagues, Baum et al. did not calculate formant differences for normal and bite block conditions, but reported the overall formant values reported by fluent, nonfluent, and normal speakers. Baum et al. reported similar levels of compensation for the aphasic groups and the control group, with minimal formant differences noted across conditions for all groups. Interestingly, while formant values were generally maintained across conditions for all speaker groups, naïve and trained listeners had difficulty identifying the vowels produced. The fact that listeners were not able to accurately identify vowels, particularly for the compensatory condition, suggests that different analyses of acoustic compensation are warranted. A further difficulty with the study is that only group data were presented; considering the variation of patient populations and the fact that 3 of 6 nonfluent aphasic participants also had verbal apraxia, the inclusion of individual data might have proven instructive in determining whether compensatory articulation is differentially affected in individuals with varying severity and with different behavioral profiles.

Baum (1999) published a follow-up to the previous study with nonfluent aphasic participants (n=8) and a control group (n=10), reporting similar findings to Baum et al. (1997). As a group, the nonfluent aphasic speakers performed comparably to the control group in the production of speech with bite blocks. In this study, Baum did not report the presence or absence of apraxia in the nonfluent participants, so it is unknown whether these findings apply to individuals with AOS or only to individuals with agrammatic aphasia.

The ability to compensate for unusual speaking conditions is an important component of intact speech motor control, and bite block tasks may prove useful as a diagnostic tool for individuals with apraxia of speech. Correlation between oral apraxia and compensatory articulation abilities (Sussman et al., 1986) suggests that sensory information may play an important role in the planning of speech movements in AOS.

Auditory perception in AOS

Auditory perception rarely has been examined in AOS, with a few notable exceptions. Aten and colleagues (1971) first tested auditory perception in speakers with AOS and non-brain-damaged control participants. Participants listened to recorded sequences of two or three words varying minimally in initial or final consonant or vowel and identified the words in the order heard by pointing to line drawings. The findings indicated that three of 10 speakers with AOS identified the sounds heard with accuracy similar to NBD participants (e.g. 98-100%), three speakers performed more poorly but with relatively few errors (e.g. 93-95% accuracy), and four had clearly impaired auditory perception (75-89% accuracy). Aten and colleagues interpreted the results to suggest that AOS can occur "in a fairly pure form without sensory—or at least without auditory—components", and generally that sensory impairment is not sufficient to explain the speech production deficit in AOS.

Square and colleagues studied auditory processing abilities in AOS, comparing participants with "pure" AOS to those with coexisting aphasia and apraxia, aphasia without apraxia, and non-brain-damaged adults (Square et al., 1981; Square-Storer et al., 1988). Performance on a battery of nonspeech and speech processing tasks suggested that speakers with "pure" AOS were not significantly different from NBD adults. Participants with aphasia plus apraxia and those with aphasia only performed similarly, with more errors than the "pure" AOS group. In particular, differences between "pure" AOS and aphasic apraxic speakers were noted on same/different discrimination of monosyllabic word and nonword pairs. The results are striking and suggest a clear pattern of normal auditory discrimination in participants with apraxia but no aphasia, with impaired discrimination for those with aphasia.

Aten and colleagues (1971) reported a heterogeneous pattern of auditory identification ability in their group of apraxic speakers, with normal performance for a subset of three participants that they suggest have relatively "pure" AOS. Square and colleagues (1981, 1988) reported normal auditory discrimination in pure apraxic speakers. This might suggest that individuals with pure AOS have no auditory perceptual deficits, so long as they are screened thoroughly for aphasic impairments.

The question of how speakers with "pure" apraxia are selected is of importance. It is notable that all apraxic participants in the Aten et al. study passed an auditory comprehension screening and had minimal or no linguistic involvement, suggesting that apraxia was relatively pure. Why, then, did four participants in Aten et al. have clearly impaired auditory perception, in contrast to the three best performers in the same study and in contrast to the normal performance of "pure" AOS speakers in Square et al.? It is possible that the Aten et al. screening process was not as stringent as that used by Square and colleagues, thus allowing inclusion of participants with some aphasic impairment and explaining the impaired perception of some participants. Another potential explanation is that differences in performance were not due to aphasic impairment, but instead result from task differences. In particular, Aten et al. asked participants to identify the phonemes heard by pointing to pictures, while Square et al. required participants to make same-different discriminations in word pairs. These tasks are sufficiently different that a direct comparison cannot be made between the two studies. Studies of auditory perception in aphasic speakers have shown that discrimination can be intact while phonemic identification is impaired (Blumstein et al., 1977), suggesting that further study is needed to assess the role of auditory perception and processing in AOS.

Phoneme identification and discrimination tasks are both frequently used as measures of categorical perception in non-brain-damaged individuals. Identification tasks are used to determine the position on a continuum of speech sounds at which the sound is not clearly identified by listeners as being a member of one phonemic category or the other (i.e. category boundary). Listeners might classify a given sound at a boundary as one phoneme in 50% of trials and as another phoneme in the remainder of trials. Discrimination tasks are used to show that listeners have greater sensitivity to differences in sounds at the category boundary than sounds that are well within a category. Both tasks are used to understand how listeners divide up the auditory perceptual space, with convergent evidence of category boundaries coming from identification and discrimination procedures. The two have distinct processing demands for listeners, however, with most discrimination tasks requiring an acoustic comparison of two sounds and a decision about whether they are the same or different, with identification tasks requiring a decision as to phonemic category assignment.

Blumstein and colleagues (1977) studied identification and discrimination of the English voiced/voiceless distinction in 15 aphasic patients, five of whom had Broca's aphasia[2]. The findings indicated that 12 of 15 participants had normal ability to discriminate the voicing contrast, with only 8 of 15 participants having normal ability to label stimuli. No participants had normal identification performance with impaired discrimination, suggesting that accurate phonemic identification requires the ability to discriminate sounds, but not the converse. In the Broca's aphasia group, four of five participants had normal discrimination, and three of five had normal identification performance. Comparison of perceptual ability with auditory comprehension scores revealed no relationship with the two. In a subset of the participants, Blumstein and colleagues also showed that there was no relationship between identification impairment and phonemic or phonetic errors of the voicing contrast in speech production.

Basso and colleagues studied identification of a voicing contrast in 11 participants with likely AOS[3], along with 39 other aphasics with LH lesions, 12 non-aphasic participants with LH lesions, 22 with right hemisphere lesions, and 53 NBD participants (Basso, Casati, & Vignolo, 1977). Identification performance was classified on a scale of "phonemic identification defect" (PID) on the basis of the presence of a distinct category boundary. All RH participants and LH participants without aphasia had no impairment, or only slightly impaired phonemic identification. In contrast, 33 of 50 aphasic patients had either severe or very severely impaired identification, including 10 of 11 likely AOS participants. The identification defect occurred in greater proportion in the nonfluent

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[2] Specific behavioral profiles of individual participants and groups were not provided, so it is not known for certain if the Broca's group was apraxic as well as aphasic. At the time of the Blumstein et al. paper, use of Broca's aphasia to describe patients with characteristics of AOS was common; thus the comparison with perceptual studies in AOS is appropriate.

[3] Basso and colleagues described their study group II as having "nonfluent aphasia with good comprehension", noting that 10 individuals presented with labored articulation and one with mild disprosody. They further state that all participants fit the clinical profile of Broca's aphasia.

than in the fluent participant groups, a finding at odds with expected greater perceptual deficits in fluent aphasics due to lower auditory comprehension in this group.

A similar finding was reported by Baum (2002) in a study of consonant and vowel discrimination in participants with LH lesions and fluent aphasia, LH lesions and nonfluent aphasia, RH lesions, and NBD participants. Ten participants with nonfluent aphasia performed consistently more poorly than fluent aphasics, RH lesion, and NBD participants on discrimination of consonants and vowels.

The contention that auditory perceptual ability is necessarily related to auditory comprehension and not related to speech motor control has been overstated. Studies of perception in individuals with apraxia of speech are limited, but the available literature suggests that auditory perceptual impairment, while not sufficient to explain articulatory deficits in AOS, does occur with substantial frequency in this population. Auditory perceptual impairment does not appear to be related to degree of articulatory error nor to auditory comprehension. The evidence indicating higher rates of perceptual impairment in individuals with nonfluent aphasia than fluent aphasia is perplexing, especially so because of the lack of correspondence between production and perceptual errors. Further research is needed to understand the role, if any, of auditory perceptual skills in the planning of speech movements in AOS.

Chapter 6.3
Rhyme processing in AOS

The role of linguistic processing in AOS frequently has been discussed and linguistic (i.e. aphasic) deficits frequently occur in some adults with AOS. The prevailing thought among researchers of AOS is that the disorder results from a deficit in subphonemic processes, although phonological processes may have some role in speech motor control, insofar as they represent the abstract constructs of speech sounds.

Rhyme processing tasks are used to determine the ability to maintain and manipulate speech sound representations once they have undergone initial auditory, phonetic, and phonemic analysis. Rhyming ability has been explored in adults with apraxia of speech in at least one study (Waters et al.,1992) and the effects of rhyme stimuli on linguistic processing in aphasia has been studied in several others (Blumstein et al., 2000; Cermak et al., 1984; Gordon & Baum, 1994).

Waters and colleagues (1992) studied auditory and visual rhyme judgment in six apraxic participants as part of a study of verbal memory in AOS. Mean scores on auditory rhyme judgment were similar in apraxic and normal participants, while judgment of visual rhyme was significantly impaired in apraxics. The authors also found impaired verbal rehearsal on several other tasks and concluded that individuals with AOS have impaired articulatory rehearsal in verbal working memory.

Studies of rhyming ability in nonfluent aphasic individuals, who often have concomitant apraxia of speech, have indicated that verbal memory deficits may be related to speech motor planning. For example, Cermak and colleagues (1984) found that Broca's aphasics have difficulty identifying rhyming words when they are separated from a target word by two or more intervening stimuli. Gordon and Baum (1994) found that aphasic participants have higher error rates in rhyme judgment than normal participants, particularly for written rhyme judgments. Blumstein and colleagues (2000) showed lack of priming for rhyme information in nonfluent aphasics, indicating impaired ability to use phonological ability for lexical access.

Rhyme processing has been studied in apraxic and non-fluent aphasic participants with results indicating that phonological processing skills may be related to speech motor control in adults with AOS. Cognitive and linguistic abilities rarely are studied in individuals with speech motor control disorders, but may be important factors in understanding AOS. Rhyme judgment, in particular, may be important in learning more about systems of phonological processing in people with apraxia of speech.

Summary

The research record is mixed on the status of sensory and linguistic impairments as central or concomitant aspects of the speech disorder in AOS. To understand the nature of speech targeting in normal speech motor control and in AOS, it is crucial to consider the extent to which sensory, linguistic, and motor systems interact and to study impairment of different skill domains in speakers with speech motor control disorders.

CHAPTER 4: PURPOSE

The purpose of this study is to investigate speech motor control mechanisms in adults with apraxia of speech, with spatial targeting of vowels as the central point of focus and related sensory abilities (i.e. compensatory articulation, auditory perception) providing convergent evidence as to the nature of spatial targeting deficits in the disorder. While spatial targeting for consonant production has been shown to be imprecise (Haley et al., 2000), findings of vowel errors mostly have been limited to temporal measures indicating longer duration for apraxic vowel production. Many acoustic studies of vowels in monosyllables produced by speakers with AOS or related disorders have shown vowel spaces with vowel categories as well differentiated as unimpaired speakers. Some evidence of spatial targeting deficits for vowel production has been reported by Kent and Rosenbek (1983) and Ryalls (1981) using at least some multisyllabic words and/or phrases. Vowel targeting has not been investigated systematically in adults with AOS and remains an important focus of study to improve the understanding of how control of speech movements is accomplished.

Specific experimental hypotheses are listed as follows:

1. Participants with AOS have impaired vowel targeting for the front vowels [ɪ], [ɛ], and [æ], as measured with acoustic analysis.
2. Increasing word length (e.g. a) vowel in isolation, b) monosyllabic word, c) disyllabic word, and d) trisyllabic word) results in less accurate vowel targeting.
3. Participants with AOS have difficulty compensating for insertion of small and large bite blocks in vowel targeting for the front vowels [ɪ] [ɛ] and [æ].
4. Participants with AOS have difficulty categorizing front vowels in /hVd/ context.
5. Participants with AOS have difficulty discriminating between pairs of front vowels in /hVd/ context, with F1 varying in increments of 30, 60, 90, and 120 Hz.

6. Participants with AOS have difficulty processing rhyme information in a rhyme generation task, an auditory rhyme judgment task, and in a written rhyme judgment task.
7. Vowel targeting ability is correlated with vowel perception ability.

CHAPTER 5: METHOD

Chapter 5.1

Participants

Five adults with apraxia of speech (AOS) participated in the study, as well as five non-brain-damaged (NBD) control participants matched by gender, regional dialect, and approximate age. Each group included two males and three females between the ages of 45 and 75. All participants were native speakers of American English, including Northern Cities and Southern American dialects (Labov, Ash, & Boberg, 2005). Participants' dialects were assessed and matched informally via geographical history and perceptual judgment by the investigator for a series of screening words produced by participants (appendix A). Audiometric screening was performed to confirm that participants were able to hear the frequencies 500, 1000, and 2000 Hz at 30 dB or lower in at least one ear.

AOS participant selection

Participants with AOS were five individuals known to the University of Texas Speech and Hearing Center or referred from local hospitals for participation in the study. Four of the five participants experienced left-hemisphere damage due to cerebrovascular accident and one person (A3) due to a missile wound to the head. All participants sustained their injuries at least six months prior to the study and were medically stable. Neurological reports were obtained to ascertain site of lesion and to document any confounding neurological conditions.

Apraxia of speech was diagnosed on the basis of criteria reported by Kent and Rosenbek (1983), including: 1) effortful trial and error groping of articulators during speech and attempts at self correction, 2) dysprosody unrelieved by extended periods of normal rhythm, stress, and intonation, 3) error inconsistency on repeated trials of the same utterance, and 4) obvious difficulty initiating utterances. Participants had varying degrees of linguistic impairment characteristic of Broca's aphasia, including anomia and agrammatism, although apraxia was the major area of impairment. Individuals with clinical signs of neuromuscular weakness and slowing were excluded from the study, as well as those with coexisting neurological conditions (e.g. Parkinson's Disease, Multiple Sclerosis, Muscular Dystrophy).

The Apraxia Battery for Adults (ABA-II, Dabul, 2000) was administered to each potential participant to obtain an inventory of AOS characteristics in spontaneous speech, reading, and automatic speech. Aphasia status was assessed using the Western Aphasia Battery (Kertesz, 1982). When possible, scores from recent assessments were used to document aphasia status.

Speech intelligibility of participants with AOS was assessed using the target words from the multiple choice version of a single word intelligibility test developed by Kent and colleagues (1989). The test comprised 70 monosyllabic target words, listed in Appendix B. Participants were asked to produce each word following the presentation of an auditory and written cue. Independent raters (M.A. students in speech-language pathology) listened to recordings from the test and transcribed the gloss for each word. Different raters were used to rate each participant's productions to avoid learning effects of the target words. Intelligibility scores were calculated by dividing the number of correctly perceived words by the total number of words produced.

Phonetic transcriptions of the words from this test were also completed by two Ph.D. students in communication sciences and disorders, using broad transcription. The percentage of targets that were complete phonetic matches was computed, as well as the number of phonetic errors, and the relative frequencies of errors for vowels and for consonants in initial or final position.

Results of aphasia and apraxia assessments, hearing screenings, and lesion site description are shown in table 5.1.1, speech intelligibility testing scores are shown in table 5.1.2. Narrative descriptions of each participant also are provided.

Table 5.1.1
AOS participant information

		Participants with Apraxia of Speech				
		A1	**A2**	**A3**	**A4**	**A5**
Gender		F	F	M	F	M
Regional Dialect		Northern	Southern	Southern	Northern	Southern
Age		74;10	64;0	48;7	58;4	58;0
Years Post-Onset		9;11	9;11	26;11	1;0	1;1
Site of Lesion		left basal ganglia and internal capsule	left fronto-parietal cortical and subcortical infarcts	left frontal and anterior temporal lesion	4 cm left posterior frontal lobe infarct	left basal ganglia, insula, frontal operculum, and superior temporal gyrus
Apraxia Battery for Adults	**Overall Severity**	Mod	Mild-Mod	Mod	Mild-Mod	Mild
	Diadocho-kinesis	Mild	Mild	Mild	Mild	None
	Inc. Word Length (1-3 syll.)	Mod	Mild	Mod	Mild	Mild
	Inc. Word Length (2-5 syll.)	‡	Mod	‡	Mod	Mod
	Limb Apraxia	None	None	None	None	None
	Oral Apraxia	None	Mild	None	None	None
	Repeated Trials	Mod	Mild	Mild	Mild	None
Western Aphasia Battery	**Aphasia Quotient**	93	80	68	90	96
	Compre-hension*	100	94	78	100	100
	Naming*	87	90	80	87	91
Hearing Screening	**Rt/Lft Screening Thresh. (dB)**	45/30	25/35	30/65	20/20	20/25

‡ The second increasing word length subtest is not administered if severity is moderate or worse on the first increasing word length subtest.
* Comprehension and naming subtest scores for the Western Aphasia Battery are expressed as a percentage of the possible points.

Table 5.1.2
Single-word intelligibility testing results

		A1	A2	A3	A4	A5
		Participant				
% Intelligibility		88	81	88	88	99
% Phonetic Match		87	91	93	91	97
Error Type Frequency	**% Vowel Err.**	33	33	0	100	25
	% Initial Cons. Err.	67	33	57	0	50
	% Final Cons. Err.	0	33	43	0	25
# Phonetic Errors		9	6	7	6	4

AOS participant description

Participant A1 is a 74-year-old female from Illinois whose stroke almost 10 years ago resulted in damage to the left basal ganglia and internal capsule. She presented with apraxia of moderate severity, characterized by difficulty producing words of increasing length and repeating the same word multiple times. Her language ability was only mildly affected, with no demonstrated comprehension difficulties on the WAB and mild anomia.

A2 is a 64 year old female from Texas whose stroke almost 10 years ago resulted in damage to left frontal and parietal cortex as well as subcortical structures. She had mild-to-moderate apraxia severity with greatest difficulty on words of increasing length and also signs of nonspeech oral apraxia. She had minor deficits in auditory comprehension and word naming in addition to the apraxia.

A3 is a 48-year-old male from Texas who sustained a gunshot wound to the head nearly 27 years ago, causing a large lesion of the left frontal cortex and anterior temporal lobe. A3 had moderate apraxia severity with significant difficulty producing words of increasing length. He had the most aphasic involvement of all participants, presenting with naming difficulties and significant deficits comprehending sequential commands, although other auditory comprehension abilities are relatively unaffected.

A4 is a 58-year-old female from Michigan with a small, 4 cm lesion in the left posterior frontal lobe that resulted from a stroke one year prior to her participation in the study. Her apraxia severity was mild-to-moderate, characterized by difficulty mainly with producing words of increasing length. Her auditory comprehension of language was normal and she had minor difficulty with word naming.

A5 is a 58-year-old male from Texas with a lesion due to a stroke one year before the study that damaged the left basal ganglia, insula, frontal operculum, and superior temporal gyrus. His apraxia was the least severe of all participants, with a severity rating of mild. Like other participants, he had difficulty producing words of increasing length but had normal diadochokinetic rates and no difficulty in repeating words multiple times.

Control participant selection

Each AOS participant was matched to an individual of the same gender and similar regional language dialect with no history of speech disorder or neurological disease. Two participants were selected from a pool of typically-aging adults that have agreed to participate in studies of communication in aging. Three additional participants were known personally to the investigator and were recruited specifically to obtain the closest possible dialect matches.

Control participants were screened for speech and language impairment on the basis of interview, conversational speech sample, and reading sample. The Questionnaire for Verifying Stroke-Free Status (QVSFS; Jones, Williams, & Meschia, 2001) was administered to confirm the lack of neurological impairment. The QVSFS has a negative predictive value of 0.96 and a positive predictive value of 0.60. Use of this instrument is conservative, as it tends to over-identify participants without stroke as stroke-positive; thus participants who are identified as stroke-free have a high likelihood of being stroke-free. Individual NBD participant data are shown in table 5.1.3.

Table 5.1.3
Control participant information

		Control Participants				
		N1	**N2**	**N3**	**N4**	**N5**
Gender		F	F	M	F	M
Regional Dialect		Northern	Southern	Southern	Northern	Southern
Age		60;6	59;10	55;0	58;10	61;2
Hearing Screening	**Rt/Lft Thresh. (dB)**	20/20	25/25	35/20	20/20	20/20

Participants completed two experimental sessions, approximately one and a half hours in duration per session. During the first session, participants produced words with vowels varying in the height dimension for two speaking conditions, including a normal production condition and a bite block condition. During the second session, perceptual testing was completed, including vowel identification, same/different vowel discrimination, and rhyme processing tasks. Experimental stimuli, procedures, and instrumentation will be described separately as Experiment 1 (Normal and bite-block vowel production), Experiment 2 (Vowel identification and discrimination), and Experiment 3 (Rhyme Processing).

Chapter 5.2

Experiment 1: Vowel targeting in normal and bite block conditions

Stimuli

The vowels [ɪ] [ɛ], and [æ] were produced in four conditions, including isolation, one-syllable (VC), two-syllable ((h)VCVC), and three-syllable (VCV(C)VC) words. The stimuli are listed in table 5.2.1. Digital recordings of the stimuli were made by the experimenter to be used as auditory cues. The vowel in isolation was selected from the steady state of the vowel from the one-syllable production. During the production tasks, written cues and auditory cues were presented simultaneously, with vowels [ɪ], [ɛ], and [æ] in isolation represented by the written forms "ih", "eh", and "ae", respectively. Each vowel or word was produced ten times for each of three conditions (normal, small bite-block, and large bite-block), yielding a total of 120 productions per condition and 360 productions total.

Table 5.2.1
Vowel production stimuli, including three vowels [ɪ], [ɛ], and [æ] produced in isolation and in one-, two-, and three-syllable words.

Isolation	One-syllable	Two-syllable	Three-syllable
ɪ	id	hid it	idiot
ɛ	Ed	edit	edited
æ	add	add it	additive

Materials

Bite blocks were constructed from solid nylon rod material in square or rectangular shape, with semicircular indentations carved on the inferior and superior aspects of the block for participants to grip with the teeth (figure 5.2.1). In the opposite end of the bite block from the indentations, a piece of nylon fishing line was threaded through a hole and attached to the participant's clothing, serving as a precaution to prevent swallowing of the bite block. Small bite blocks have the dimensions of 0.25 inches x 0.25 inches x 1.0 inches, with an indentation in the square cross section measuring 2.5 mm (i.e. Baum et al., 1997; Lindblom et al., 1979). Large bite blocks have the dimensions of 1.0 inches x 0.25 inches x 1.0 inches, with a 22.5 mm indentation. Participant A4 was unable to tolerate the large bite block, therefore an alternate large block was used with a 14.5 mm indentation. Because of cutting variation, the width and the length of the bite blocks listed are approximate; however, the height of the blocks of each size is identical. The indentations were cut to the specifications listed with +/- 0.5 mm precision, as measured using a vernier-style caliper. A hand-held rotary tool with a 1/8 inch diameter tungsten carbide cutting attachment was used to make the cuts.

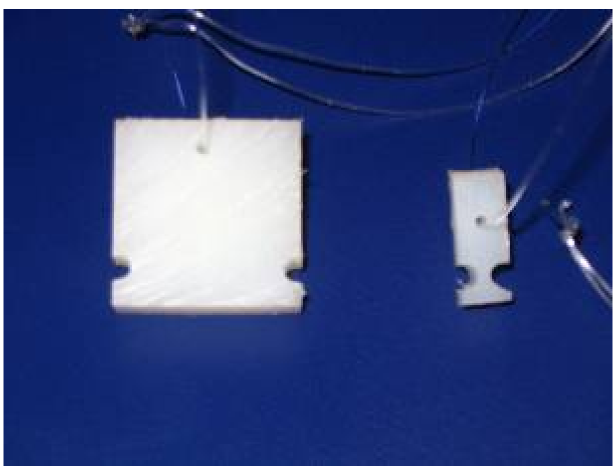


Figure 5.2.1. Large and small bite blocks constructed of nylon material. The large bite block has indentations measuring 22.5 mm and the small block has indentations measuring 2.5 mm.

Procedures

Participants produced the vowels and words in three phases, with the first phase consisting of production in normal (non bite-block) condition, and the second and third phases consisting of mixed small and large bite block conditions.

In the first phase (normal condition) a visual target "xxxxx" was displayed, followed by the written and auditory cue. Participants were instructed that "it is important to say the word as soon as you see it, but there is no need to rush" (adapted from Lindblom et al., 1979).

In the second and third phases, participants first saw the words "small block" or "large block" to indicate which bite block to use, followed by the written and auditory cue. Prior to the bite block phases, participants were instructed as follows:

> This task is the same as before, the only difference being that now you will have one of these bite blocks between your teeth. I would like for you to say the words as closely to normal as possible. It is important that you start saying the word as soon as you see it on the screen (adapted from Lindblom et al., 1979).

The stimuli were arranged such that half of the words were produced with a small bite block in the second phase and a large block in the third phase, with the remainder produced with a large block in the second phase and a small block in the third phase.

Participants were seated in front of a computer monitor in a quiet, but not sound-proof room. Audio recordings were made directly to a PC using a one-point stereo microphone (Sony Model # ECM-MS57) and a high-quality PC sound card, with experimental control mediated using Alvin (Hillenbrand & Gayvert, 2005), an open-source software program. To ensure that an adequate signal was acquired for the audio recordings, the gain of the audio signal was adjusted while the participant repeated the phrase "Testing, testing, 1, 2, 3". Prior to the first and second phases, practice trials with each word were provided with feedback from the experimenter to ensure that participants were able to complete the task.

Data analysis

Acoustic measurements

Recordings made by Alvin were digitized at a sampling rate of 16 KHz with 16-bit quantization. The resulting ".wav" files were analyzed using Praat, an open-source software program for speech analysis and synthesis (Boersma & Weenink, 2005). For each recorded stimulus, frequency values for the first three formants (F1, F2, and F3) were selected at vowel onset and at the steady state of the vowel nucleus. For two- and three-syllable stimuli, formant measures for the final syllable [ɪ] vowel at steady state also were selected.

A partially automated process using analysis scripts for Praat written by the investigator were employed to facilitate the management of sound files, displaying analysis windows, selecting vowel formants, and recording numeric data to text files. For each stimulus sound file, the locations of the vowel onset at the first measurable glottal pulse and the vowel nucleus first were determined. The vowel nucleus was selected as the maximum point of the intensity envelope for the portion of the vowel that perceptually most closely resembled the target vowel.

Fast fourier transform (FFT) spectra and linear prediction coding (LPC) spectral envelopes were generated for each of the measurement points, using a Gaussian-like analysis window with a 52 Hz bandwidth. Spectral peaks were determined by the measurer on the basis of the FFT and LPC spectra, with the full spectrogram used to confirm the most likely formant values if either of the two spectra were ambiguous. Alternative formant values were computed at each measurement point using an automatic formant-tracking process in Praat. These values were retained for comparison to the values selected manually from acoustic spectra.

Measured formant values were compared to ranges defined by the minima and maxima of formant frequencies produced by males and females in two studies of normal vowel production (table 5.2.2). Measurements outside of these ranges were re-checked, with final formant determinations made on the basis of consensus between FFT, LPC, and spectrographic analyses.

Table 5.2.2
First, second, and third formant frequency ranges for the vowels [ɪ], [ɛ], and [æ]

	F1	F2	F3
ɪ	338 - 594	1701 - 2654	2432 - 3684
ɛ	387 - 981	1580 - 2426	2197 - 3652
æ	511 - 1097	1498 - 2701	2255 - 3655

Note. Ranges were determined based on data from Hillenbrand, Getty, Clark, and Wheeler, (1995) and Katz and Assmann (2005).

Acoustic analysis primarily was completed by the investigator, with one of the ten participants measured in full by another doctoral student in the speech motor control laboratory, who also performed reliability measurements. The secondary measurer was trained by the investigator in the use of the software and scripts, the methods for determining appropriate analysis windows, and for selecting formant values, as described above.

Reliability of acoustic measurements was completed for a pseudo-random sample of 10% of all productions. Since participants produced ten repetitions each for 36 combinations of vowel by syllable by bite block conditions (for a total of 360 productions total), one of the ten repetitions was randomly selected to be re-measured, for a total of 36 reliability stimuli per participant. The secondary measurer completed reliability for the nine participants measured by the investigator for a total of 324 reliability stimuli and the investigator performed reliability for the one participant measured by the secondary measurer (36 stimuli).

Comparison of the primary and secondary formant measurements was completed using a Pearson correlation analysis. Reliability was very high for first and second formant measurements made both at the first glottal pulse and at the vowel nucleus, with Pearson coefficients above 0.90 ($R^2_{F1\text{-}FGP}$= 0.96, $R^2_{F2\text{-}FGP}$= 0.98, $R^2_{F1\text{-}VNC}$= 0.97, $R^2_{F2\text{-}VNC}$= 0.93). Reliability for F3 was poorer, with Pearson's coefficients of 0.63 for F3 at the first glottal pulse and 0.76 at vowel nucleus. Due to the low reliability for F3, all formant analyses in the study will include only F1 and F2 measurements.

Perceptual goodness ratings

In addition to the acoustic analysis, vowel productions also were rated by listeners to determine the vowel formants that correspond to the best productions of vowels for a given participant. Perceptual goodness was determined for the initial vowel only, eliminating the possibility that goodness measures would be influenced by consonant errors or other irregularities in the word.

Stimuli and procedure. The vowels from the unconstrained and bite block production tasks were cropped to include only the initial vowel. Three graduate students in speech-language pathology were recruited to rate the goodness of the vowels. The listeners rated the vowels for one participant at a time, with vowel stimuli presented in randomized order using Alvin. The auditory stimulus was presented as well as the phonetic symbol for the targeted vowel. Ratings were made on a visual analog scale from 0 to 1000, with the low end of the scale representing poor exemplars and the high end representing good exemplars. Listeners were instructed to label vowels that were good exemplars of a non-target vowel as very poor exemplars. A subset of ten percent of each participant's vowel productions were presented twice to listeners, comprising a set of 360 total stimuli (36 vowels X 10 participants) from which to compute intra-rater reliability.

Perceptual goodness rating analysis. A Pearson's correlation analysis was performed for the repeated ratings made by each listener. Two listeners had higher intra-rater reliability than the third, with Pearson's coefficients of 0.76 and 0.71. Ratings of the least reliable listener (r= 0.53) were discarded from further analyses.

Perceptual goodness of vowels produced in the study is reported as the mean of ratings between the two listeners with high intra-rater reliability. Vowel ratings also served as the weight values to determine the optimal vowel formants for each speaker. Standard scores of vowel ratings by each listener for each stimulus were calculated based on the mean and standard deviation of their ratings for that particular participant. The mean standard score (z-score) between the two listeners was calculated for each stimulus, and then this value was transformed to its value in a normal cumulative distribution. This last transformation was performed to ensure that the distribution of vowel ratings would center on a non-zero value.

The optimal (i.e. target) formants for each vowel were calculated as a weighted average of the formants actually produced, with the vowel ratings described above serving as the weighting factors. For example, to calculate the target F1 value for the vowel [ɪ] produced in isolation, the sum of the product of each F1 value and its corresponding perceptual goodness rating was divided by the sum of the perceptual goodness ratings alone. The formant values of vowels that had very poor perceptual goodness ratings (i.e. close to zero) counted minimally towards the weighted average, while the formants of better rated vowels contributed more, proportionally. Vowel targets were calculated separately for vowels produced in the four syllable contexts based on production in the unconstrained condition.

Vowel targeting analysis

Vowel targeting was assessed by determining the Euclidean distance (ED, equation 5.2.1) between the produced vowel in F1/F2 space and the target vowel as defined above. Euclidean distance was computed for each stimulus, and the mean ED by vowel, syllable, and bite block condition will serve as a measure of vowel targeting for vowel production in each of those conditions.

$$\sqrt{\Delta F1^2 + \Delta F2^2} \qquad \text{(equation 5.2.1)}$$

Vowel distinctiveness analysis

Distinctiveness of vowels produced in different vowel categories was assessed using a measure termed the "acoustic distance ratio" (ADR). The ADR is conceptualized as the ratio of the acoustic distance between two categories to acoustic variance within those vowel categories. Specifically, the numerator of the ratio is the Euclidean distance between the mean formant values of two adjacent vowel categories and the denominator is the average of the mean within category Euclidean distances for those two categories. The acoustic distance ratio was calculated for the [ɪ]/[ɛ] distinction and for the [ɛ]/[æ] distinction. Large ADR values indicate that the acoustic distance between vowel categories is large relative to the within category variance (i.e. the vowels are very distinctive), while ADR values of 1.0 indicate that the distance between vowels is equaled by the variation within the category, and values less than one indicate that the variance within categories is greater than the variance between the categories.

Vowel analysis for different conditions

Analysis of vowel production proceeded first by examining vowel production in unconstrained production, followed by analysis of production in bite block speaking conditions, and production in different word length conditions. Each of these analyses included perceptual goodness ratings of vowels, description of mean vowel formants, as well as vowel targeting and acoustic distinctiveness analyses.

Chapter 5.3

Experiment 2: Vowel perception

Perception for the vowels [ɪ], [ɛ], and [æ] was tested in /hVd/ context using standard categorical perception procedures, including vowel identification and same/different vowel discrimination.

Experiment 2a: Vowel identification

Stimuli

Nineteen /hVd/ stimuli on a continuum ranging from "hid" to "head" to "head" were re-synthesized from a single production of the word "hid" by the author. The method of re-synthesis is based on the source-filter theory of speech production and was accomplished using Praat (Boersma & Weenink, 2005).

The procedure for source-filter synthesis entails the extraction of "source" and "filter" characteristics from a recorded speech sample, using linear predictive coding (LPC). The source signal includes the glottal volume-velocity source and radiation characteristics at the lips, while the filter represents signal characteristics attributed to resonance cavities in the vocal tract, i.e. formant frequencies. The "filter" is created by using LPC to estimate the frequencies of the first five vocal tract resonances. The "source" is created by applying an inverse filtering procedure using the LPC-determined “filter” to the original sound recording that effectively damps or cancels the signal characteristics resulting from vocal tract resonances. The values of the formant frequencies in the “filter” then are custom-modified to reflect the desired stimulus characteristics (e.g. lowering F1 to create a “higher” vowel). The modified filter is applied to the original source, thus creating a new sound with resonance characteristics specified by the experimenter.

Fundamental frequency for the original word “hid” spoken by the author, on which the source signal was based, ranged from 135.9 Hz at the first glottal pulse to 127.1 Hz at the final glottal pulse, with an average value of 130.0 Hz. This is comparable to the average of fundamental frequencies reported by Syrdal (1985) for [ɪ], [ɛ], and [æ] produced by men, namely 129.6 Hz. Vowel duration for the original word “hid” was 201.4 milliseconds, as measured from the point at which intensity fell 10 dB below the maximum value of 77 dB. This duration is comparable to the average durational value of the vowel [ɛ] in syllable context, as reported by Peterson and Lehiste (1960).

Steady-state formant values for the endpoint vowels [ɪ], [ɛ], and [æ] were derived from average values of formants 1-4 for males as reported by Syrdal (1985), with formant 5 held constant at 4500 Hz for all vowels (table 5.3.1). The hid-to-head continuum was created by varying formants 1-4 in equal-Bark spaced intervals based on the endpoint values for [ɪ] and [ɛ] and the head-to-had continuum varied between endpoint formant values for [ɛ] and [æ]. The formant frequencies (f) were converted to Bark equivalents (z) using the formula described by Traunmüller (1990)

$$z = \frac{26.81 f}{1960 + f} - 0.53 \quad \text{(for } f > 200 \text{ Hz).} \quad \text{(Equation 5.3.1)}$$

Intermediate formant patterns were created with equal-Bark steps for F1, F2, F3, and F4. For example, since the difference between Bark values of F1 for [ɪ] (stimulus #4) and [ɛ] (stimulus #10) is 0.59 Bark (i.e. 5.07 Bark - 4.48 Bark), the F1 difference between the stimuli is approximately 0.10 Bark. Bark values were converted back to frequency values for speech synthesis using the inverse of equation 1 (Traunmüller, 1990):

$$f = \frac{1960(z + 0.53)}{26.28 - z} \quad \text{(for } f > 200 \text{ Hz).} \qquad \text{(Equation 5.3.2)}$$

Table 5.3.1

Target formant frequency values for a continuum of 19 synthetic vowels

	Stimulus #	F1	F2	F3	F4
	1	417	1883	2544	3396
	2	428	1876	2542	3410
	3	439	1869	2541	3424
ɪ	**4**	450	1862	2539	3438
	5	461	1855	2537	3452
	6	472	1848	2536	3466
	7	484	1841	2534	3481
	8	495	1834	2533	3495
	9	506	1827	2531	3509
ɛ	**10**	518	1820	2530	3524
	11	547	1810	2514	3522
	12	577	1799	2498	3520
	13	608	1789	2482	3517
	14	639	1779	2466	3515
	15	671	1769	2451	3513
æ	**16**	704	1759	2435	3511
	17	738	1749	2420	3509
	18	772	1739	2404	3507
	19	808	1729	2389	3505

Note. F0= 130 Hz.; F5= 4500

Formant contours for the synthetic continua were custom-modified from the original formant contour using Microsoft Excel spreadsheets. Formants 2-5 were held constant for the duration of the production, while Formant 1 was constant for the initial 200 ms of vowel duration and decreased linearly to 375 Hz over the final 50 ms of vowel duration to simulate oral closure (see figure 5.3.1). Bandwidth for F1 was set at 300 Hz for the /h/ portion and 80 Hz for the remainder of the signal (Hillenbrand and Nearey, 1999) and bandwidths for F2, F3, F4, and F5 were held constant for the duration of the signal at 90, 150, 350, and 500 Hz, respectively.

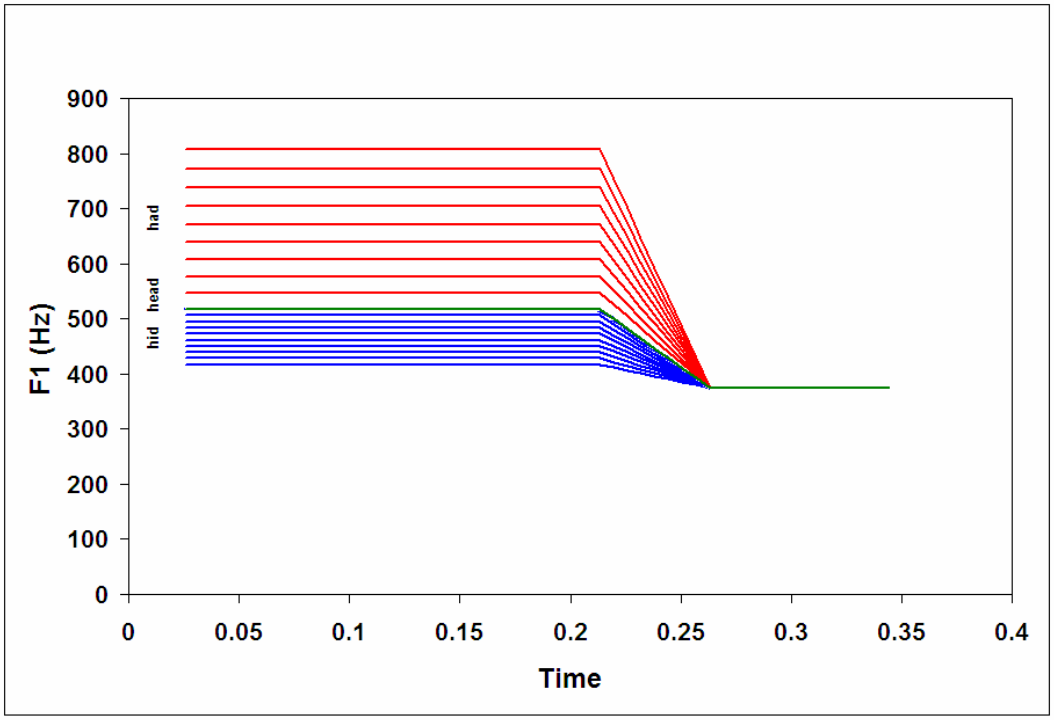


Figure 5.3.1. First formant contours of a continuum of front vowels synthesized in /hVd/ context. F1 is constant for all vowels for 200 ms and linearly decreases for 50 ms to 375 Hz in order to simulate closure.

The modified formant contours were imported to Praat as text files, converted into formant objects (i.e. "filters"), and combined with the "source" signal derived from the original signal, thus creating a new word with experimenter-specified formant values. In the process of resynthesis, some distortion of the initial /h/ and the final /d/ occurred, and the intensity of the vowel portion was not equivalent with the initial signal. To remedy these side effects of the resynthesis process, the vowel portion of the resynthesized signal was modified to equalize the root-mean-square value with the same portion of the initial signal, and the /h/ and /d/ portions of the initial signal were spliced with the resynthesized vowel to create a more natural speech sound (Hillenbrand & Nearey, 1999).

Vowel synthesis rarely yields formants exactly to the desired specifications, due to interactions between vowel formants and harmonics in the source signal. Formant frequencies of resynthesized signals were measured for the steady-state portion of the signal and compared to the targeted formant values, as shown in figure 5.3.2. While some variations from the target formant values occurred, the values of measured formants remain in the same order as intended. Measured formants deviated on average 1.1% from the target formant value, with a range of 0.8% to 3.3%.

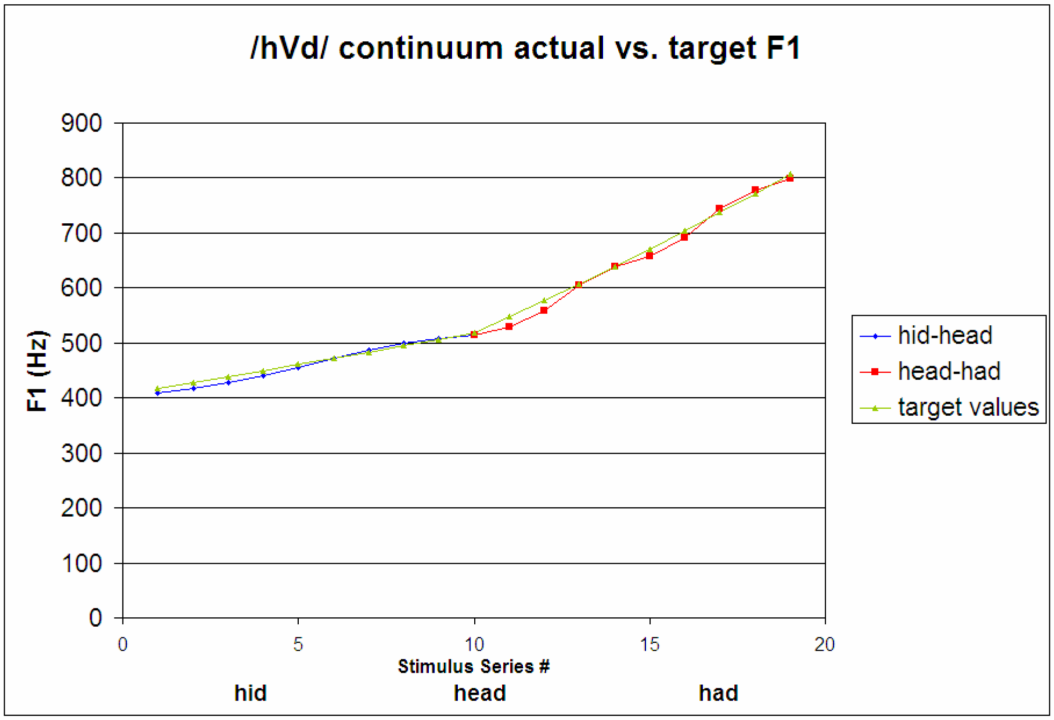


Figure 5.3.2. Actual and targeted first formant values of a continuum of vowels in /hVd/ context. Formant values of vowels measured from a continuum of synthesized stimuli are plotted against the targeted frequency values, which were designed to vary in equal-Bark steps from hid to head and from head to had.

Procedure

Stimuli were presented to participants and responses recorded using Alvin (Hillenbrand & Gayvert, 2005). Vowel identification was assessed separately for the two continua, with stimuli 1-13 presented for the hid-head continuum, and stimuli 10-19 presented for the head-had continuum. Participants listened to each stimulus and indicated the word they perceived. Responses were indicated by pointing to the word on the screen corresponding to the perceived word, or if they were able, by manipulating the computer mouse to the desired response. Only two response choices were given per continuum, i.e. the word “had” was not a response choice when listening to words on the hid-head continuum. Participants were instructed to choose the word response that sounded most like the presented stimulus and to guess if they were not certain. Each stimulus was presented 10 times in random order, yielding a total of 130 responses for the hid-head continuum and 100 responses for the head-had continuum. A training trial was administered in which participants first listened to each stimulus on the continuum without responding, and then listened to each endpoint stimulus twice, indicating the word they perceived by selecting the corresponding word on the computer screen. Participants were required to answer correctly to 3 of 4 stimuli to continue in the study. If they were not able to answer correctly at first, the experimenter re-trained them to the task and presented the practice items again.

Data analysis

Vowel identification curves were plotted with the F1 formant as the independent variable and percent of stimuli identified as [ɪ], [ɛ] or [æ] as the dependent measure. Participant data were fit to best fit logistic growth curves using the equation:

$$y = \frac{e^{(ax+b)}}{1+e^{(ax+b)}} \qquad \text{(Equation 5.3.4)}$$

The coefficients a and b were determined by solving the equations using a least squares criterion, i.e. the sum of squared deviations between the actual data and the data predicted by the model were minimized. The coefficient a represents the slope, with higher values representing steeper slopes, while the coefficient b is a determining factor for where the category boundary is located. The boundary at which 50% of stimuli are identified as one vowel and the other 50% as the adjacent vowel was calculated by dividing the equation slope by the intercept.

Consistency of vowel identification was assessed using the goodness of fit of the best fit curve, represented by the sum of squared deviations (SSD) of the actual data from the best fit curve. Low values of SSD indicated a close fit between the curves and therefore consistent vowel identification performance and high SSD values suggested less consistent identification.

Experiment 2b: Vowel discrimination

Stimuli

Five additional series of stimuli were synthesized to assess vowel discrimination ability. Each of the five series of stimuli includes a base vowel and four vowels that vary from the base vowel in F1 increments of 30, 60, 90, and 120 Hz. The base vowels for the five series represent within- and between- category vowels for [ɪ], [ɛ], and [æ]. This procedure, using a subset of stimuli on a continuum for more detailed discrimination testing, has precedent in previous studies of categorical perception (Pisoni, 1973; Repp, Healy, & Crowder, 1979). The formant frequencies from stimuli 4, 7, 10, 13, and 16 from Experiment 2a (table 5.3.1) were used to represent vowels that were found in pilot testing to be 1) definitely [ɪ], 2) between [ɪ] and [ɛ], 3) definitely [ɛ], 4) between [ɛ] and [æ], and 5) definitely [æ].

The use of four step sizes was designed to capture a range of stimulus discriminability, such that participants are able to a) with large step sizes, demonstrate the ability to perceive the difference between stimuli varying in F1 and b) with smaller step sizes, show a differential ability to perceive distinctions when the stimuli are clearly between categories compared to when they are clearly within a vowel category.

Previous research has shown that the minimal discriminable difference (viz. difference limen (DL)) in vowel formants varies based on several parameters, including formant frequency value, phonetic context, and age of listener. For example, Kewley-Port and colleagues have found that two variants of /ɪ/ can be discriminated more easily than /æ/, i.e. with smaller frequency difference limens (e.g. Kewley-Port & Watson, 1994; Kewley-Port & Zheng, 1999). In isolated vowels, highly trained listeners could hear the difference between variants of /ɪ/ with F1 varying by only 13 Hz, while variants of /æ/ could be discriminated when the difference was 22 Hz (Kewley-Port & Watson, 1994). Under more ordinary listening conditions, i.e. not highly trained, listeners required 32 Hz differences in F1 to discriminate /ɪ/ vs. 55 Hz for /æ/ (Kewley-Port & Zheng, 1999). Comparisons of difference limens for vowels in varying phonetic contexts revealed that vowels were more easily discriminated in isolation than in syllable context (e.g. average DL= 49 Hz in isolation vs. 68 Hz in /bVd/ context; Kewley-Port & Zheng, 1999). Finally, comparisons of vowel difference limens in younger and older adults have shown that older listeners require greater F1 differences than younger listeners to discriminate vowels in isolation (Coughlin, Kewley-Port & Humes, 1998). Under minimal uncertainty listening conditions, average DLs for /ɪ/ were 41 Hz for older listeners vs. 34 Hz for youngers; for /æ/ average DLs were 92 Hz for the older group vs. 30 Hz for the younger group.

On the basis of these previous studies of vowel discrimination in normal listeners, and in consideration of the fact that listeners with brain damage might perform less well with vowel discrimination (e.g. Keller et al., 1982), it was determined that increment values of 30, 60, 90, and 120 Hz would prevent ceiling and floor effects by enabling participants to discriminate at least some vowels. Further, the different increment values provides for potential differences in discriminability of high-, mid-, and low-front vowels.

For each stimulus series, the base vowel was modified to create three “different” vowels by adding 30, 60, 90, and 120 Hertz to the first formant value. First formant values for the discrimination stimuli are listed in table 5.3.2 and formants 2 through 5 were identical to those listed in table 5.1 for each stimulus series.

Since the purpose of testing vowel discrimination is to assess the ability of participants to hear small distinctions in spectral cues, it was important to ensure a high degree of precision for the formant values of the discrimination stimuli series. While the first formant values for the base/anchor stimuli (from the identification continua in experiment 2a) varied somewhat from the original target frequencies, the formant values for each series of stimuli varying in 30, 60, 90, and 120 Hz were carefully controlled. To achieve the precision desired, a trial-and-error procedure was employed by incrementally changing the target formant values and measuring the resulting formants until the measured formant was within 0.5 Hz of the desired value.

Pilot results of the discrimination task revealed that discriminability of the [æ] base stimulus from comparison stimuli was very poor, even at the 120 Hz step size. A whole spectrum analysis of the stimuli was undertaken to ascertain the overall spectral similarities and differences between the stimuli as a potential explanations for this finding. A fast fourier transform (FFT) analysis of each stimulus was performed, and the long term average (LTA) spectrum obtained with bandwidth of 10 Hz in the range of 0 to 5000 Hz. Each base stimulus was compared to the different step size stimuli (30, 60, 90, 120 Hz) by taking the sum of squared differences of the spectral power for each frequency bin from the LTA analysis. The sum of squared differences for each stimulus pair (e.g. definitely "had" vs. definitely "had" + 120 Hz F1) represents an overall spectral difference metric between the two stimuli, apart from the controlled F1 difference. This analysis indicated that the [æ] base stimulus differed less from its comparison stimuli than any other base stimulus, with an average spectral difference value of 27.2 dB, compared to values of 54.8, 52.8, 56.8, and 37.9 for the definitely [ɪ], [ɪ]/[ɛ] boundary, definitely [ɛ], and [ɛ]/[æ] boundary series. In sum, the [æ] base stimulus was less spectrally different from its comparison stimuli, thus clarifying why pilot participants had more difficulty discriminating these stimuli for all step sizes. Although greater uniformity across stimulus series would have been preferable, this is not fatal for the present study, as a fair comparison of AOS discrimination performance was made to NBD control participants.

Table 5.3.2
First formant values for vowel discrimination

	Stim #	Base stimulus		+30 Hz	+60 Hz	+90 Hz	+120 Hz
		intended	actual				
definitely [ɪ]	**4**	450.0	440.6	470.4	500.7	531.0	560.6
between [ɪ] and [ɛ]	**7**	483.5	486.1	515.8	546.1	576.3	606.2
definitely [ɛ]	**10**	518.0	514.6	544.7	574.8	604.7	635.0
between [ɛ] and [æ]	**13**	607.6	604.8	635.1	664.7	694.9	724.8
definitely [æ]	**16**	704.0	691.7	721.4	751.9	782.0	811.9

Procedure

Discrimination of vowels was assessed using an AX (i.e. same-different) methodology in four incremental phases (stages), beginning with the easiest-to-distinguish pairs (base stimulus vs. base + 120 Hz) and ending with the most difficult to distinguish pairs (base stimulus vs. base + 30 Hz). This approach was chosen so that if an individual participant was not able to tolerate testing of distinctions that they are not able to discriminate, then testing might be discontinued without abandoning data from previous, less difficult testing series. Progression to the next most difficult testing phase was contingent on discrimination accuracy from the previous phase.

In each phase, each of five base stimuli (viz. #4, 7, 10, 13, 16) was paired with the given comparison stimulus (i.e. varying by 30, 60, 90, or 120 Hz) eight times. The comparisons were counterbalanced for order of presentation such that in half of the presentations the base stimulus occurred first with the different stimulus presented second and in half the different stimulus was presented first followed by the base stimulus. Half of the stimuli presented to the participant were the same and half were different. For each phase, 5 base stimuli compared to the different stimulus 8 times and to themselves 8 times yielded a total of 80 presentations per phase.

Vowel pairs were randomized and presented to participants and responses recorded using Alvin (Hillenbrand & Gayvert, 2005). Participants listened to each pair of stimuli and indicated whether the stimuli were the same or different. Responses were indicated by pointing to the word “same” or “different” on the screen. Participants were instructed to decide whether the stimuli sound the same or different and to guess if they were not certain. Each pair of stimuli was presented 8 times, counterbalanced for order, with 8 control trials where the presented stimuli were identical (yielding a total of 80 stimuli per phase). Participants were informed that half of the trials are the same and half are different. A training trial was given in which participants first listened to obviously different stimulus pairs (i.e. stimuli that were at least 6 steps apart on the continuum). Participants were required to answer same or different correctly in at least 6 of 8 trials to participate in the task. If they were initially unable to complete the task, the experimenter re-trained them and re-administered the practice trial.

Data analysis

Vowel discrimination was analyzed according to percent accuracy of discrimination (i.e. correct determination of same vs. different). Effects of F1 step size (i.e. 30, 60, 90, 120 Hz differences from the base stimulus) and position in the continuum (i.e. [ɪ], [ɪ]/[ɛ] boundary, [ɛ], [ɛ]/[æ] boundary, and [æ]) were analyzed in addition to group differences.

Chapter 5.4

Experiment 3: Rhyme Processing

Three rhyme processing tasks were included to assess higher level phonemic processing of vowels and their relationship to consonants in apraxia of speech. The first task required participants to generate words that rhyme with a target word. The second task assessed the ability to judge whether two auditorily-presented words rhyme or not. The third task tested rhyme judgment for written words.

Experiment 3a: Rhyme Judgment

Stimuli

The stimuli for all rhyme processing tasks were structured around the three vowels of focus in this study, [ɪ], [ɛ], and [æ], as well as the additional vowels [u] and [a]. The five words "kick", "shed", "cap", "suit", and "lock" served as the target words for rhyme generation.

Procedure

Participants were told that they would be asked to produce some words that rhymed with a target word given them by the experimenter. Prior to beginning the task, rhyming words were defined as words that sound very much the same. Further explanation was given to indicate that the vowels and the final consonants are the same in rhyming words, and that only the beginning sounds differ. Following this explanation, a target word containing a vowel not tested in the experimental stimuli was presented to participants to practice generating rhyming words. All participants were able to generate two or more rhymes for the practice target word, suggesting that they comprehended the task.

Participants were allowed 30 seconds for each word target to generate as many rhyming words as possible. On occasion, individuals with AOS would wait for several seconds and repeat the word to clarify before beginning. When this occurred, a full 30 seconds from the clarification was allowed to give them the full time to respond. The investigator wrote down each word response as it was produced.

Rhyme responses were scored as being a) rhyming words, b) rhyming non-words, c) a repetition of the target, d) an already produced rhyme, e) a rhyming proper name or slang word, and f) a non-rhyme. For the purposes of analysis, all rhyming real words, including proper names and slang but not repetitions of previously produced words, were considered acceptable rhyming responses.

Experiment 3b: Auditory rhyme judgment

Stimuli

Each of the five vowels used in the rhyme generation task were included in four sets of word pairs, for a total of 20 auditory rhyme judgment pairs. For each vowel, two rhyming word pairs were created (e.g. rag-lag, hat-vat) as well as two non-rhyming word pairs, including one that differs only in the final consonant (i.e. a "half-rhyme", e.g. rib-hid), and one that differs in the vowel but has the same final consonant (e.g. pack-luck).

Procedure

Participants were told that they would listen to a number of word pairs and decide if they rhymed or not. They were briefly reminded of the definition of rhyming given before the rhyme generation task. Recordings of the word pairs were presented to the participant using Alvin (Hillenbrand & Gayvert, 2005) and responses recorded using the same software. Analysis of the responses was determined on the basis of correct yes and no responses (i.e. true positives and negatives) and incorrect yes and no responses (i.e.

false positives and negatives). Accuracy was analyzed separately for actual rhymes, half rhymes, and non-rhymes.

Experiment 3c: Written rhyme judgment

Stimuli

Four sets of written word pairs were created for each of the five vowels, including two pairs that rhyme and two that do not. Of the rhyming pairs, one half had similar orthography and are described as “obvious rhymes” (e.g. bat-cat), while the other half rhyme but have dissimilar orthography, described as “foil rhymes” (e.g. dead-bed). Similarly, for the nonrhyming pairs, one half were “obvious nonrhymes” with clearly different orthography (e.g. suit-cop) and the other half were “foil nonrhymes”, with similar orthography (e.g. laugh-rough).

Procedure

Participants were asked to read the word pairs silently and decide if they would rhyme or not if they were to say them aloud. The written pairs were displayed on a computer screen, using Alvin for presentation and recording of responses. If participants were observed to be trying to say the words aloud, they were reminded that they should read the words silently. Analysis of responses was similar to that for the auditory rhyme judgment task, including true and false positive and negative evaluations for each response. Response accuracy was examined separately for the obvious rhymes and nonrhymes as well as for the foils.

Chapter 5.5

Cross domain analysis

The study was designed to examine vowel targeting and perception, and additionally the relationship between abilities and deficits in the two processing domains. Since both production and perception tasks were divided along the front vowel continuum, it was possible to compare the ability to produce [ɪ] and [ɛ] distinctively with the ability to perceive the distinction between the same vowels. In particular, small subject linear regression analyses were performed with perceptual sum of squared deviations as the independent measure and the acoustic distance ratios as the dependent measure. This analysis was made for the two vowel pair distinctions separately and for perceptual and production measures averaged across the two vowel distinctions.

In addition to the perception-production relationship, several other cross participant linear regression analyses were performed to determine the relationships between vowel distinctiveness and assessment battery results (e.g. apraxia subtest scores), between identification performance and auditory comprehension scores, and between perceptual identification and rhyme judgment results.

CHAPTER 6: RESULTS

The purpose of this study was to examine articulatory targeting of front vowels in adults with acquired apraxia of speech (AOS) and the relationship between targeting and auditory-perceptual processing abilities for the same vowels. Vowel targeting was examined in several conditions, including variations in production mode (i.e. normal unconstrained production vs. small- and large- bite block production) and in stimulus length (i.e. vowel produced in isolation or in one-, two-, or three-syllable words). Vowel perception was examined using standard categorical perception tasks, including identification of vowels along a continuum and same-different discrimination among stimuli varying systematically in the first formant frequency. Phonemic processing of vowels was also assessed using rhyme production and judgment tasks. Non-brain-damaged (NBD) control participants were matched to the AOS participants by gender, regional dialect, and approximate age. To the extent possible, reported results focus on the performance of apraxic participants, although the NBD results are often presented alongside to provide perspective.

Vowel production results will be presented first, followed by the perception and rhyme findings, and finally analyses of the relationship between production and perception abilities.

Chapter 6.1
Vowel production in apraxia of speech

Vowel production was assessed via acoustic measures of formant frequencies, perceptual goodness ratings, Euclidean distances in vowel space between productions and vowel targets, and a measure of acoustic distinctiveness between different vowels. Vowel production results will be subdivided into sections addressing a) normal, unconstrained vowel production, b) the effects of bite block constraints, and c) the effects of stimulus length on production.

Normal unconstrained vowel production

Perceptual goodness of vowels

Two independent raters (graduate students in speech-language pathology) listened to the vowels produced by the participants and rated the perceptual goodness of each vowel. Initial vowels were presented along with a written cue indicating the target vowel, and listeners were asked to rate the goodness of the vowel using a direct magnitude estimation procedure (scale from 0 to 1000).

Average vowel goodness ratings for all participants are shown in figure 6.1.1, indicating better vowel productions for the NBD participants than the AOS group, with the exception of the A2-N2 pair. Vowel goodness was very similar for A4-N4 and A5-N5, and more prominent differences were found between A1 and N1 and A3 and N3. Vowel goodness differed by vowel category, with [ɪ] rated higher than [ɛ] or [æ], as shown in figure 6.1.2.

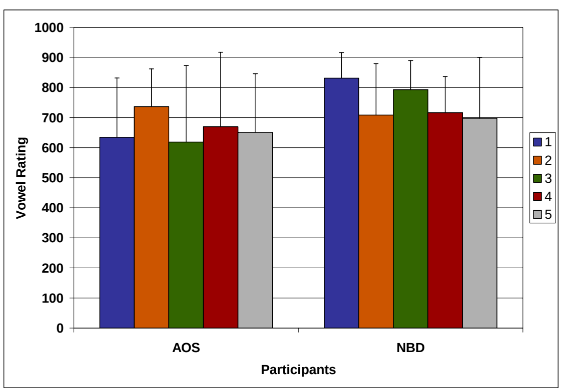


Figure 6.1.1. Individual vowel rating results for unconstrained production.

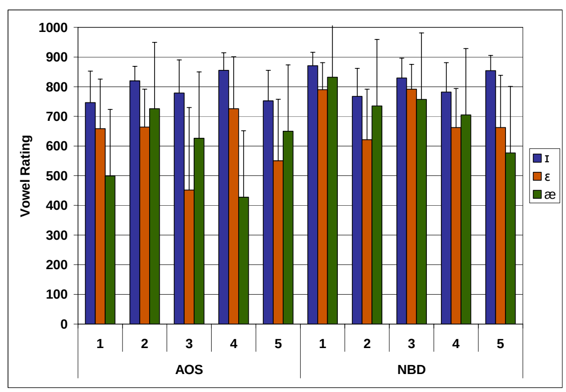


Figure 6.1.2. Individual vowel rating results for the vowels [ɪ], [ɛ], and [æ] in unconstrained production.

F1/F2 vowel space

The placement of vowels in the vowel space in relation to vowel targets is shown in figures 6.1.3(a)-(e) for each of the AOS participants and their matched pair. Mean and standard deviation values of the first and second formants measured at the vowel nucleus are plotted in Bark-transformed frequencies. Vowel targets were determined individually for each participant as the weighted average of produced formants, with perceptual goodness ratings serving as the weightings. The axes of the graph are oriented to match the traditional presentation of the vowel space, with F2 increasing from right to left on the abscissa and F1 increasing from top to bottom on the ordinate, such that high front vowels appear in the top left corner of the graph and lower back vowels appear in the bottom right corner.

Inspection of the vowel spaces indicates an adequate use of the vowel space for most apraxic participants as well as their NBD pairs. Mean formant values for [ɪ], [ɛ], and [æ] are generally well separated, with standard deviation error bars showing a lack of overlap between the different vowels. The vowel space of A1 is a notable exception, with mean (F2, F1) coordinates very close together and large error bars indicating overlap between [ɛ] and [æ]. Vowels of other apraxic participants, although apparently well-differentiated, are closer to neighboring vowels with greater deviations than in normal participants. Other variations include lower F2 values for male speakers in both groups (e.g. A3, N3, A5, and N5), a difference that does not appear to affect vowel space differentiation.

Comparison of the mean vowel formants with the target formant values indicates that, at least in normal unconstrained production, vowel formants are produced very close to the optimal formants for those vowels. In figures 6.1.3 (a)-(e) the markers for mean formant values mostly overlap the markers for the vowel targets, at least partially. Some exceptions include N1's [æ] productions (higher F2 values than the target), A3's [ɛ] production (higher F2, lower F1), A4's [æ] (higher F2, lower F1), and N5's [ɛ] (higher F2, lower F1). All of these differences are minimal and do not demonstrate impaired use of the vowel space in apraxic speakers compared to NBD participants.

Vowel targeting

The vowel space data show that speakers with AOS are using the vowel space in a similar manner as NBD participants, with vowel formants in comparable ranges and mean formants very close to the vowel targets. One of the hallmark characteristics of apraxic speech, however, is variability across multiple productions. Although average formants were generally on target, individual repetitions of stimuli by apraxic speakers varied in their acoustic proximity to the target. Vowel targeting was quantified by

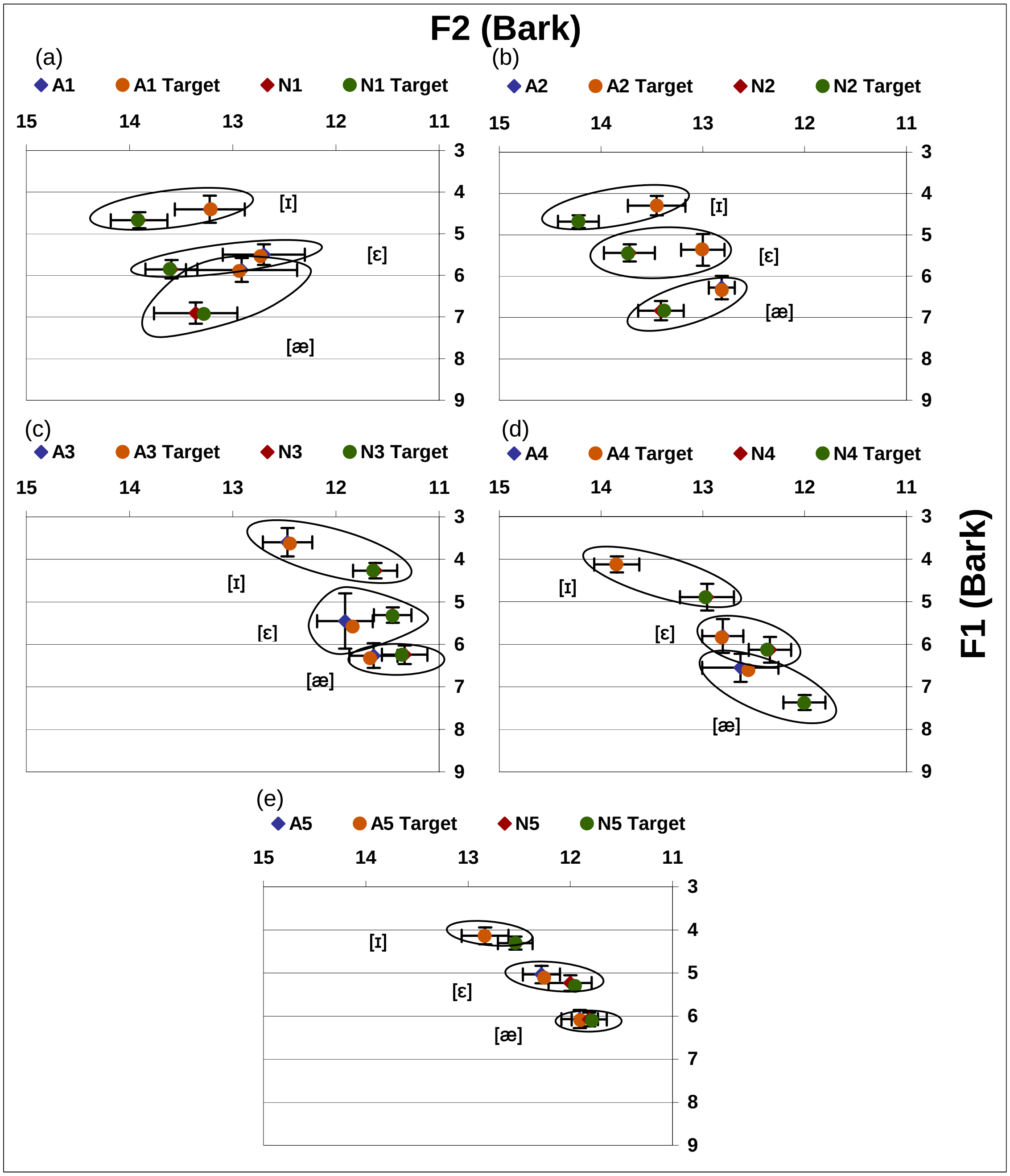


Figure 6.1.3. F1 x F2 vowel spaces in unconstrained speech production for each apraxic-normal participant pair. Mean produced vowel formants are plotted with standard deviation error bars as well as formant target values. Formants are displayed in Bark-transformed values.

computing the Euclidean distance (ED, viz. straight line distance in F1/F2 space) between each vowel production and the vowel target.

Overall results by group indicated that apraxic speakers produced formants further away from the vowel target than the control group (ED_{AOS} = 0.35 Bark vs. ED_{NBD}= 0.27 Bark). Mean Euclidean distances for each participant are shown in figure 6.1.4 and results subdivided by vowel category in figure 6.1.5. Each apraxic speaker had a greater ED compared to their NBD pair, with the greatest differences for A1 and A3. No clear effect was found of vowel category on targeting as measured by ED (figure 9). Participants A1, A4, and N1 had highest EDs for the vowel [æ], A2 and N5 had highest ED for [ɛ], and N4 had highest ED for [ɪ].

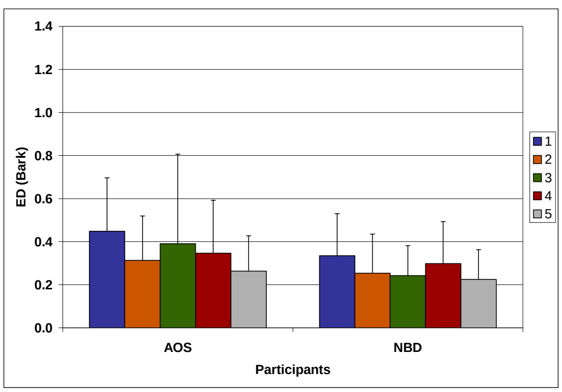


Figure 6.1.4. Euclidean distance from vowel targets for AOS and NBD participants in unconstrained production.

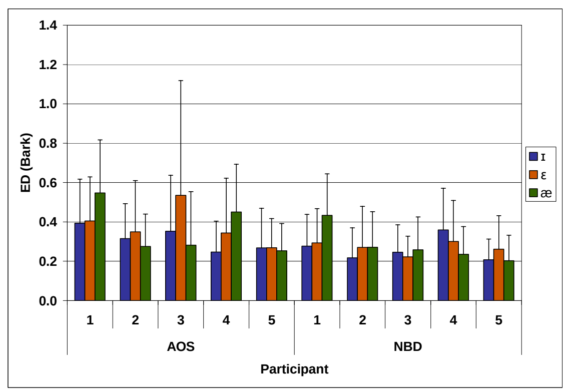


Figure 6.1.5. Euclidean distance from vowel targets for the vowels [ɪ], [ɛ], and [æ] for AOS and NBD participants in unconstrained production.

Vowel distinctiveness

The vowel space results indicated that most apraxic participants use the vowel space adequately by producing the front vowels [ɪ], [ɛ] and [æ] with distinctive formants, albeit with somewhat greater variability among repeated productions. The vowel targeting results also reveal greater variance in the apraxic group, demonstrated by greater acoustic distance from production to target vowel formants. A further analysis was undertaken to quantitatively assess the differentiation of the vowel space. The metric employed, the acoustic distance ratio (ADR), consists of a ratio of the Euclidean distance between mean formant values of adjacent categories to the mean Euclidean distances of productions within those categories. An ADR value of 1.0 indicates that the acoustic distance between two vowel categories (e.g. [ɪ] and [ɛ]) is equaled by the mean ED of repeated productions of [ɪ] and [ɛ] from their respective targets (i.e. within category variance). Larger values of ADR indicate greater distinctiveness between two vowels, while values less than 1.0 signify overlap between the vowels.

Group results indicate lower ADRs for the apraxic speakers compared to the NBD participants (ADR_{AOS}= 3.50, ADR_{NBD}= 4.52). Most of the difference between groups is accounted for by lack of differentiation between [ɛ] and [æ] for the AOS speakers. For example, the mean ADRs for the [ɪ]/[ɛ] distinction are very similar for the two speaker groups (ADR_{AOS}= 4.47 vs. ADR_{NBD}= 4.69) while [ɛ] and [æ] are much less distinctive for AOS speakers (ADR_{AOS}= 2.54 vs. ADR_{NBD}= 4.35).

Comparison of mean ADR results for all participants and by vowel pair distinction are shown in figures 6.1.6 and 6.1.7. All apraxic participants had lower ADR values than their matched pair, with most pronounced differences for A1 and A2 (figure 6.1.6). Examination of ADR results by vowel pair shows that AOS speakers had greater differentiation for the [ɪ]/[ɛ] distinction than for [ɛ]/[æ], particularly for A1, A3, and A4 (figure 6.7). Differences by vowel pair for the normal group were less prominent, with [ɪ]/[ɛ] slightly more distinct than [ɛ]/[æ] for N1, N3, and N5 and [ɛ]/[æ] more distinct for N2.

The vowel space is less differentiated for the apraxic speakers than their matched pairs. Notably, however, all mean ADR values in normal unconstrained speech production were above 1.0, indicating that vowels are generally being produced distinctively in this speaking condition.

Summary

Vowel production in normal speaking conditions is not greatly different in speakers with AOS than in non-brain-damaged speakers. Perceptual goodness ratings suggest that apraxic vowels are slightly less good than vowels produced by controls. Apraxic speakers produced repetitions of the same vowels more variably and acoustically more distant from the perceptually-derived vowel targets than their matched pairs. Nevertheless, the vowel space of speakers with AOS appears very similar to NBD controls, and the measure of acoustic differentiation suggests that in normal conditions apraxic speakers are producing different vowels distinctly, if not as distinctly as their unimpaired counterparts.

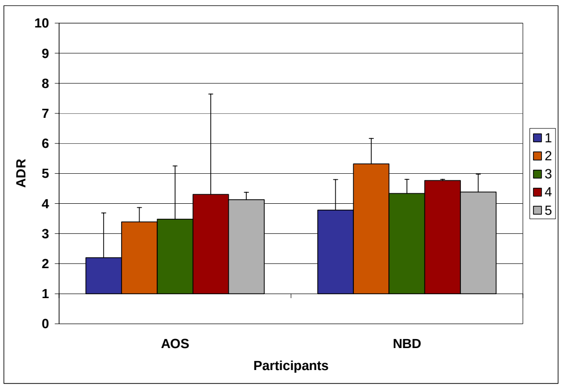


Figure 6.1.6. Acoustic distance ratio for AOS and NBD participants in unconstrained production.

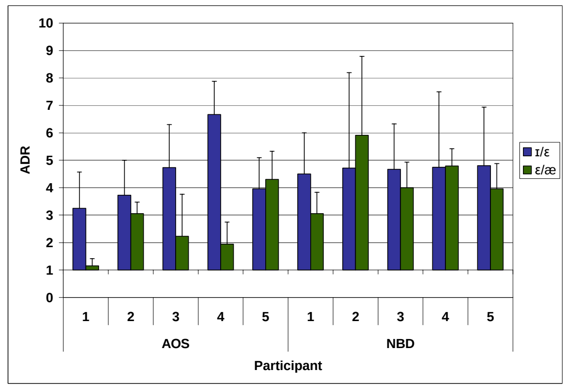


Figure 6.1.7. Individual acoustic distance ratio results in unconstrained production for the adjacent vowel pairs [ɪ]/[ɛ] and [ɛ]/[æ].

Bite block vowel production

The effect of bite block constraints on vowel production typically varies depending on the size of the bite block employed and the height of the targeted vowel. Placement of a small bite block during production of the high vowel [ɪ] or a large bite block for the low vowel [æ] are considered to be non-compensatory conditions, because the jaw is constrained to a position that is generally consistent with the desired positions for those vowels. Production of [ɪ] with a large bite block or [æ] with a small block is considered to be compensatory, because the speaker must adjust to a non-optimal jaw position to produce the targeted vowel. Due to the varying effects of constraints on different vowels, the bite block results will be examined individually by vowel.

Perceptual goodness of vowels

Average vowel goodness ratings for all participants in the three speaking conditions (NB= no block, SB= small block, LB= large block) are displayed in figure

6.1.8, and separately for the vowels [ɪ], [ɛ], and [æ] in figures 6.1.9-6.1.11. Vowel ratings for most participants are very similar across the three production conditions, with the exception of A1, N3, and A4, who showed clear patterns of decreased vowel ratings for small and large block conditions, and A2 who had lower vowel ratings for the small block condition only.

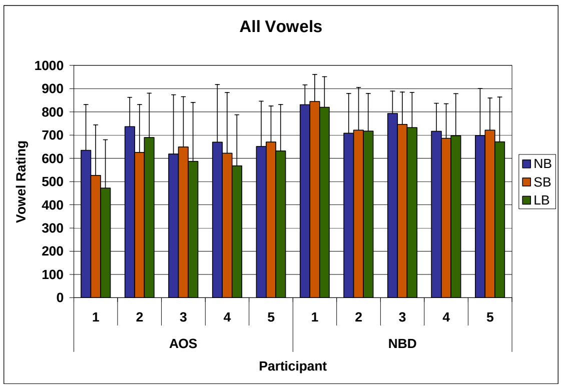


Figure 6.1.8. Vowel rating for all vowels in unconstrained and bite block conditions. Vowel ratings are displayed separately for no block (NB), small block (SB) and large block (LB) conditions.

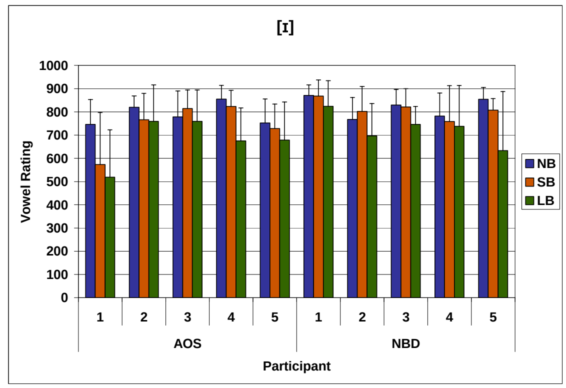


Figure 6.1.9. Vowel rating for [ɪ] in unconstrained and bite block conditions. Vowel ratings are displayed separately for no block (NB), small block (SB) and large block (LB) conditions.

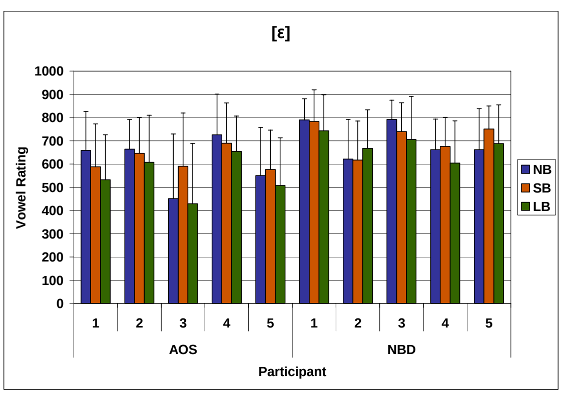


Figure 6.1.10. Vowel rating for [ɛ] in unconstrained and bite block conditions. Vowel ratings are displayed separately for no block (NB), small block (SB) and large block (LB) conditions.

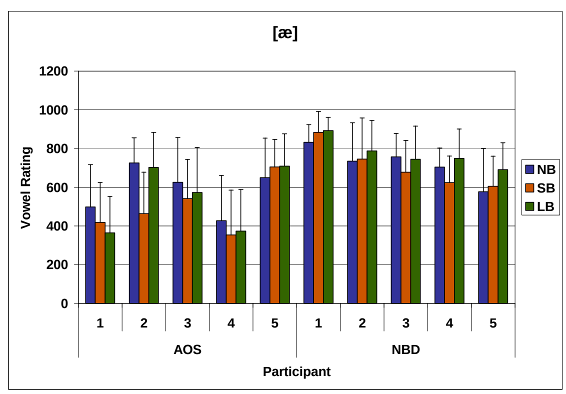


Figure 6.1.11. Vowel rating for [æ] in unconstrained and bite block conditions. Vowel ratings are displayed separately for no block (NB), small block (SB) and large block (LB) conditions.

Examined by individual vowel, expected compensatory effects on vowel goodness were found, including better ratings of [ɪ] in the small block than the large block condition (figure 6.1.9), and better ratings of [æ] in the large block than the small block condition (figure 6.1.11). The extent of these effects varied across participant, and the compensatory [æ] effect was not found for A1, but no apparent differences were seen between the apraxic and normal participants. Ratings of [ɛ] were better in small block than large block conditions for all participants except N2, whose large block [ɛ] productions were higher rated than small block or no block productions (figure 6.1.10).

F1/F2 space at vowel onset

Acoustic analysis of bite block speech has traditionally focused on formant measurement at the first measurable glottal pulse, in order to determine the extent of immediate compensation without the benefit of auditory or proprioceptive feedback. Vowel formant and targeting measures here will be examined at the first glottal pulse (i.e. vowel onset) and at the vowel nucleus, assessing both immediate and delayed compensation.

The vowel spaces at vowel onset for the five participant pairs are displayed in figures 6.1.12 (a)-(e), including mean formant values for the vowels [ɪ], [ɛ], and [æ] in the no block (NB), small block (SB), and large block (LB) conditions. The vowel plots suggest that many participants produced distinctive vowel formants at onset, although A1, A4, and N5 show patterns of overlap or near overlap between neighboring vowel categories. The vowel space of A1 at onset is compressed relative to N1, and while the formants show the expected patterns of higher F1 for [æ] compared to [ɛ] and higher F1 for [ɛ] compared to [ɪ], the separation between these vowels is much less than for most other participants. In contrast, A4 displays a clear pattern of overlap, with a lower F1 for [æ] in the small block condition than for [ɛ] in the no block condition; in this participant [ɛ] and [æ] are clearly not differentiated. For A5, formants of [ɛ] in the large block condition are nearly the same as those for [æ] in the no block condition, indicating lack of compensation for the large block for that vowel.

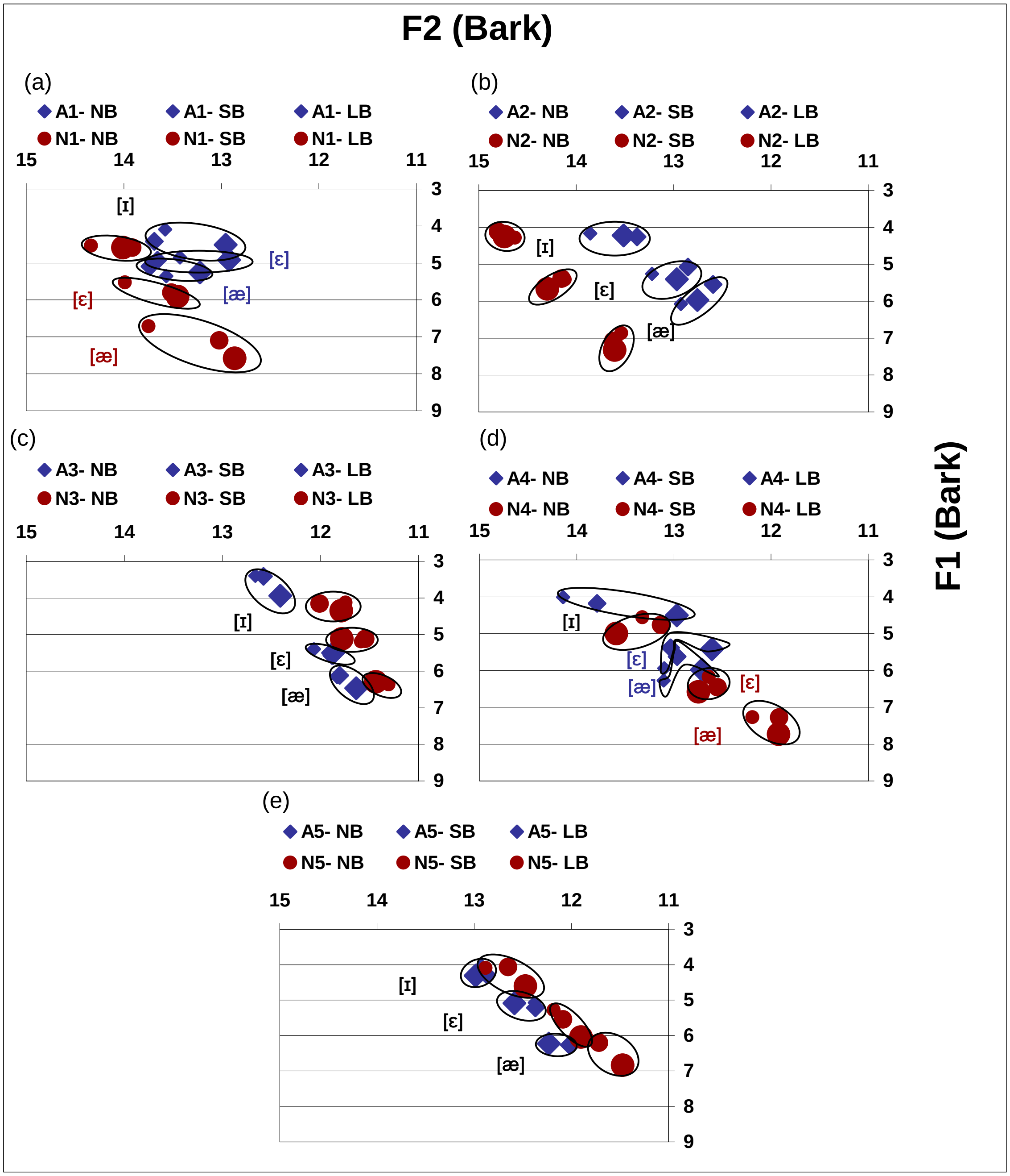


Figure 6.1.12. F1 x F2 vowel spaces for unconstrained and bite block speech production for each apraxic-normal participant pair at vowel onset. AOS formants are plotted as blue diamonds and NBD formants as red diamonds. Formant values for no block (NB), small block (SB), and large block (LB) conditions are plotted as small, medium, and large markers. Formants are displayed in Bark-transformed values.

Visual inspection of the mean formants at vowel onset indicates lack of compensation for the bite block for several participants. Placement of the large bite block resulted in higher F1 values (i.e. "lower" vowels) for [ɪ] production in all participants except for N2. The mean difference in F1 between the large block and no block conditions was +0.36 Bark for AOS participants (i.e. higher F1 for large block) and +0.24 Bark for NBD participants. NBD participants showed the same F1-raising effect for [ɛ] and [æ], with average F1 difference between LB and NB conditions of +0.24 and +0.49 Bark, respectively. The F1-raising effect of the large block on [ɛ] and [æ] production was seen for several of the AOS participants, but A4 had considerably lower F1 for these vowels in the large block condition. The AOS group mean differences between LB and NB conditions were -0.04 and -0.03 Bark for [ɛ] and [æ], indicating slightly lower F1 values for large bite block production of these vowels on average. The effect of the small bite block on vowel formants at onset was less pronounced than the large block, particularly for the NBD participants. The expected effect of the small bite block is a lowering of F1 formants for [ɛ] and [æ]. Mean F1 differences between the SB and NB conditions showed F1 lowering for [ɛ] and [æ] production in AOS speakers ($\Delta_{F1SB-F1NB}$= -0.07 Bark, $\Delta_{F1SB-F1NB}$= -0.28 Bark), and higher F1 for the same vowels in NBD speakers ($\Delta_{F1SB-F1NB}$= 0.15 Bark, $\Delta_{F1SB-F1NB}$= 0.06 Bark). F1 formants for [ɪ] in small block production were higher for both groups ($\Delta_{F1SB-F1NB}$= 0.17 Bark, AOS; $\Delta_{F1SB-F1NB}$= 0.02 Bark, NBD).

F1/F2 space at vowel nucleus

The vowel formant spaces as measured at the vowel nucleus are shown in figures 6.1.13 (a)-(e). As with the formants measured at onset, most participants had well differentiated vowel spaces both for the no block and the bite block conditions. Participants A1 and A4 again had overlapping or nearly overlapping distributions for [ɛ] and [æ]. The first formant for A1's production of [æ] in the large block condition was equivalent to F1 for [ɛ] produced with the small block. Notably, these values run counter to what would be predicted based on the jaw constraint (i.e. the small block should lower

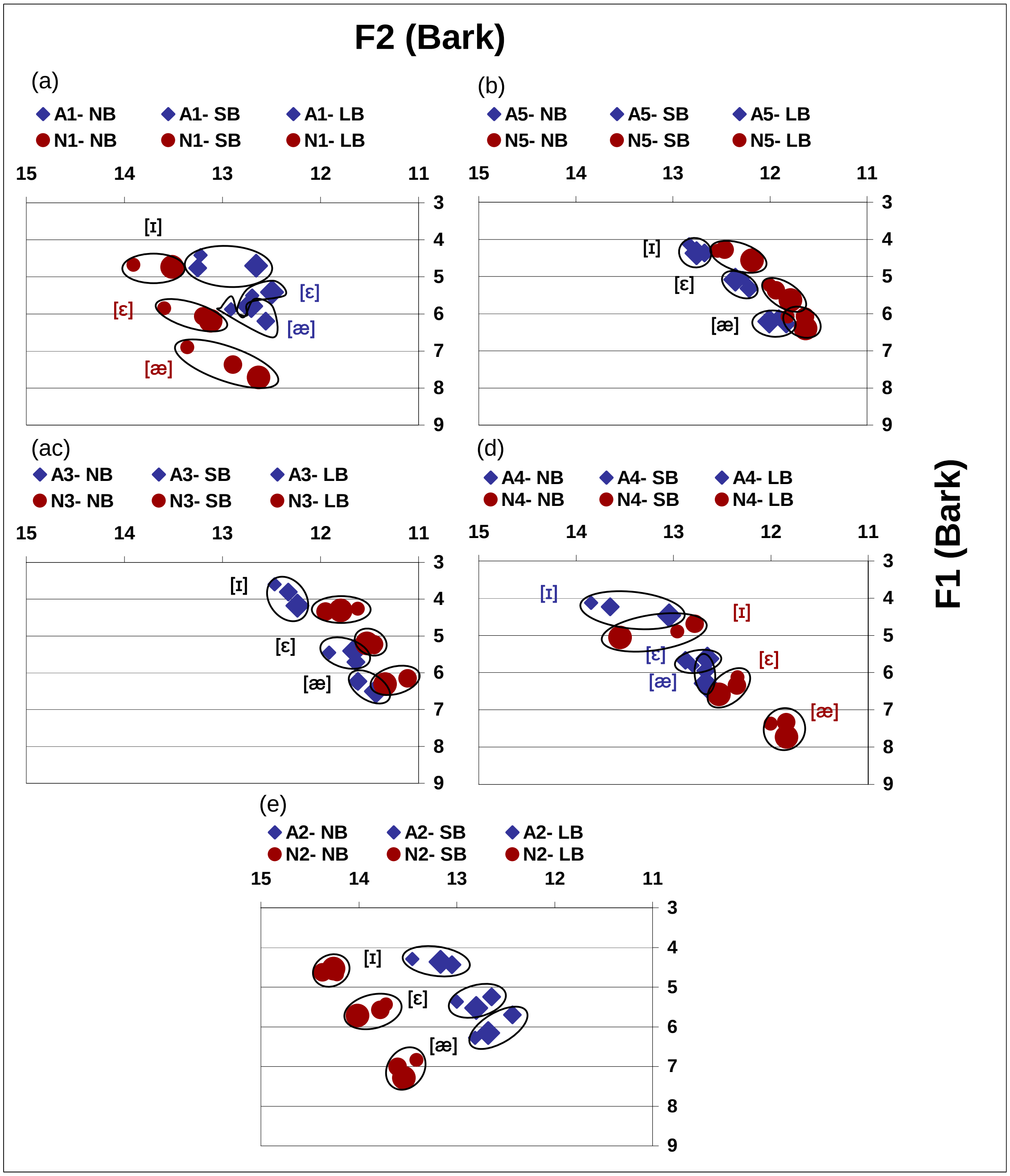


Figure 6.1.13. F1 x F2 vowel spaces for unconstrained and bite block speech production for each apraxic-normal participant pair at vowel nucleus. AOS formants are plotted as blue diamonds and NBD formants as red diamonds. Formant values for no block (NB), small block (SB), and large block (LB) conditions are plotted as small, medium, and large markers. Formants are displayed in Bark-transformed values.

F1 and the large block should raise F1). While A4 did not have any formants of different vowels that overlapped, F1 of [æ] in the small block condition was very close to F1 of [ɛ] in the no block condition.

In large bite block production, all AOS participants had higher F1 for [ɪ] produced with the large block than in the no block condition, with an average F1 difference between LB and NB conditions of +0.30 Bark, compared to a +0.07 Bark difference for the NBD participants. The large bite block had no consistent effect on [ɛ] or [æ] productions by the AOS participants ($\Delta_{F1(LB)-F1(NB)}$= -0.02 Bark for both vowels) and larger F1-raising effects for the NBD group ($\Delta_{F1(LB)-F1(NB)}$= 0.27 Bark for [ɛ], $\Delta_{F1(LB)-F1(NB)}$ = 0.40 Bark for [æ]).

In small bite block production, A2, A4, and N3 had lower F1 for [æ], the expected direction of F1 change for the constraint. On average, the SB condition resulted in lower F1 for [æ] produced by AOS participants ($\Delta_{F1(SB)-F1(NB)}$= -0.14 Bark) and higher F1 for the NBD group ($\Delta_{F1(LB)-F1(NB)}$= 0.10 Bark). For [ɪ] and [ɛ], the small block condition resulted in higher F1 for AOS speakers ($\Delta_{F1(SB)-F1(NB)}$= 0.21 Bark and $\Delta_{F1(SB)-F1(NB)}$= 0.11 Bark). F1 was higher for [ɛ] and lower for [ɪ] produced by the NBD participants in the SB condition ($\Delta_{F1(SB)-F1(NB)}$= 0.12 Bark and $\Delta_{F1(SB)-F1(NB)}$= -0.04 Bark).

Vowel targeting

The vowel space results for bite block production indicate that most participants continue to acoustically differentiate front vowels, with varying degrees of compensation for small and large bite block constraints. Euclidean distances of vowel productions from their targets were calculated to quantify the effects of bite blocks on vowel targeting. Results of Euclidean distance at vowel onset are shown in figures 6.1.14 and 6.1.15, including bite block results by group and for individual participants.

Euclidean distance results show that the AOS group had poorer vowel targeting than the NBD group for all three bite block conditions (figure 6.1.14). Individual results also indicated that most AOS participants were less accurate in vowel targeting, with higher ED values than the NBD speakers (figure 6.1.15). Some exceptions included similar ED values for the small block condition for the A1-N1, A3-N3, and A5-N5 pairs, and higher ED in the large block condition for N5 compared to A5.

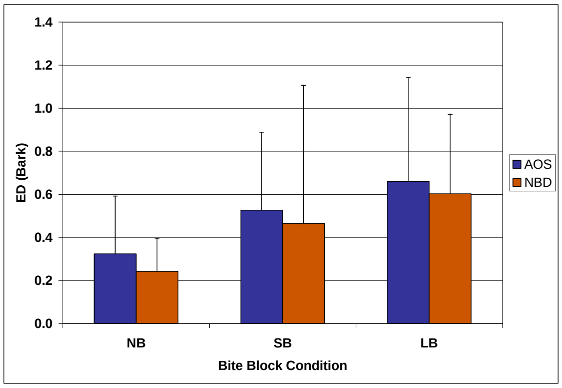


Figure 6.1.14. Euclidean distance from vowel targets at vowel onset in unconstrained and bite block production for AOS and NBD groups.

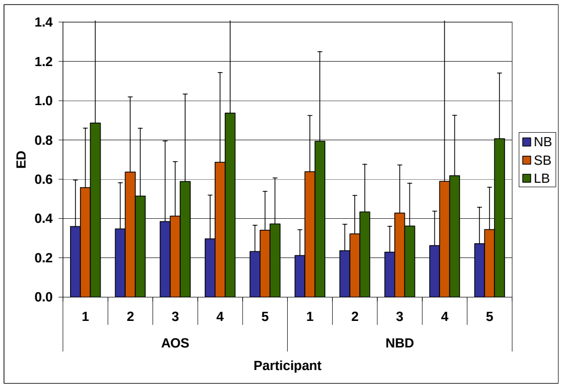


Figure 6.1.15. Euclidean distance from vowel targets at vowel onset in unconstrained and bite block production for individual AOS and NBD participants.

ED findings at vowel nucleus (figures 6.1.16 and 6.1.17) revealed similar patterns, with poorer targeting for AOS participants than their matched pairs. Exceptions were A2 and A5, who had lower ED values in the large block condition than N2 and N5, respectively.

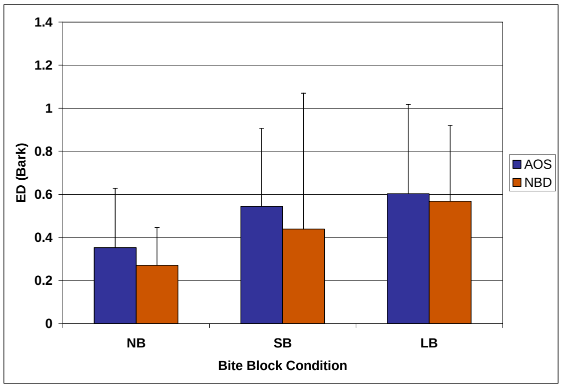


Figure 6.1.16. Euclidean distance from vowel targets at vowel nucleus in unconstrained and bite block production for AOS and NBD groups.

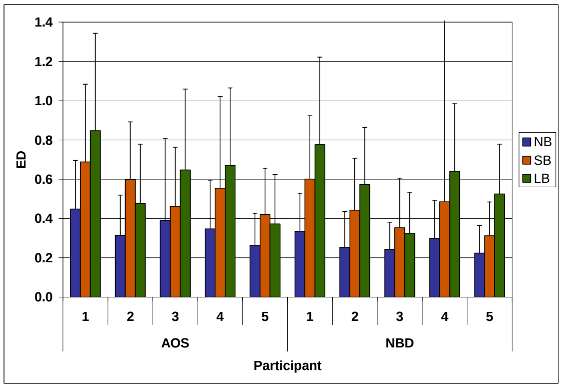


Figure 6.1.17. Euclidean distance from vowel targets at vowel nucleus in unconstrained and bite block production for individual AOS and NBD participants.

Notably, both AOS and NBD participants had best targeting (i.e. lowest EDs) in no block vowel production, with higher EDs for small and large block production. This indicates that both NBD and AOS participants are susceptible to the destabilizing effects of bite block constraints on vowel production.

Vowel distinctiveness

Acoustic distinctiveness of vowels produced in the three production conditions was assessed using the acoustic distance ratio. ADR results from formant measurements made at vowel onset are displayed in figures 6.1.18 and 6.1.19.

Several patterns are evident from the group results at vowel onset (figure 6.1.18). First, the AOS group had lower ADR values than the NBD group for all vowel distinction pairs in each bite block condition, indicating less acoustic differentiation between neighboring vowels for the apraxic speakers. Second, ADR values were generally highest in no block productions, with lower values for the small and large block conditions. Third, acoustic differentiation between [ɪ] and [ɛ] was greater than that between [ɛ] and [æ] for both groups in all production conditions.

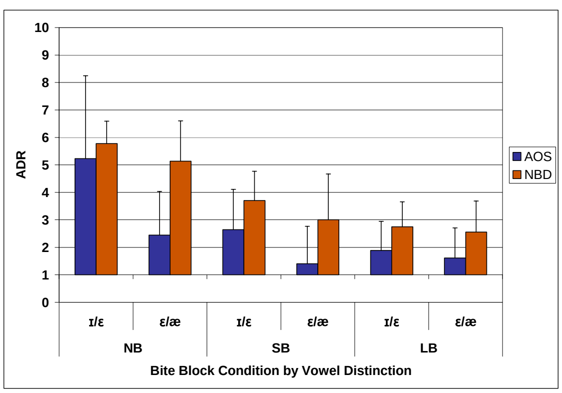


Figure 6.1.18. Group acoustic distance ratio results at vowel onset in unconstrained and bite block production for the adjacent vowel pairs [ɪ]/[ɛ] and [ɛ]/[æ].

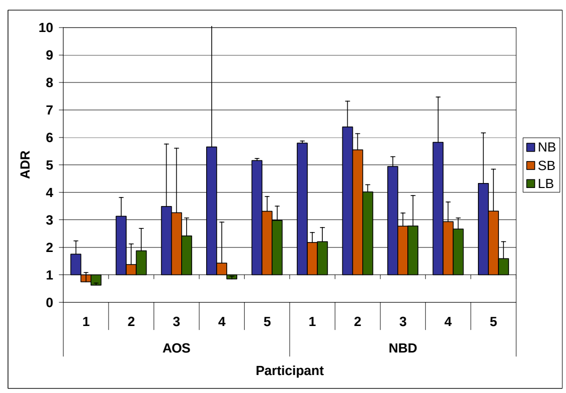


Figure 6.1.19. Individual acoustic distance ratio results at vowel onset in unconstrained and bite block production.

Acoustic differentiation results at vowel onset by participant pair are shown in figure 6.1.19, indicating lower ADR values for the AOS participants in most comparisons. Two exceptions were A3 and A5, who had ADR values similar to or greater than their matched NBD participants. Figure 6.1.19 reveals more marked production differences between normal production and bite block conditions for the apraxic participants A1, A2, and A4. In particular, mean ADR values for A1 and A4 in the large block condition and for A1 in the small block condition are less than 1.0, indicating that the distance between neighboring vowel categories in F1/F2 space is less than the acoustic variability within those vowel categories.

Acoustic distance ratio findings for formants measured at the vowel nucleus are displayed in figures 6.1.20 and 6.1.21, showing very similar patterns of vowel differentiation as those found for vowels measured at onset. Group results (figure 6.1.20) indicate greater differentiation between vowels for a) the NBD group than the AOS group, b) the no block condition versus the small and large block conditions, and c) for [ɪ]/[ɛ] distinctions compared to [ɛ]/[æ] distinctions. One exception is noted, with slightly greater distinctiveness for [ɛ]/[æ] compared to [ɪ]/[ɛ] in the large block condition for NBD speakers. Results by participant pair (figure 6.1.21) indicate that A1 and A2 continue to have less differentiated vowels when measured at nucleus, while A4 has increased ADR values relative to those measured at onset.

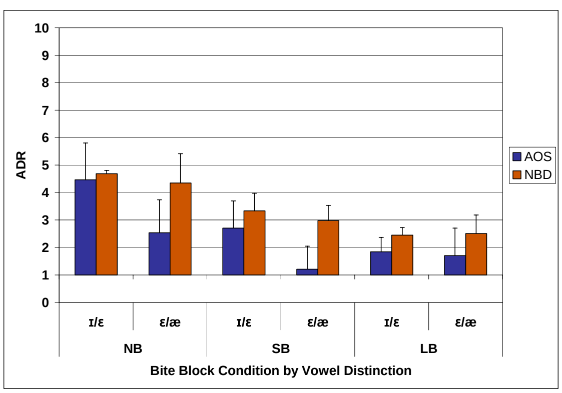


Figure 6.1.20. Group acoustic distance ratio at vowel nucleus in unconstrained and bite block production for the adjacent vowel pairs [ɪ]/[ɛ] and [ɛ]/[æ].

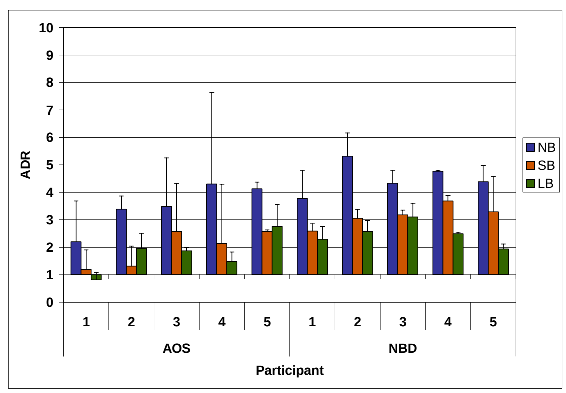


Figure 6.1.21. Individual acoustic distance ratio results at vowel nucleus in unconstrained and bite block production.

Summary

Presence of a novel articulatory constraint (i.e. small and large bite blocks) results in altered vowel production both for speakers with AOS and for matched NBD participants. Most participants maintained differentiated vowel spaces even during bite block production, with the exception of the two apraxic speakers A1 and A4. Nevertheless, results of vowel targeting (i.e. Euclidean distance) and acoustic distinctiveness clearly indicated reduced compensation during bite block speech production for both participant groups. Overall, participants with AOS compensated less well than their NBD pairs, with higher Euclidean distances from vowel targets, and lower acoustic distance ratio measures. The apraxic participants A1 and A4 in particular had poorer performance in vowel targeting and differentiation of adjacent vowels than other participants.

To a limited extent, predicted effects of compensation by bite block condition (e.g. more impaired production for [ɪ] in large block and [æ] in small block conditions) were found, with higher vowel goodness ratings of [æ] in large block than in small block condition and higher ratings of [ɪ] in small block than in large block condition. These effects were not consistently found in ED or ADR measures.

Few differences were observed between bite block measures obtained at the first glottal pulse (i.e. vowel onset) compared to vowel nucleus, suggesting minimal delayed compensation effects. In other words, if speakers are able to compensate for the articulatory constraint, they typically do so immediately (i.e. by the first glottal pulse) and do not require a time delay to enable compensation.

Impaired vowel production in bite block speech is not limited to speakers with AOS, although two apraxic participants in particular were clearly more affected by the constraint.

Vowel production by word length

Previous studies of bite block speaking conditions have focused on vowel production in isolation or in one-syllable words. Increased errors with increasing length of response is an often reported speech characteristic of individuals with AOS. This study examined the initial vowel produced in several word length conditions.

Perceptual goodness of vowels

Average vowel goodness ratings by word length are shown in figure 6.1.22 for the two participant groups and for each participant in figure 6.1.23. The group findings indicate decreased vowel goodness with increased word length for both groups, with greater differences for the AOS group than the NBD group. On average, vowel goodness was better in the AOS group for one-syllable words than for isolated vowels, and the reverse for the NBD group. Results of the individual participants largely reflect this general pattern. Two exceptions were participants A1 and A3, who had lowest vowel goodness for vowels produced in isolation.

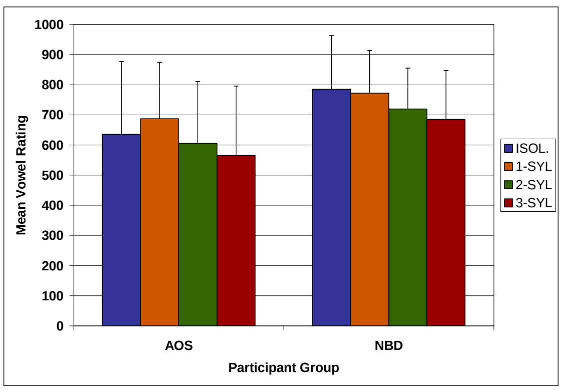


Figure 6.1.22. Group vowel rating results for all vowels in different word length conditions. Vowel ratings are displayed for vowels in isolation and 1-syllable, 2-syllable, and 3-syllable words.

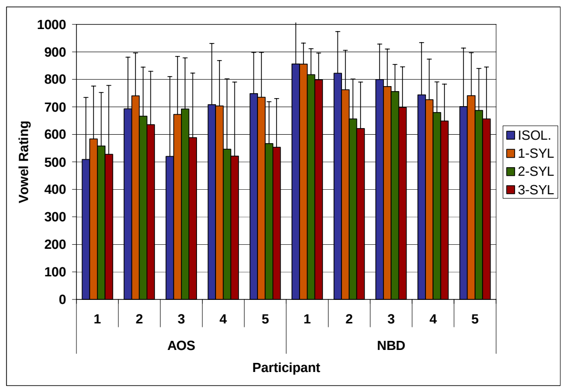


Figure 6.1.23. Individual vowel rating results for all vowels in different word length conditions. Vowel ratings are displayed for vowels in isolation and 1-syllable, 2-syllable, and 3-syllable words.

Group vowel goodness ratings by word length and bite block conditions (figure 6.1.24) indicate that the pattern of decreased vowel goodness with increased word length is present in the no block, small block, and large block conditions for both participant groups. Vowel goodness was lower in the small and large block conditions than in unconstrained production. However, the effect of word length does not appear to be modulated by the bite block condition.

Vowel goodness ratings by word length and vowel category (figure 6.1.25) also show a similar pattern for the NBD group. For the AOS group, however, goodness for the vowels [ɪ] and [ɛ] is higher in the two-syllable condition than in isolation; AOS [æ] goodness is higher in the three-syllable condition than in one-syllable or isolation productions.

Overall, these findings suggest that vowels produced in isolation or in one-syllable words are perceived as better than the same vowels produced in two- or three-syllable words. The pattern of inferior vowel goodness with increased word length was generally consistent across bite block conditions and vowels for the two groups, although two AOS speakers showed poorer goodness for vowels produced in isolation than in any other length condition.

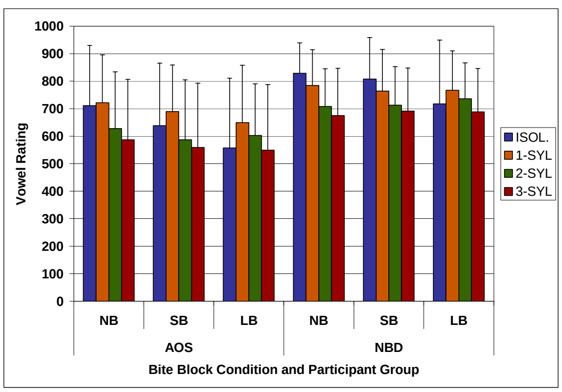


Figure 6.1.24. Group vowel rating results for all vowels by word length and bite block condition.

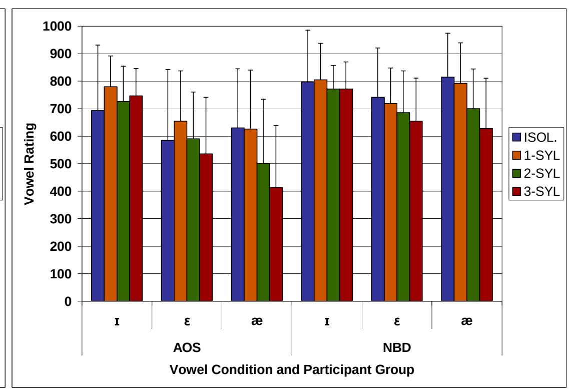


Figure 6.1.25. Group vowel rating results for all vowels by word length and vowel category.

F1/F2 vowel space

Vowel spaces for the five participant pairs are plotted with values for formants produced in word length conditions for unconstrained vowel production (figures 6.1.26 (a)-(e)), small block (figures 6.1.27 (a)-(e)), and large bite block conditions (figures 6.1.28 (a)-(e)).

The findings indicate more variability among vowel formants due to word length by AOS and NBD participants than those previously found for bite block vowel production. In the no block condition, all AOS participants and NBD participants N2 and

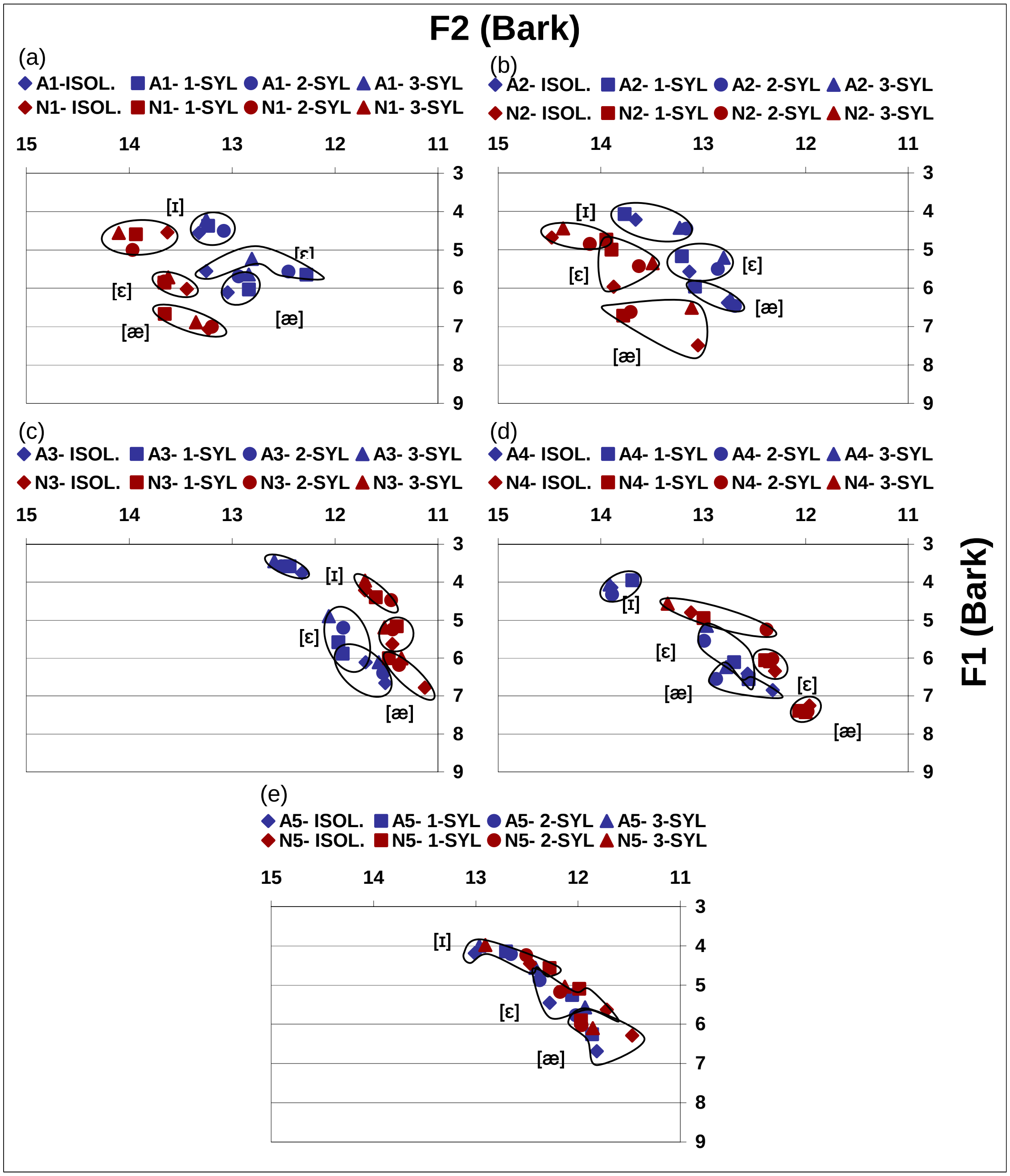


Figure 6.1.26. F1 x F2 vowel spaces for unconstrained production by word length in each apraxic-normal participant pair. AOS formants are plotted as blue markers and NBD formants as red markers. Formant values for isolated, one-syllable, two-syllable, and three-syllable conditions are plotted as diamond, square, circle, and triangle shapes, respectively. Formants are displayed in Bark-transformed values.

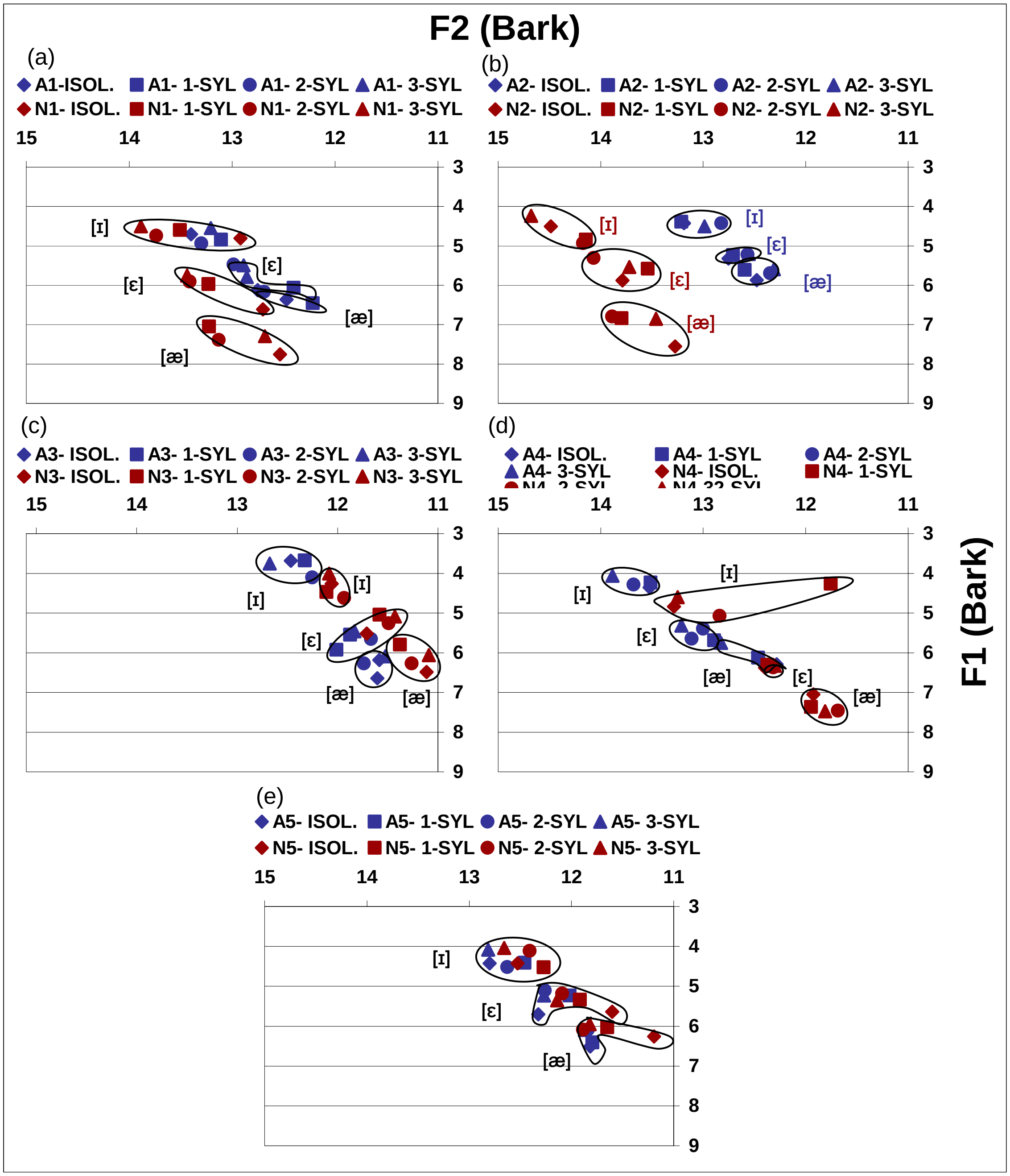


Figure 6.1.27. F1 x F2 vowel spaces for small bite block production by word length in each apraxic-normal participant pair. AOS formants are plotted as blue markers and NBD formants as red markers. Formant values for isolated, one-syllable, two-syllable, and three-syllable conditions are plotted as diamond, square, circle, and triangle shapes, respectively. Formants are displayed in Bark-transformed values.

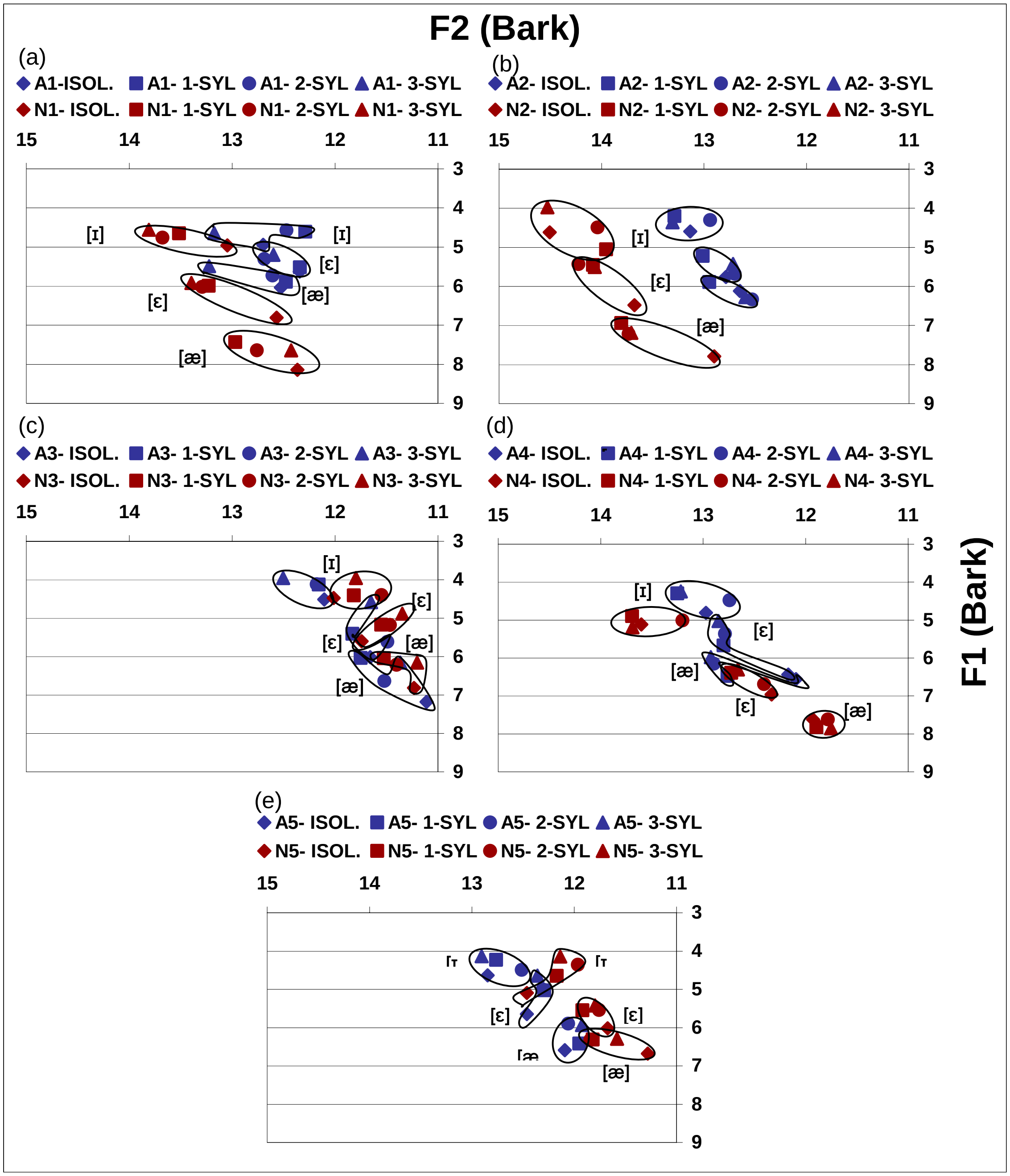


Figure 6.1.28. F1 x F2 vowel spaces for large bite block production by word length in each apraxic-normal participant pair. AOS formants are plotted as blue markers and NBD formants as red markers. Formant values for isolated, one-syllable, two-syllable, and three-syllable conditions are plotted as diamond, square, circle, and triangle shapes, respectively. Formants are displayed in Bark-transformed values.

N3 had vowel formants in at least one length condition that overlapped or nearly overlapped with neighboring vowels (figure 6.1.26). In the small block condition, AOS participants A1, A2, A3, and A4 and NBD participant N3 had nearly overlapping distributions (figure 6.1.27). In the large block condition, all AOS participants and NBD participant N5 had nearly overlapping distributions (figure 6.1.28).

Vowel targeting

Although vowel formants varied when produced in different word length conditions, the perceptually-derived vowel formant targets were determined uniquely by syllable condition. The vowel targeting and distinctiveness measures were calculated from these perceptually-based vowel targets, so that vowel formant variability by word length may not indicate poorer targeting or vowel distinctiveness.

Vowel targeting results by word length (i.e. Euclidean distance measures of vowel formants from targets) are shown for participant groups in figure 6.1.29 and for individual participants in figure 6.1.30. Mean ED values for the AOS group indicate poorest targeting (i.e. higher ED from target) for vowels produced in isolation, with little difference between one-, two-, and three-syllable conditions. ED measures for the NBD group were similar in different word length conditions, with no clear pattern shown by increasing word length. Individual participant results show highest ED values (i.e. poorer targeting) in isolated production for all AOS participants except A5 and for NBD participant N1 (figure 6.1.30). No other clear pattern of vowel targeting by word length was found for either participant group.

Group vowel targeting results by word length and bite block condition are displayed in figure 6.31 and by word length and vowel category in figure 6.1.32. Findings indicate higher ED values for all three bite block conditions in the isolated condition for the AOS group; this pattern was found for the NBD group in the large block condition only (figure 6.1.31). No other consistent effect of word length on vowel targeting by bite block condition was found. Group targeting results by word length and vowel category also showed no clear pattern (figure 6.1.32). For the AOS group, ED values were greatest in isolated productions for the three vowel categories, but no other clear pattern was found. The NBD group had highest ED values in the one-syllable condition for [ɪ] productions and in three-syllable condition for [æ] productions.

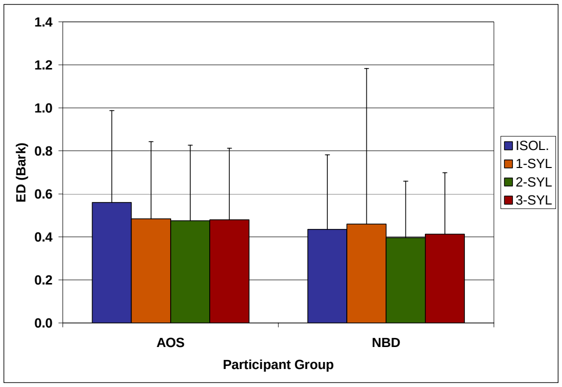


Figure 6.1.29. Group Euclidean distance results from vowel targets by word length.

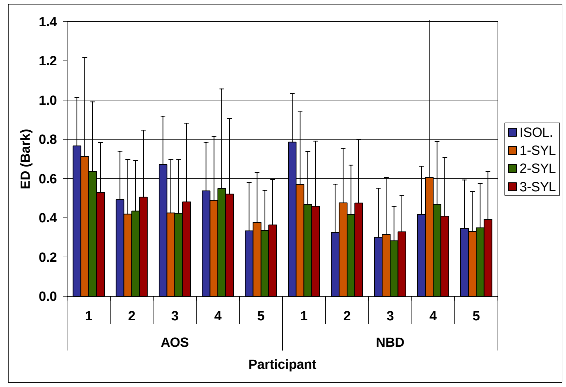


Figure 6.1.30. Individual Euclidean distance results from vowel targets by word length.

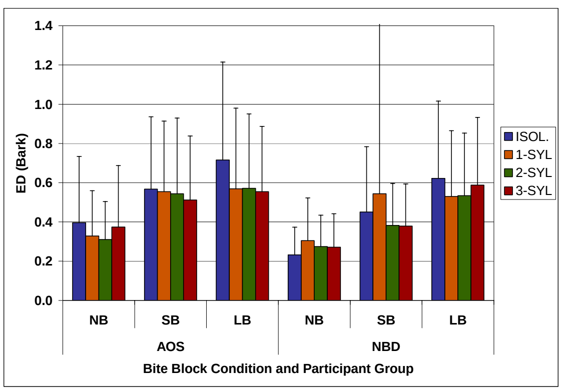


Figure 6.1.31. Group Euclidean distance results from vowel targets by word length and bite block conditions.

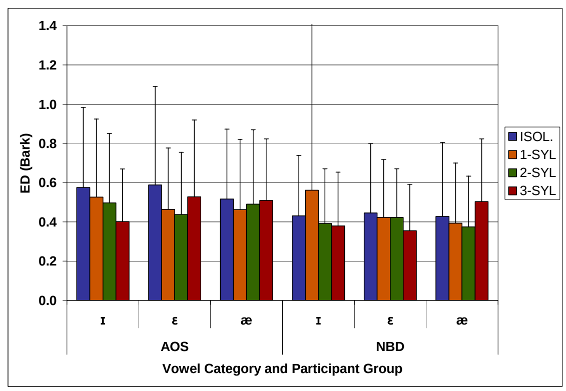


Figure 6.1.32. Individual Euclidean distance results from vowel targets by word length and vowel category.

The Euclidean distance findings for vowels produced in different word length conditions indicate one clear pattern, namely that most participants with AOS have poor targeting for vowels produced in isolation, particularly for A1 and A3. This parallels the vowel goodness results showing that vowels produced by these two participants in isolation were perceived more poorly than those produced in any other syllable condition. Only one NBD participant (N1) showed the same pattern of high ED for vowels in isolation, and this was not accompanied by poorer vowel ratings.

Vowel distinctiveness

Acoustic distance ratios by word length are shown for the participant groups and individuals in figures 6.1.33 and 6.1.34 to show the distinctiveness of initial vowel production as it varies in different word lengths. Group results showed very little difference in vowel distinctiveness for AOS participants by word length (figure 6.1.33). NBD participants, however, had much higher ADR values in the isolated vowel and three-syllable condition, indicating greater vowel distinctiveness in these conditions. Individual results confirmed the lack of a clear pattern of ADR by word length for AOS participants (figure 6.1.34), with highest ADR in the one-syllable condition for A1, A2, and A4, highest ADR in two-syllable words for A3 and in isolation for A5. NBD participants N2 , N3, and N5 had very large acoustic distance ratios in the isolated condition, and the ratio for vowels in the three-syllable condition was the highest or second-highest for all NBD participants.

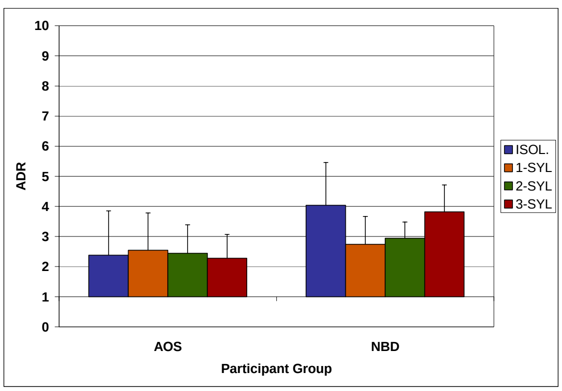


Figure 6.1.33. Group acoustic distance ratio results by word length.

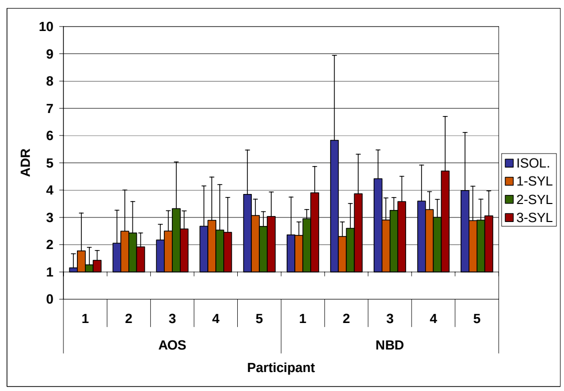


Figure 6.1.34. Individual acoustic distance ratio by word length.

Acoustic distance ratio results by word length and bite block conditions are shown in figure 6.1.35, and by word length and vowel pair in figure 6.36. The results by bite block condition reveal the previously reported finding of lower ADR (i.e. less vowel distinctiveness) for vowels produced in small or large bite block conditions, compared to the no block condition (figure 6.1.35). The AOS participants showed no clear difference in ADR by bite block condition. The NBD group had highest ADR for vowels produced in isolation and in three-syllable words for the no block and small block conditions. Less difference in ADR due to word length was found in large block productions for the NBD group.

Acoustic distance ratio results by length and vowel pair for AOS participants indicate greater distinctiveness for the [ɪ]/[ɛ] pair than for the [ɛ]/[æ] pair (figure 6.1.36). Small differences in ADR by word length were found for the AOS group both for [ɪ]/[ɛ] and [ɛ]/[æ] ADR measures. The NBD group had markedly higher ADR values for the [ɪ]/[ɛ] distinction in isolation and three-syllable words than in the other conditions. ADR values for [ɛ]/[æ] were similar for the NBD group across syllable conditions.

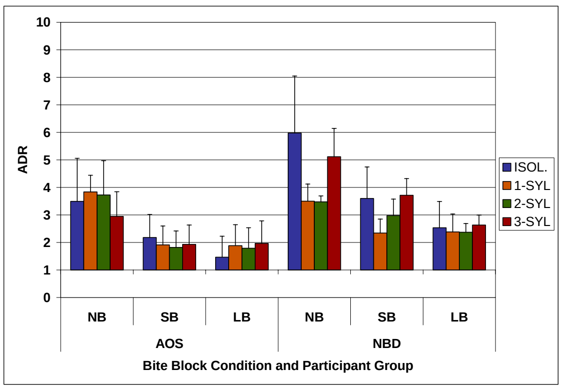


Figure 6.1.35. Group acoustic distance ratio results by word length and bite block conditions.

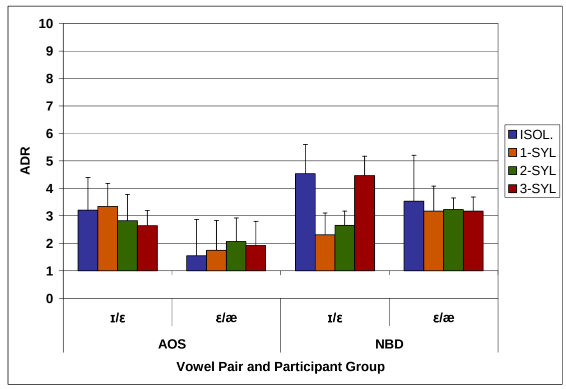


Figure 6.1.36. Group acoustic distance ratio results by word length and vowel pair distinctions for AOS and NBD groups.

Vowel distinctiveness varied minimally for vowels produced by AOS speakers in different word length conditions. NBD participants, except for N1, produced [ɪ] and [ɛ] more distinctively in isolation and in three-syllable words compared to those produced in one- or two-syllable words. Increased vowel distinctiveness in these syllable conditions was unexpected and has no apparent explanation, but the pattern was maintained in all bite block conditions. One possible explanation is that the vowel formants for [ɪ] and [ɛ] are produced more distinctly when the vowels are produced in isolation and in the three-syllable words "idiot" and "edited" compared to when they are produced in the one-syllable words "id" and "Ed" and in the two-syllable phrase "hid it" and word "edit".

Summary

Analysis of vowel production by word length revealed no consistent pattern of results across the measures employed. For both participant groups, vowel goodness ratings were highest for vowels produced in isolation or in one-syllable words. Vowel space analysis revealed differences in formants produced in different syllable constructions. However, Euclidean distance measures indicated similar vowel targeting in different syllable conditions, with the exception of poorer targeting for isolated vowels produced by AOS participants. Acoustic distinctiveness of neighboring vowels was similar across syllable conditions for the AOS group, while NBD participants had higher distinctiveness between the vowels [ɪ] and [ɛ] in isolation and in three-syllable words. In the face of this collection of word length effects on measures of vowel production, it is notable that there was no consistent pattern of decreased vowel targeting or distinctiveness with increased word length. Objective measures of vowel production suggest that production of a targeted vowel in the first syllable is no more adequate for vowels produced in one-syllable stimuli than in two- or three-syllable words.

Chapter 6.2

Vowel perception in apraxia of speech

Vowel Identification

Categorization of the front vowels [ɪ], [ɛ], and [æ] was tested in two stages, with a 13-step continuum from “hid” to “head” presented first and a 10-step continuum from “head” to “had” presented second.

Identification curves

Identification curves for the individual AOS and NBD participants are shown in figures 6.2.1 (a)-(e) and 6.2.2 (a)-(e). The dependent measure is the percentage of repetitions of each stimulus that are perceived as the words “hid”, “head”, or “had”. The stimuli vary in the first formant frequency from 4.18 Bark to 7.3 Bark. NBD participant results indicate that the stimuli with the three lowest F1 values are clearly perceived as “hid” (e.g. 4.18 Bark-4.38 Bark), the stimuli in positions 11 through 13 on the continuum

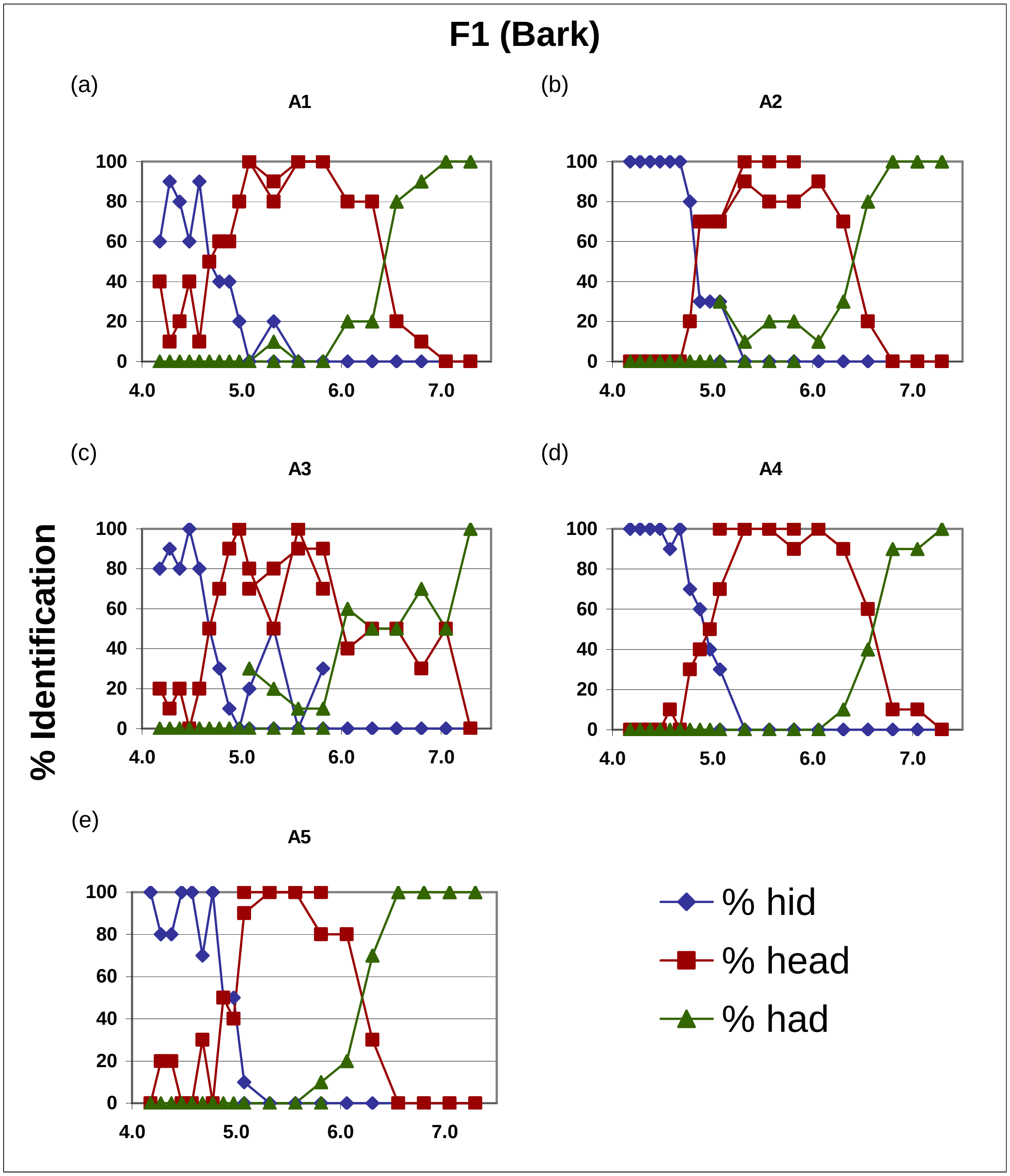


Figure 6.2.1. Vowel identification curves for AOS participants. Percent identification values for "hid", "head", and "had" are plotted against the Bark frequency values of each stimulus.

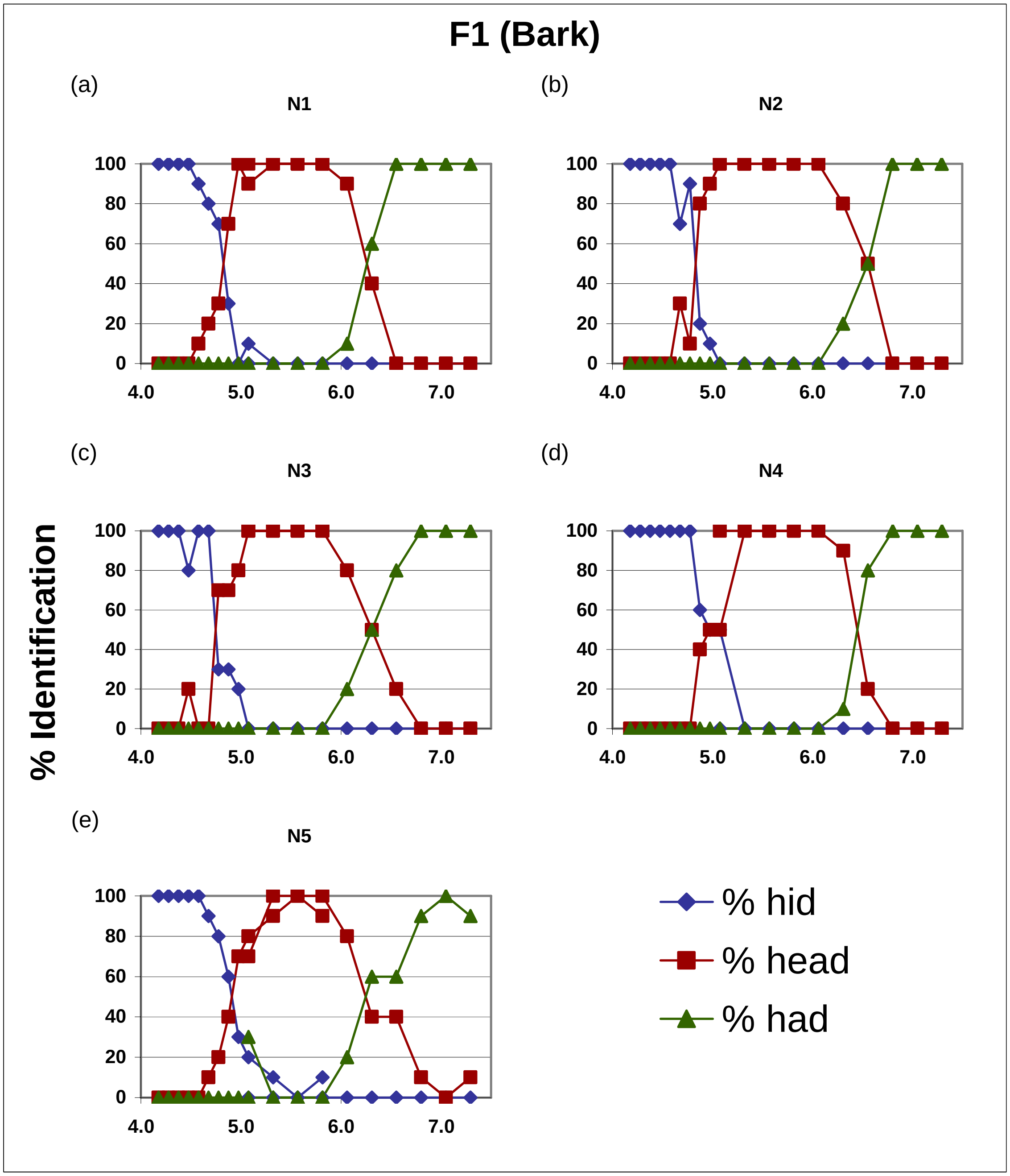


Figure 6.2.2. Vowel identification curves for NBD participants. Percent identification values for "hid", "head", and "had" are plotted against the Bark frequency values of each stimulus.

are perceived as “head” (e.g. 5.32 Bark-5.81 Bark), and the stimuli with the three highest F1 values are perceived as “had” (e.g. 6.8-7.3 Bark).

Visual inspection of the identification curves of AOS participants (figure 6.2.1) reveals that all but A4 had irregular perceptual responses for the hid-head continuum, the head-had continuum, or both. A1 and A5 had irregular identification curves for the “hid”-“head” continuum and more consistent responses to “head”-“had”. A2 had difficulty with “head”-“had” responses, while A3’s identification curves were irregular and had multiple identification curve crossovers for both continua.

NBD listeners, while showing some variation between participants, were more consistent in their perceptual responses. Deviations from the identification curve were less extensive and less numerous for the NBD participants. Some variation resulted from the inclusion of some stimuli in the “head”-“had” continuum that may have been perceived as “hid” and not “head”. For example, participants N1 and N5 responded “had” to 10% and 30% of repetitions of stimulus # 10 (F1= 5.07 Bark). Interpretation of this result is that, since only two choices were available for response per continuum, a listener hearing a stimulus on the low F1 end of the head-had continuum may have decided that, not perceiving the stimulus as “head”, it must be “had” by default.

Mean group results for vowel identification are shown in figures 6.2.3 and 6.2.4 for the AOS and NBD participants, including standard deviation bars for each stimulus. These findings indicate consistent identification of the vowel endpoints for the NBD group, with lower standard deviations for stimuli that were clearly within categories, compared to those for stimuli between categories. The AOS group had lower mean endpoint identification values than the NBD group, and standard deviations were similar for within- and between-category stimuli.

Best fit identification curves

To quantify the goodness or irregularity of the identification curves, logistic growth curves were fit to the individual participant response data, and the sum of squared deviations between the logistic model curve and the actual data served as an index of adequate perceptual responses. Two examples of actual identification with the best fit curves superimposed are shown for A1 and N1 in figures 6.2.5 and 6.2.6. Responses by A1 on the hid-head continuum were erratic and clearly deviate from the best fit curve. In contrast, points on the best fit curve for NBD correspond very closely with the actual data points.

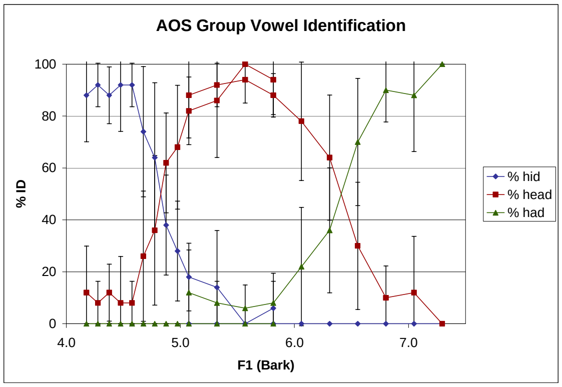


Figure 6.2.3. Mean AOS vowel identification curves. Percent identification values for “hid”, “head”, and “had” are plotted against the Bark frequency values of each stimulus. Standard deviations for identification percentages are plotted as error bars for each stimulus.

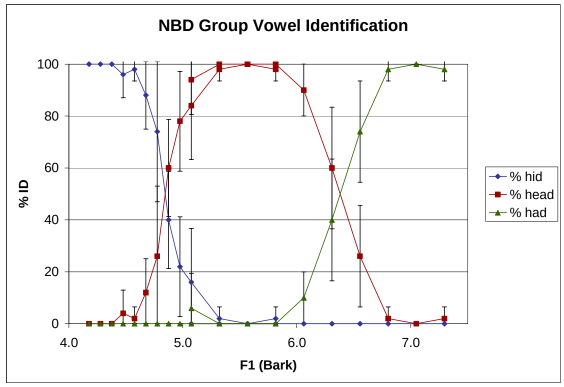


Figure 6.2.4. Mean NBD vowel identification curves. Percent identification values for “hid”, “head”, and “had” are plotted against the Bark frequency values of each stimulus. Standard deviations for identification percentages are plotted as error bars for each stimulus.

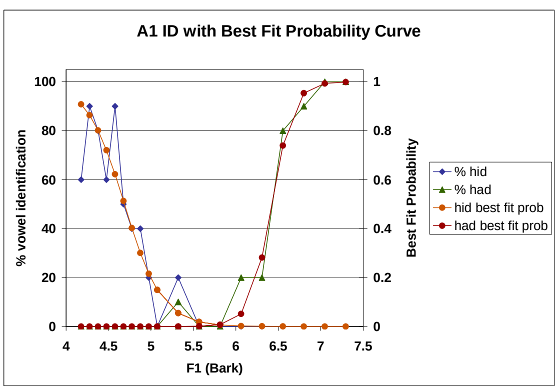


Figure 6.2.5. Actual vowel identification curve with best fit probability curve for Participant A1. Percent identification values for “hid”, “head”, and “had” and the predicted probability values for those data are plotted against the Bark frequency values of each stimulus.

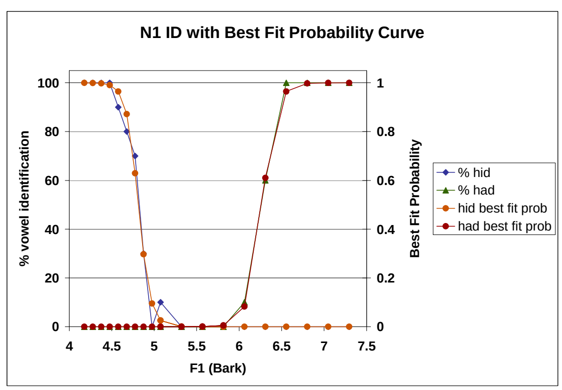


Figure 6.2.6. Actual vowel identification curve with best fit probability curve for Participant N1. Percent identification values for “hid”, “head”, and “had” and the predicted probability values for those data are plotted against the Bark frequency values of each stimulus.

The sum of squared deviations (SSD) of actual data points from those predicted by the best fit curves are displayed for the two groups in figure 6.2.7 and for individual participants in figure 6.2.8. As a group, AOS participants had higher SSDs than the NBD group for both vowel continua, indicating less orderly identification curves in the AOS listeners (figure 6.2.7). For both groups, SSD was higher for the hid-head continuum than the head-had continuum, suggesting less regular performance for hid-head identification. Sum of squared deviations of individual participants confirmed the subjective descriptions of irregular identification based on visual inspection (figure 6.2.8). Participants with erratic hid-head curves had high SSD values for that continuum (A1, A3, and A5), while SSD for head-had was higher for A2 and A4, two participants who had irregular head-had identification.

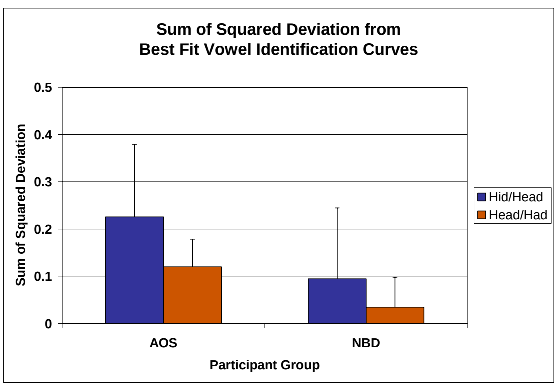


Figure 6.2.7. Deviation of identification data from predicted values from the logistic best fit curve for the hid/head and head/had continua for AOS and NBD groups. The sum of squared deviations between actual and predicted data represent the consistency of identification performance.

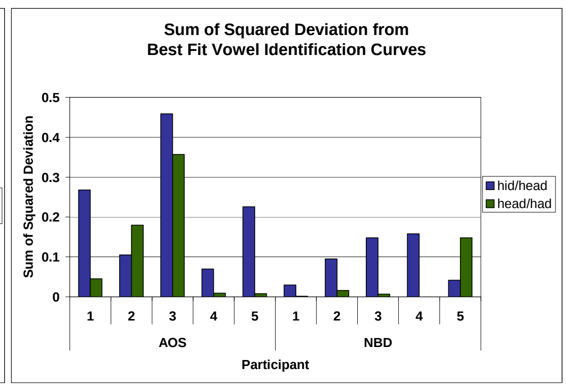


Figure 6.2.8. Deviation of identification data from predicted values from the logistic best fit curve for the hid/head and head/had continua for individual AOS and NBD participants. The sum of squared deviations between actual and predicted data represent the consistency of identification performance.

Boundary measures

The logistic best-fit curves yielded slope coefficients which correspond to the steepness of the vowel category boundary. Frequency locations of the 50% identification boundaries also were calculated using the slope and intercept coefficients of the best-fit curves.

Slopes of category boundaries for groups and individuals are displayed in figures 6.2.9-10, with more negative slopes indicating steeper hid-head boundaries and more positive slopes corresponding to steeper head-had boundaries. On average, AOS participants had less steep category boundaries than the NBD participants, with a greater difference seen for the hid-head boundary (figure 6.2.9). While group results show less steep boundary curves for the AOS group, individual results do not reveal consistent patterns of shallower slopes for the participants who had erratic identification curves (e.g. A1, A3, and A5 for hid-head, see figure 6.2.10). Individual hid-head slopes for the NBD participants indicate that most have steeper boundary curves (i.e. more negative slopes) than AOS participants, although much of the group difference may be explained by N2's slope that was almost twice that of all other participants. This slope corresponded to a very steep identification boundary, although this participant's identification curve was not free from irregularities (refer back to figure 6.2.2 (b)).

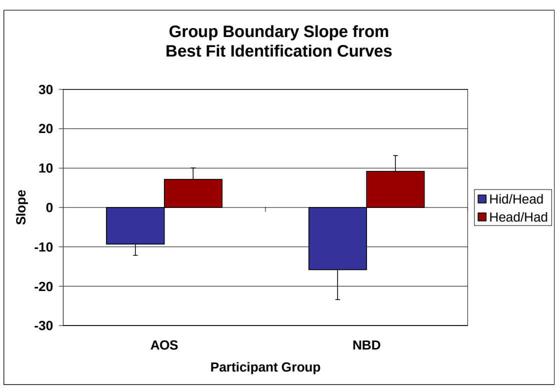


Figure 6.2.9. Mean boundary slopes of the best fit identification curves for AOS and NBD groups. Slopes are plotted separately for the hid/head and head/had continua.

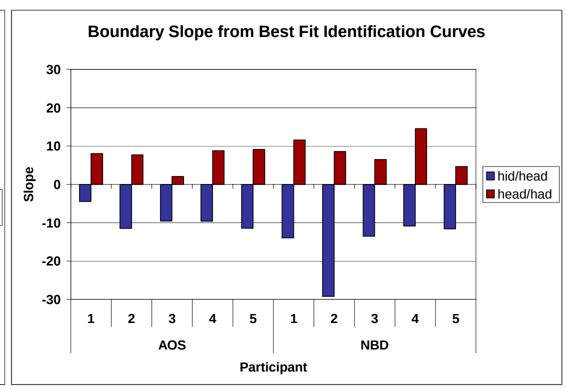


Figure 6.2.10. Boundary slopes of the best fit identification curves for individual AOS and NBD participants. Slopes are plotted separately for the hid/head and head/had continua.

The slope results provide useful information about the steepness of the category boundaries, an important aspect of categorical perception. They are useful as an indication of how "categorical" a given perceptual task is, but they are not an effective index of consistent performance on the perceptual task. Participants with clearly aberrant identification had similar slopes to other participants with more consistent performance on this task.

First formant frequencies at the 50% identification boundary for hid-head and head-had identification are shown for groups and individuals in figures 6.2.11-12. Findings indicate nearly identical vowel category boundaries in the two participant groups for both hid-head and head-had boundaries, with very little within-group variance as demonstrated by standard deviation error bars (figure 6.2.11). Individual results confirm these group findings (figure 6.2.12). The mean category boundaries across all participants were 4.84 Bark for hid-head and 6.40 Bark for the head-had continuum.

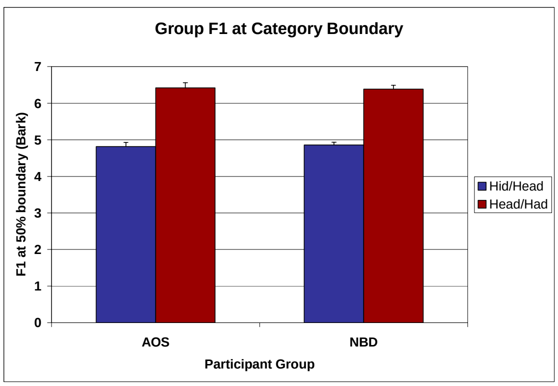


Figure 6.2.11. F1 category boundaries of the best fit identification curves for AOS and NBD groups. Categories boundaries are plotted separately for the hid/head and head/had continua.

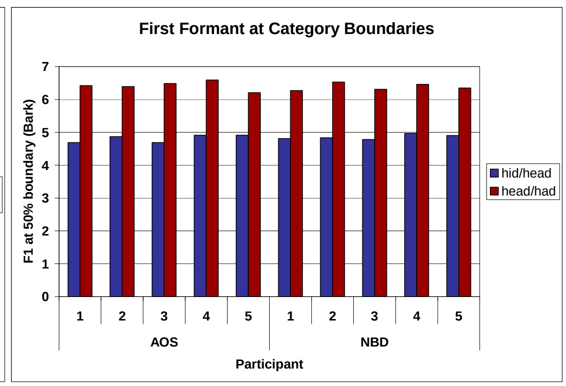


Figure 6.2.12. F1 category boundaries of the best fit identification curves for individual AOS and NBD participants. Categories boundaries are plotted separately for the hid/head and head/had continua.

It is notable that participant A3 had similar category boundaries to other listeners, given that this individual demonstrated multiple boundary crossings for both vowel continua (figure 6.2.1 (c)). The presence of "normal" vowel category boundaries in participants with varying degrees of impaired categorization suggests that phonemic boundaries have not shifted but that ability to process these stimuli effectively and consistently has been somehow affected.

Summary

Four of five participants with AOS showed diminished ability to categorize front vowels consistently. This impairment was apparent upon visual inspection of identification curves as well as in sum of squared deviation (SSD) measures derived from comparison of actual performance to best fit logistic curves. Only one participant had impaired categorization for both vowel continua (A3), with two having more difficulty with hid-head (A1, A5), and one with impaired head-had identification (A2). NBD participants showed minor deviations in vowel identification, with less frequent and less pronounced deviation from expected performance.

Slope of the category boundaries varied slightly between the groups, and was not related to inconsistent performance evident from visual inspection of the results and SSD measures. First formant values at the category boundaries were nearly identical between the groups for both vowel continua, suggesting that perceptual impairment is not related to shifted phonemic vowel boundaries.

Vowel discrimination

Vowel discrimination was tested for five stimuli along the front vowel continuum from hid to head to had (i.e. "base stimuli"), with comparison stimuli varying in four F1 step sizes (30, 60, 90, or 120 Hz. different). The five base stimuli represented within category exemplars for [ɪ], [ɛ], and [æ] and stimuli at the category boundaries between [ɪ]/[ɛ] and [ɛ]/[æ]. Participants were presented pairs of stimuli and asked to determine if they were the same or different; one half of stimuli were actually different and one half were the same.

Vowel discrimination abilities were very similar across participants and across group, with overall mean accuracy of 81% for AOS participants and 78% for NBD participants (s.d.= 3.6 and 2.5, respectively). Mean discrimination accuracy across conditions is displayed for all participants in figure 6.2.13. Individual values ranged from 78 to 87% for AOS listeners and from 74 to 81% for NBD listeners. AOS participant A5 had the highest rate of correct discrimination, due largely to greater ability to discriminate the [æ] base stimulus from the comparison stimuli, a contrast that was difficult to distinguish for all other listeners regardless of step size (see individual results for all participants and conditions in Appendix C).

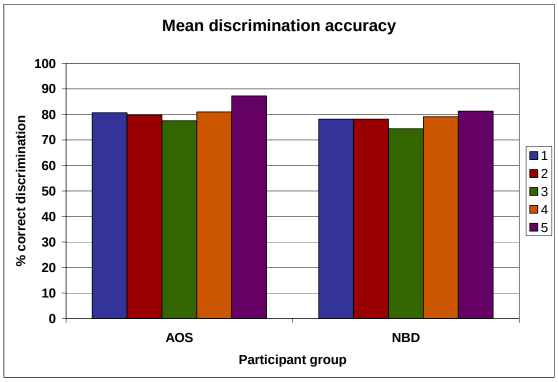
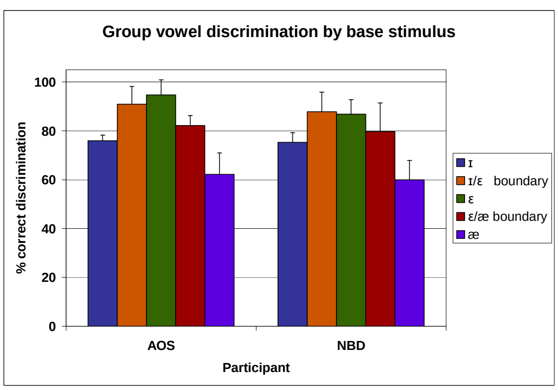


Figure 6.2.13. Individual discrimination accuracy results.

Group and individual results for discrimination of the five base stimuli are shown in figure 6.2.14-15, confirming the overall poor discrimination of [æ] from comparison stimuli. The vowel [ɪ] was the second least discriminable for both groups, while [ɛ] and the [ɪ]/[ɛ] boundary stimulus were the most discriminable. Individual participant results confirm higher discrimination for [ɪ] and [ɪ]/[ɛ] in the AOS participants (figure 6.2.15). NBD results indicate similar levels of accuracy among the [ɪ]/[ɛ] boundary, [ɛ], and [ɛ]/[æ] boundary.



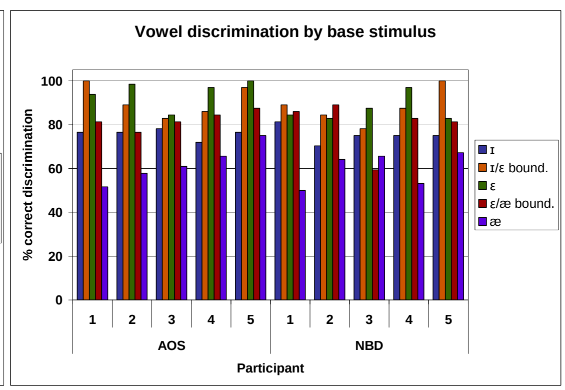


Figure 6.2.14. Group vowel discrimination by vowel stimulus series. Discrimination accuracy is plotted separately for the vowel series with the base stimuli for [ɪ], [ɛ], [æ], and the [ɪ]/[ɛ] and [ɛ]/[æ] boundaries.

Figure 6.2.15. Individual vowel discrimination results by stimulus series. Accuracy is plotted separately for the vowel series with the base stimuli for [ɪ], [ɛ], [æ], and [ɪ]/[ɛ] and [ɛ]/[æ] boundaries.

Full-spectrum analysis of the stimuli, described in the method, has indicated that the [æ] base stimulus was spectrally less different than the four comparison stimuli than other base stimuli from their comparisons. This anomaly in the stimulus properties accounts for the fact that [æ] was less discriminable for most listeners, but does not account for the higher accuracy of participant A5 for this stimulus.

Discrimination of vowel comparisons varying in F1 step size is shown in figures 6.2.16-17 for the groups and individuals. These findings indicate an expected pattern of increased discrimination accuracy as the F1 step size distance between base and comparison stimuli increases from 30 Hz to 120 Hz. The pattern was present in group and individual results, although discrimination accuracy was often very similar for the 90 and 120 Hz step sizes, indicating a possible ceiling effect.

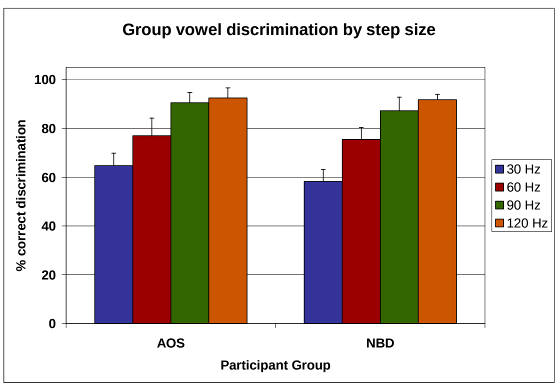


Figure 6.2.16. Group vowel discrimination results by F1 step size. Discrimination accuracy is plotted separately for comparisons made between base stimuli and stimuli varying in F1 by 30, 60, 90, and 120 Hz.

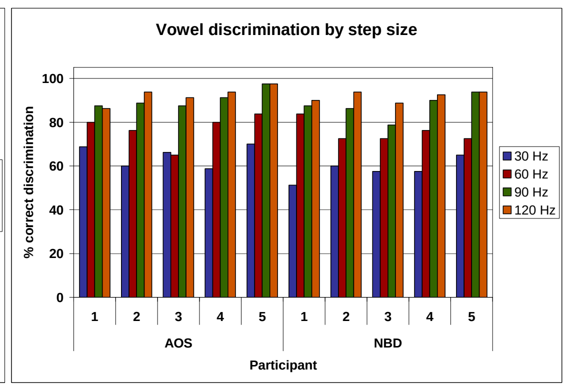


Figure 6.2.17. Individual vowel discrimination results by F1 step size. Discrimination accuracy is plotted separately for comparisons made between base stimuli and stimuli varying in F1 by 30, 60, 90, and 120 Hz.

Summary

Vowel discrimination testing revealed no consistent or appreciable differences between the participant groups, with overall discrimination accuracy higher in the AOS group than in the NBD group. The base stimuli [ɛ] and the [ɪ]/[ɛ] boundary were more discriminable from comparison stimuli than other base stimuli. Accuracy was particularly low for discrimination of [æ] from comparison stimuli, due to inherent uncontrolled stimulus properties. All participants showed increased discrimination of vowel pairs as the F1 step size between the base and comparison stimuli was increased.

The vowel discrimination results stand in contrast to the identification findings, where four of five AOS participants had erratic vowel categorization responses. This incongruity indicates that auditory processes necessary for direct acoustic comparisons are unimpaired in AOS participants, while one or more of the processes necessary for vowel categorization are deficient or inefficient in the four participants with impaired identification.

Chapter 6.3

Rhyme processing in apraxia of speech

Higher-level phonemic processing abilities were tested using three rhyme processing tasks, including a rhyme generation task, judgment of auditorily-presented rhyme and non-rhyme pairs, and silent judgment of written rhyme and non-rhyme pairs. Individual results for all three rhyme processing tasks are displayed in figure 6.3.1.

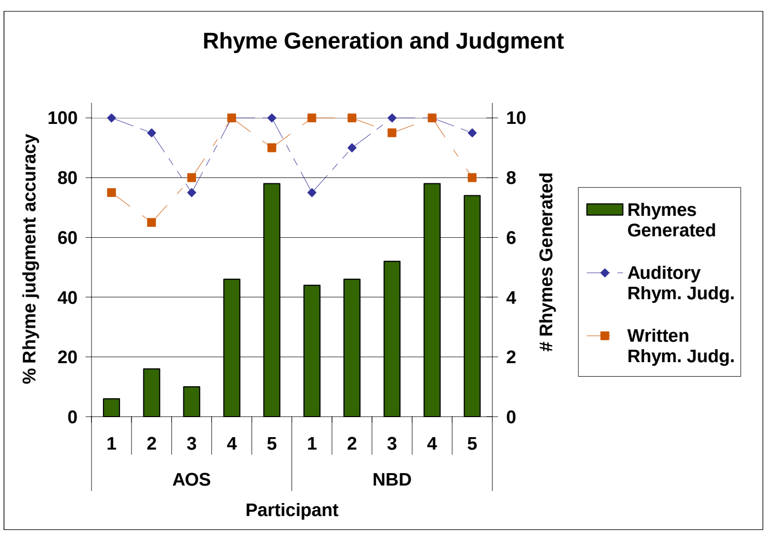


Figure 6.3.1. Rhyme generation, auditory rhyme judgment, and written rhyme judgment results. Individual results of rhyme judgment tasks are plotted as percent accuracy scores in a broken line graph and rhymes generated are plotted as a bar graph of mean rhymes produced per target.

Rhyme generation

Rhyme generation was tested by asking participants to name as many rhyming words to each of five target CVC words in a 30 second period. Three of five AOS participants (A1, A2, and A3) had great difficulty with this task, producing less than 2 rhyming words per target (figure 6.3.1). AOS participants A4 and A5 and all NBD participants produced an average of four or more rhyming words per target in the same time period.

Auditory rhyme judgment

Auditory rhyme judgment was tested by presenting 20 CVC pairs, including 10 that rhyme (i.e. matching vowels and final consonants), five that were half-rhymes (i.e. matching vowels, non-matching final consonants), and five that were non-rhymes (i.e. non-matching vowels and consonants). Participants were told the definition of a true rhyme and asked to decide if each pair rhymes or not.

Participants in the two groups performed similarly in the auditory rhyme judgment task, with mean accuracy of 94% and 92% for the AOS and NBD groups, respectively. Two participants, A3 and N1, had the most difficulty, with less than 80% accuracy (figure 6.3.1). Analysis of the rhyme error types for individual participants is shown in figure 6.3.2. A3's rhyming errors included false negative responses, actual rhymes, and false positive errors for half-rhymes. The other participant with low auditory rhyme judgment accuracy, N1, had errors in all three categories.

Written rhyme judgment

Silent judgment of written rhyme was assessed by presenting 20 written word pairs on a computer screen and asking participants to decide if they would rhyme if they said them aloud. Half of the word pairs rhymed and half did not. Of the rhyming pairs, half were orthographically similar (i.e. obvious rhymes) and half were orthographically dissimilar (i.e. foil rhyme, e.g. laugh- staff). Similarly, for the non-rhyming pairs, half were orthographically similar (i.e. foil non-rhymes, e.g. head-beat), while the other half were orthographically dissimilar (i.e. obvious non-rhymes, e.g. suit-cop).

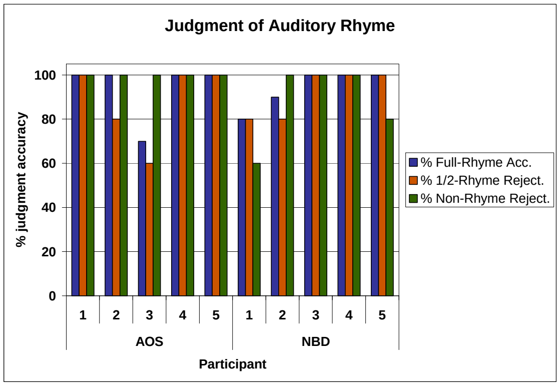


Figure 6.3.2. Auditory rhyme judgment accuracy. Individual results are presented separately for stimulus pairs that were full rhymes, half-rhymes, or non-rhymes.

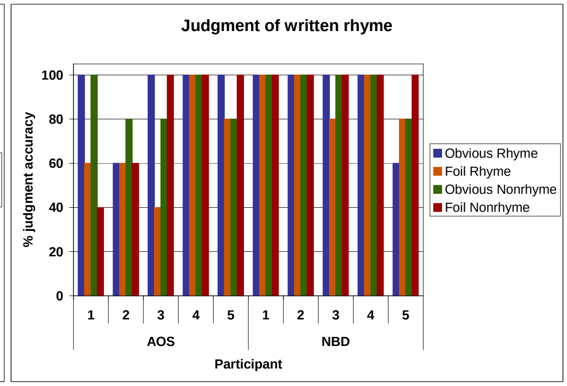


Figure 6.3.3. Written rhyme judgment accuracy. Individual results are presented separately for obvious and foil rhyme and nonrhyme stimulus pairs.

Three AOS participants (A1, A2, and A3) and one NBD participant (N5) had difficulty with the written rhyme judgment task, with less than 80% accuracy (figure 6.3.1). All four of these participants had different patterns of rhyme error (figure 6.3.3). Participant A1 made all errors on the foil conditions, while A2 made a similar number of errors in the different condition and A3 made errors only on the Foil Rhyme and Obvious Non-Rhyme conditions. N5 made no errors in the foil non-rhyme condition, two errors in the obvious rhyme condition, and one each in the foil rhyme and obvious non-rhyme condition.

Summary

Rhyme processing results revealed a mixed pattern of results across participant groups and tasks. The most consistent pattern of impairment was for three AOS participants (A1, A2, and A3) who had difficulty with silent judgment of written rhyme and rhyme generation (i.e. more than 4 errors per judgment task; 2 or less words generated per target). Two NBD participants had four or more errors in at least one rhyming task (N1 with auditory rhyme; N5 with written rhyme) and A5 had four errors in the written rhyme task. Only A3 had difficulty with all three rhyming tasks.

Chapter 6.4

Cross domain analyses

Perception-production links

One of the overarching objectives of this study was to examine the relationship between perceptual processing and motor targeting for vowels. Perceptual and production tasks were specifically designed to enable a comparison between the two domains. The acoustic distance ratio (ADR) serves as a metric of the distinctiveness between the two vowel pairs [ɪ]-[ɛ] and [ɛ]-[æ], while the sum of squared deviations (SSD) represents the goodness of perceptual categorization between the same vowel pairs. The relationship between production and perception was assessed by comparing summary measures of ADR and SSD for all participants, to determine if relatively good ability to produce distinctive vowel pairs (i.e. high ADR) corresponded with consistent perceptual identification (low SSD) and vice versa.

The perception-production relationship for the [ɪ]-[ɛ] and [ɛ]-[æ] vowel pairs are shown in figure 6.4.1 and 6.4.2 for participants in the two groups and for mean values across these two distinctions in figure 6.4.3. Linear regression analyses were completed to determine the strength of the relationship. While the number of participants was limited, very low and very high correlation coefficients between perception and production measures may indicate the lack or presence of a relationship between the two domains.

Findings suggest there is minimal or no relationship between perception and production for the tasks in this study. Very little of the variance in production measures was explained by the perceptual values for either the [ɪ]-[ɛ] or the [ɛ]-[æ] comparison, with R^2 statistics indicating that perceptual SSD accounts for between 1% and 18% of the variance in ADR (figures 6.4.1 and 6.4.2). Summary data across the two vowel distinctions confirms the lack of relationship between the two measures, with R^2 values of 0.00 and 0.30 for AOS and NBD participants, respectively (figure 6.4.3). These analyses underscore previous findings indicating higher vowel ADR in NBD compared to AOS participants and perceptual performance for some AOS participants that is similar to NBD participants and higher SSD values (i.e. less consistent) for others.

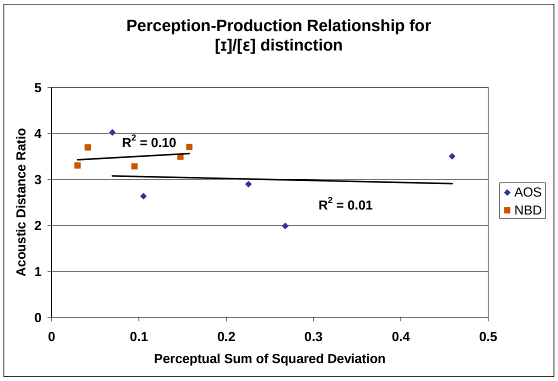


Figure 6.4.1. Perception-production relationship for the [ɪ]/[ɛ] vowel distinction in AOS and NBD participants. Acoustic distance ratio is plotted against the perceptual sum of squared deviation, with coordinates for AOS participants plotted as blue markers and NBD participants as orange markers. Linear regression lines and R^2 values for the relationship between production and perception are shown for each group.

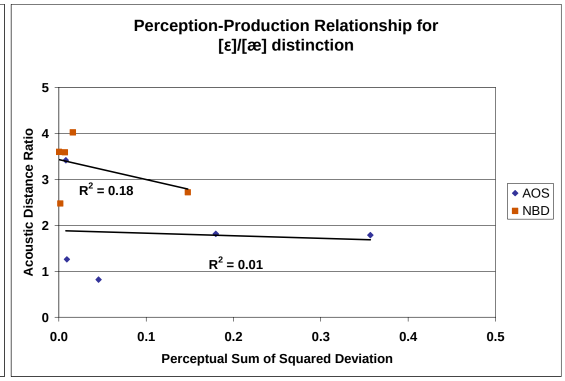


Figure 6.4.2. Perception-production relationship for the [ɛ]/[æ] vowel distinction in AOS and NBD participants. Acoustic distance ratio is plotted against the perceptual sum of squared deviation, with coordinates for AOS participants plotted as blue markers and NBD participants as orange markers. Linear regression lines and R^2 values for the relationship between production and perception are shown for each group.

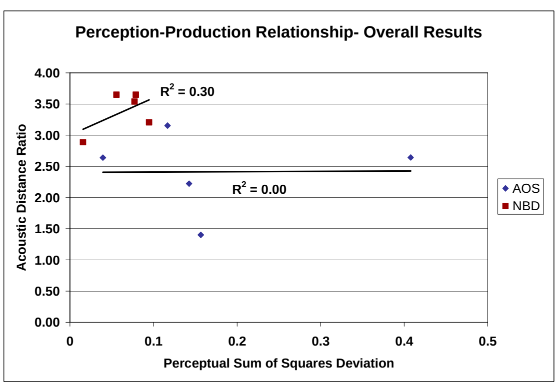


Figure 6.4.3. Overall group relationship of vowel production and perceptual identification. Acoustic distance ratio is plotted against the perceptual sum of squared deviation, with coordinates for AOS participants plotted as blue markers and NBD participants as orange markers. Linear regression lines and R^2 values for the relationship between production and perception are shown for each group.

Perception and production relationships with aphasia and apraxia battery results

Comparison of perception and production measures from the study revealed minimal relationship between the two domains. Further analyses were completed to determine the relationship of perceptual and production performance with results from apraxia and aphasia battery subtests for the AOS participants. For each of the analyses, the most salient factors from linear regression are presented, with comparison to linear regression models that include the Western Aphasia Battery aphasia quotient (WAB AQ) as an index of overall aphasic severity.

Production performance predicted by apraxia battery results

The comparison of acoustic vowel differentiation (i.e. ADR) with apraxia and aphasia battery results revealed a strong positive correlation between ADR and the ABA repeated trials subtest score (figure 6.4.4). High scores on the repeated trials subtest (i.e. fewer errors on repeated trials) predicted higher vowel distinctiveness, accounting for 77% of the variance in ADR measures ($p=0.051$). Addition of the WAB aphasia quotient, a general measure of aphasic impairment, did not significantly improve the fit of the model including only the ABA subtest ($p=0.72$).

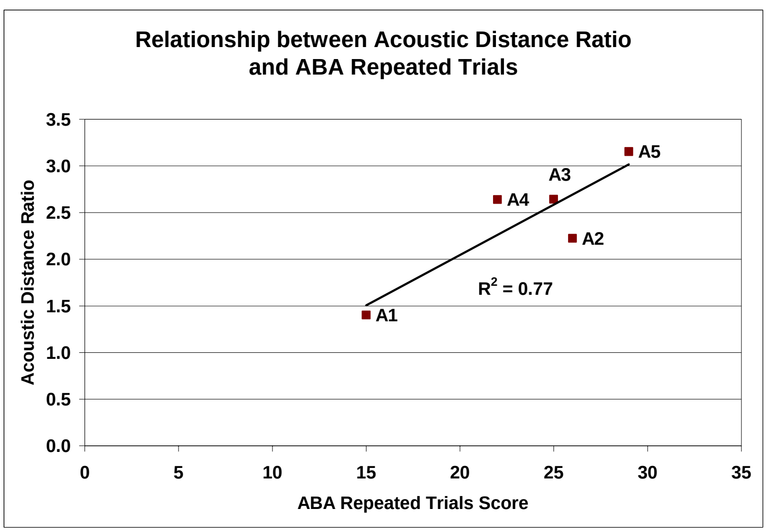


Figure 6.4.4. Relationship of vowel targeting and apraxia battery repeated trials performance in AOS participants. Acoustic distance ratio is plotted against the repeated trials subtest score from the Apraxia Battery for Adults (Dabul, 2000). A linear regression line and R^2 value indicates the direction and strength of the relationship between the variables.

Perceptual results predicted by aphasia battery results

Perceptual sum of squared deviation measures from vowel categorization were compared to apraxia and aphasia battery subtest measures, indicating a strong negative correlation of the WAB sequential commands subtest with perceptual SSD (figure 6.4.5). This finding suggests that individuals with poorer performance on performing multiple commands presented auditorily perform less consistently on the vowel categorization task, with sequential commands scores accounting for 88% of variance in SSD values (p= 0.018). The results of this analysis are tempered by the fact that three participants achieved ceiling performance on the sequential commands subtest. Nevertheless, it is clear that the participant with the least consistent perception (i.e. A3) had the poorest ability to complete multiple step commands, while participants with more consistent perception performed better on the WAB subtest. Addition of the general aphasia quotient did not improve the fit of the model (p= 0.26).

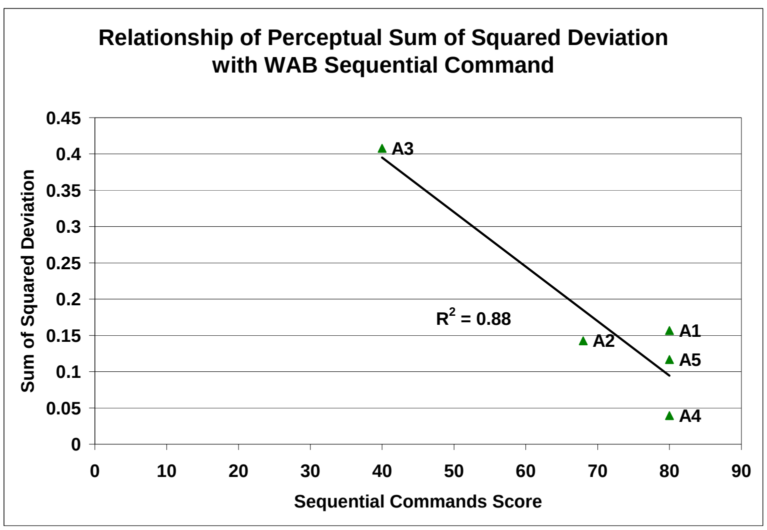


Figure 6.4.5. Relationship of vowel identification and comprehension of sequential commands in AOS participants. The perceptual sum of squared deviations is plotted against the sequential commands subtest score from the Western Aphasia Battery (Kertesz, 1982). A linear regression line and R^2 value indicates the direction and strength of the relationship between the variables.

Auditory rhyme judgment scores also were compared to battery subtest results. As with the perceptual SSD measure, auditory rhyme judgment was highly correlated with sequential command scores, with subtest results accounting for 99% of the variance in auditory rhyme perception (figure 6.4.6, p= 0.000). This finding is accounted for largely because participants A1, A4, and A5 all scored perfectly on auditory rhyme judgments and sequential commands. The remaining two participants, A2 and A3, both performed more poorly on both measures. Addition of the WAB aphasia quotient again did not significantly improve the fit of the regression model (p= 0.43).

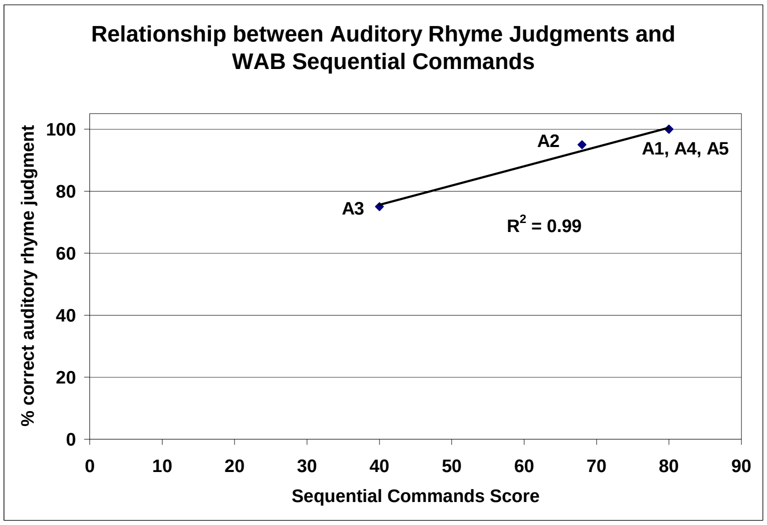


Figure 6.4.6. Relationship of auditory rhyme judgment and comprehension of sequential commands in AOS participants. Accuracy of auditory rhyme judgment is plotted against the sequential commands subtest score from the Western Aphasia Battery (Kertesz, 1982). A linear regression line and R^2 value indicates the direction and strength of the relationship between the variables.

While vowel categorization and auditory rhyme judgment were both highly correlated with the sequential commands subtest, they were also highly correlated with each other, with auditory rhyme judgment scores accounting for 90% of the variance in SSD values (figure 6.4.7; p= 0.013). As with the previous analyses, addition of the aphasia quotient did not account for significantly more variance in the model (p= 0.479).

Vowel discrimination accuracy also was compared to apraxia and aphasia battery subtest scores, revealing no strong relationships. Moderate correlations were found between vowel discrimination and auditory word recognition (R2=0.36, p=), sequential commands (R2= 0.44), and overall auditory comprehension (R2=0.44). Further comparison of vowel discrimination accuracy to the study measures of vowel identification and auditory rhyme judgment revealed only moderate correlations (R2= 0.31 and 0.40, respectively).

Summary

Auditory perceptual decisions, including vowel categorization and rhyme judgments, are not linked to vowel production distinctiveness measures in this study. Vowel production of AOS participants was correlated with performance on the repeated trials subtest of the Apraxia Battery for Adults, while perceptual decisions for vowel categorization and rhymes were highly correlated with performance on an auditory-based subtest of the WAB requiring auditory memory for multiple items. Vowel discrimination accuracy was not significantly correlated with aphasia and apraxia battery measures or with vowel categorization or auditory rhyme judgment.

Chapter 6.5

Group and participant comparisons

Individuals with apraxia of speech represent a heterogeneous population, with variability resulting from the extent of neurological damage sustained, the site of lesion, and in the degree of functional recovery from the insult. Results were reported by groups, although many exceptions to the group patterns often were observed. A list of group findings is presented to underscore the most relevant patterns that distinguished apraxic performance. A brief analysis of several exceptions to group findings is also included to better understand individual behavioral profiles in apraxia of speech.

Group findings

1. Apraxic speakers produce front vowel formants within normal ranges.
2. Bite block speech conditions increase targeting variability in both normal and apraxic speakers.
3. Vowel targeting and goodness is similar in monosyllabic and multisyllabic words for apraxic and normal speakers.
4. Perceptual ratings, targeting measures, and acoustic distinctiveness of vowels are poorer in AOS than in normal speakers in all conditions.

5. Vowel categorization was clearly impaired in most AOS participants, while NBD participants had only minor inconsistencies in identification.
6. Vowel discrimination performance was nearly identical in the two groups.
7. Perceptual and production abilities were not related in AOS or NBD participants.

Exceptions to group findings

The overall group findings indicated fairly consistent patterns of similarities and differences between AOS and NBD participants, although the differences typically were minor. Several notable exceptions were explored to better understand the disorder, including the questions of 1) why the participants A1 and A4 demonstrated such difficulty in producing distinctive vowels in bite block conditions compared to all other participants, 2) why vowel categorization is unimpaired in A4, and 3) why A5 demonstrates performance so close to normal in vowel targeting.

Apraxic participants A1 and A4 were the only two individuals in the study who demonstrated overlapping vowel formant distributions, particularly for the vowels [ɛ] and [æ] in bite block speaking conditions. These two participants were not particularly distinguished from others in the apraxic group in terms of apraxia severity, with moderate severity for A1 and mild-moderate for A4 and both had very minimal aphasic deficits. A1 and A4 were the only two apraxic participants without involvement of the temporal or parietal lobes and the only ones who were speakers of the Northern Cities dialect (Labov et al., 2005). It is possible that the frontal lesion involvement in these individuals was denser than in other participants, whose lesions were more widespread, and that the focal frontal damage resulted in greater difficulty with compensation for bite block constraints. At present the lesion data available is not detailed enough to allow for a more extensive analysis of the relationship between lesion site or size and the production deficit.

Another explanation for the vowel overlap for these two participants relates to the vowel shift affecting [ɛ] and [æ] that characteristically affects the Northern Cities dialect

(Labov et al., 2005). In particular, in this dialect [æ] is often produced more front than [ε] (i.e. higher F2) and sometimes [æ] is produced higher than [ε] (i.e. lower F1). The vowel spaces for unconstrained and bite block production depicted in figures 6.1.3 and 6.1.12 (a and e) show evidence for the vowel shift in these two participants. It is possible that the reduced vowel distinctiveness in these two speakers during bite block production was partially a result of having mean formant targets for [ε] and [æ] that were acoustically closer than for other participants in addition to the fact that both groups demonstrated increased vowel variability in bite block tasks.

Participants A4 and A5 were unique in that they were quite unimpaired in at least one experimental task. A4 had vowel categorization performance that was comparable to the NBD control participants, while A5 produced vowels in both unconstrained and bite block conditions that were as acoustically distinctive as NBD controls, with very low targeting variability. The lack of perceptual impairment in A4 might be explained by the fact that this participant had a small lesion that was limited to the posterior frontal lobe, and that the lack of temporal involvement spared auditory and phonemic processing abilities. A5 had damage to a variety of left hemisphere structures, including the basal ganglia, insula, and frontal operculum, as well as damage to the superior temporal gyrus. It is possible that, even with the number of structures damaged, A5 was spared the involvement of a neural region potentially important for spatial targeting (e.g. Broca's area). Again, the absence of more detailed lesion information precludes a definitive answer on how site of lesion impacted this participant's targeting performance. Notably, however, A4 and A5 were relatively young stroke survivors at the time of the study, approximately 1 year post-onset of insult. It is possible that these participants are more mildly affected by their strokes than the other participants, thus explaining the relatively mild nature of their deficits.

Individual differences in production and perception performance were expected, due to the unpredictable nature of brain injury. It is not certain why two participants had more difficulty with production than others, while two individuals had normal performance in at least one domain tested. Notwithstanding these unanswered questions, it is clear that spatial targeting for vowel production was affected in most individuals with apraxia of speech, albeit in a minor fashion, and that perceptual deficits in AOS, while common, are not directly linked to the control of articulatory movements for speech.

CHAPTER 7

DISCUSSION

Summary of findings

Vowel production in adults with apraxia of speech is more variable and less optimal than in non-brain-damaged (NBD) control participants, although this variation is subtle and does not represent a major contribution to the speech deficit in people with the disorder. Increased word length resulted in shifted vowel spaces for both groups but targeted vowels remained distinctive regardless of the word length context. Placement of a bite block destabilized vowel production, particularly in the most severely impaired apraxic participants. However, the bite block constraint affected the vowels of both AOS and NBD speakers.

Perceptual categorization of vowels was impaired in four of five AOS participants in the study, while same-different discrimination was unaffected for all participants. AOS participants who had the most difficulty categorizing vowels also had difficulty judging auditorily-presented rhyme pairs.

Production and perception of vowels frequently are impaired together in adults with AOS. However, the co-occurrence of these symptoms does not signify that inefficient perceptual processing is responsible for poor vowel targeting, as measures of these two domains were not related for the participants in this study. Vowel production and categorization measures were each correlated highly with clinical measures of speech errors and auditory comprehension, respectively.

The results of this study strongly indicate that apraxia of speech is a disorder of speech motor targeting, notwithstanding the frequent co-occurrence of perceptual and linguistic errors commonly found in individuals with the disorder. What remains is to determine what kind of a speech motor control theory accounts for the combination of findings observed in this study.

Interpretation of findings

The narrow purpose of this study was to better understand vowel production and perception and the relationship between them in adults with acquired apraxia of speech.

A broader intent was to learn about general principles of speech motor control, how different subsystems operate or interact, and how breakdown in these subsystems might result in impaired vowel production and/or perception. In general, the present findings reflect a speech processing system with subsystems for developing motoric programs for speech targets and for processing auditory-perceptual input that may be independently disrupted in adults who sustain brain injuries.

Articulatory variability

Vowel formant variation demonstrated by AOS participants is indicative of inefficient spatial targeting. Although this variation was minor for most participants, the question of why mean formant values are so similar between the two groups while AOS speakers have higher variability warrants further consideration.

The most likely cause of articulatory variability in AOS is that essentially intact phonemic representations are inefficiently translated into spatial articulatory parameters. This interpretation is accepted as definitional by most theorists (e.g. McNeil et al., 1997), although the mechanism by which inefficient transmission results in articulatory variability is unknown and is infrequently addressed by speech motor control models. A putative account of variable articulatory targeting in AOS will be advanced here, using the DIVA model as a theoretical framework (Guenther et al., in press).

The vowel sounds [ɪ], [ɛ], and [æ] may be considered as constituting distinct target regions in abstract representational space, conceived as an auditory perceptual speech sound map by Guenther and colleagues (in press, see figure 2.1.1). Auditory perceptual targets map onto corresponding articulatory parameters via adaptive synaptic connections, which are modified during the process of development to yield the most consistent articulatory behavior in response to desired speech targets.

The unidirectional feedforward mapping of auditory perceptual target onto articulatory parameters is characteristic of open-loop control mechanisms and direct routes of planning. Feedforward control mechanisms are most useful for the regulation of already learned and well-practiced movements in normal conditions.

Inexperienced speakers with little practice (i.e. babies) or those under unusual articulatory conditions (i.e. bite block constraints) require feedback control mechanisms (i.e. closed-loop, indirect route) to allow for corrections to the articulatory parameters derived via feedforward control. Feedback mechanisms usually are used to describe the method of adjustment for already-produced articulatory movements that result in unsatisfactory acoustic patterns. As conceptualized in the DIVA model, the same control mechanism is used to make predictive adjustments to articulatory parameters on the basis of initial vocal tract state (i.e. jaw constrained at 25 mm aperture). This is comparable to the predictive simulation concept advocated by Lindblom and colleagues (1979) to account for immediate compensation for bite block constraints.

Of interest is whether selective damage to one or more of these control mechanisms can account for the articulatory targeting deficits in AOS speakers. The most likely impaired subsystem in AOS is the more direct route of articulatory control (i.e. feedforward mechanism). Speech patterns produced using the feedforward control mechanism are theorized to be highly consistent due to the fact that the synaptic weightings from the speech sound map to articulatory parameters have been reinforced over a large volume of repeated successful mappings between the two levels.

When articulatory constraints are imposed on the speech production system, feedback control mechanisms respond by modifying the usual articulatory parameters in such a way that they result in perceptually adequate speech patterns. Bite block constraints resulted in greater targeting variability for both participant groups, although vowels were found to be acceptable variants of the intended productions for all NBD participants and for most AOS speakers. Findings of incomplete, albeit adequate compensation are consistent with decades of bite block research in normal participants (e.g. Baum, 1999; Baum et al., 1997; Fowler & Turvey, 1980; Gay et al., 1981; Kelso & Tuller, 1983; Lindblom et al., 1979; Lindblom & Sundberg, 1971). Articulatory gestures controlled by feedback mechanisms are more variable than those produced in feedforward control, although they generally result in acoustic patterns within the limits of perceptual adequacy.

Since AOS and NBD speakers demonstrated similar degrees of imperfect compensation for bite block constraints, it is unlikely that the feedback control mechanism itself is the locus of deficit and more likely that feedforward control is impaired for speakers with AOS. The hypothesis that AOS results from an inability to utilize direct or feedforward modes of articulatory control and the corollary that indirect control results in imprecise articulatory targeting has been suggested by other researchers (Varley & Whiteside, 2001; Whiteside & Varley, 1998). Preliminary evidence from the DIVA model also suggests that modifying the model to rely excessively on feedback vs. feedforward control mechanisms may result in speech errors similar to those of persons who stutter (Max, Guenther, Gracco, Ghosh, & Wallace, 2004).

The hypothesized deficit of feedforward control with takeover by the feedback system is plausible but may not account for all behavioral characteristics of AOS. Continued study of computational models of speech processing and the consequences of modeled lesions, as well as further validation of such models as realistic representations of human behavior are needed to evaluate the merits of this hypothesis.

<u>Inconsistent perceptual categorization is unrelated to articulatory inconsistency</u>

Four of five participants with AOS demonstrated erratic vowel categorization while discriminating between vowels equally well as NBD participants. The finding of normal discrimination with impaired categorization is consistent with previous studies of perception and production in aphasic participants (Blumstein et al., 1977). Quantification of the relationship between perceptual and production deficits in this study strongly indicated that impairment in the two processing domains was unrelated. A feasible theoretical model of speech motor control must account for the absence of a perception-production link and explain how perceptual categorization may be impaired in the face of normal discrimination and mostly intact auditory comprehension.

Vowel discrimination may be considered to require a relatively limited extent of auditory processing. Acoustic patterns of two stimuli, encoded as auditory states in the DIVA model, need only be compared with each other to determine if they are acoustically identical and do not require further processing to make the same/different discrimination decision. The evidence indicates that this basic level of auditory encoding is unaffected in all participants.

Further processing of auditory stimuli involves the conversion of the basic auditory state into abstract speech sound map activations. The finding of nearly identical perceptual category boundaries across participants, despite erratic vowel categorization, suggests that the auditory-perceptual representations of vowels themselves are not impaired, but inconsistently activated in perceptually impaired participants. Inconsistent activation of the speech sound map in apraxic participants may result from damaged neural projections from the basic auditory state map.

Auditory comprehension is considered to be a relative strength in individuals with AOS and this also was the case for the participants in this study. Findings of mostly normal auditory comprehension must be reconciled with the purportedly incomplete activation of the speech sound map. One potential explanation for the seemingly contradictory findings is that the speech sound map is sufficiently activated to stimulate a partial neural specification for a lexical item. Perceptually impaired listeners are able to comprehend spoken language because the mapping from phonemes to lexical units is not required to be precise.

Although auditory comprehension in AOS generally is intact, two of the participants with the most impaired perceptual identification had impaired comprehension for multiple pieces of information presented sequentially. This relationship suggests that the ability to maintain activation of auditory information over time may be related to the ability to make perceptual categorization decisions. This interpretation is consistent with proposals by several researchers that impaired auditory-verbal short-term memory is impaired in individuals with nonfluent aphasia and/or apraxia of speech (Blumstein et al., 2000; Rochon, Caplan, & Waters, 1990; Waters et al., 1992).

Comorbidity of apraxia and associated impairments

Vowel identification was impaired to various degrees in most AOS participants, suggesting that perceptual deficits are common in the disorder. Although production and perception deficits frequently co-occur in the disorder, findings also indicate that impaired processing in the two domains is not directly linked. In particular, one apraxic participant who demonstrated excellent targeting for vowel production in all conditions had inconsistent performance in vowel identification (e.g. A5), while another participant had clearly impaired vowel targeting with excellent vowel identification (e.g. A4). Motor targeting deficits can and do occur in relative isolation from sensory processing deficits, as suggested by previous researchers (e.g. Aten et al., 1971; Square et al., 1981, 1988).

Similarly, apraxia usually co-exists with various degrees of linguistic impairment (e.g. anomia, agrammatism, mild comprehension deficit). This study provides no evidence that aphasic deficits are directly related to apraxic speech impairment, although all participants presented with some degree of mild aphasia. Nevertheless, it is acknowledged that in a speech and language processing system in which cognitive, linguistic, and motoric abilities are interdependent, difficulties in one area will necessarily affect abilities in another domain.

Apraxia of speech in the isolated form is quite uncommon and is likely the consequence of a small discrete lesion to the posterior frontal lobe (e.g. participant A4). Most individuals with apraxia have neurological insults that include various degrees of damage to areas nearby to those considered responsible for AOS. The wide array of lesion sites and the corresponding variety of behavioral deficits in adults with AOS is challenging for researchers seeking to understand the core behavioral deficits associated with the disorder. However, it is important to study apraxia in cases confounded by comorbid sensory or linguistic deficits as well as in the relatively isolated cases, in order to better understand the typical presentation of the disorder and its relationship to related deficits.

Limitations of the study and future directions

The present study revealed excessive targeting variability in a small group of participants with AOS producing a limited set of vowel stimuli under controlled conditions. Imprecise vowel targeting was reflective of impaired speech motor control processes, although the task demands in the study do not capture the full extent of speech targeting deficits in individuals with the disorder. Apart from the obvious limitation in the small number of participants, the study focused exclusively on repetition of front vowels in the context of alveolar consonants.

Front vowels were chosen as the primary behavioral target for several reasons. The goal of directly comparing production and perception abilities for the same behavior necessitated using a set of stimuli that varies primarily along one acoustic and articulatory dimension (viz. first formant frequency and jaw position). The front vowel continuum also is optimal for detecting spatial targeting errors in vowels. Finally, for measurement reasons it was necessary to limit the base number of vowel categories due to the inclusion of a) four word length conditions, b) normal and bite block production conditions, and c) multiple (10) repetitions of stimuli in each condition. Notwithstanding these considerations, it is acknowledged that testing a more diverse sample of the vowel space would provide a clearer picture of articulatory targeting in individuals with AOS.

The same degree of targeting imprecision observed for the limited set of vowel stimuli may be more consequential for more complex articulatory sequences. Investigation of articulatory targeting in more complex sequences may prove beneficial to understanding the speech motor control impairment in AOS. For example, articulatory targeting may be more severely affected when the targeted vowel is not in the initial syllable and when the targeted vowel is bounded by consonants that vary both in place and manner of articulation.

This study differs from many previous studies of vowel production in AOS in that it examines targeting for vowels produced in several word length contexts. In order to study the phenomenon of immediate compensation, however, targeted vowels were always in the initial syllable position. Imprecise vowel targeting in normal and constrained production may be more exaggerated when targeted vowels occur later in the syllabic sequence.

The study also controlled the complexity of production stimuli by including only alveolar stop consonants at the inter-syllabic boundaries between vowel nuclei. Increasing syllabic complexity by including more difficult consonants (e.g. fricatives) as well as by juxtaposing vowels with one articulatory place (e.g. anterior) with consonants of another place (e.g. posterior) may serve to further highlight the motor targeting imprecision observed in relatively uncomplicated syllabic sequences. Consideration of vowel targeting in more complex sequences as just described was outside the scope of this study, but warrants further study particularly because of the temporal variability previously described in speakers with AOS (e.g. Kent & Rosenbek, 1983).

The effects of articulatory imprecision on consonant production, apart from the effects of consonant complexity on vowel targeting, also is of interest. While vowel variability had limited perceptual consequences, the same articulatory imprecision applied to consonant production may result in more pronounced effects on speech intelligibility, since more tightly controlled articulatory parameters generally are required for stop closures or fricative constrictions than for vowel positions (Guenther, 1995).

Interpretation of the study findings has emphasized that motor targeting for speech can be impaired in relative isolation and that perceptual deficits, while frequently co-occurring, do not represent a significant influence on speech production. However, the impact of "non-motoric" factors on speech production in conversational settings should not be underestimated, even in those speakers whose deficits appear to be restricted to motor targeting for speech. Individuals with AOS routinely perform better in controlled speaking tasks than in those that include demands on working memory, lexical retrieval, and management of speaking turns. A typical sequence in conversation with an apraxic person often includes the intelligible production of several words in a sentence, followed first by an articulatory breakdown, an attempt to recover from the breakdown, the "loss" of the intended word, and finally by the loss of the intended thought. Although the apraxic deficit was the primary area of difficulty for AOS participants in this study, demands of communication in real time clearly interact with the motoric act of articulation.

Final thoughts

Inconsistent spatial targeting of articulatory gestures is not the only factor that makes ordering a pizza or scheduling a doctor's appointment a task of great difficulty for people with AOS. It is argued here that impaired motor targeting is the precipitating factor in communication breakdown, exacerbated by multiple interdependent factors of cognitive and linguistic processing. Variability of motor targeting is observable in phonetically and motorically simple stimuli produced under controlled conditions of varying difficulty, although speech remains mostly intelligible in these limited contexts.

The findings in this study can be accounted for plausibly by a theory of speech motor control in which learned neural connections that map abstract representations of target sounds onto appropriate articulatory parameters are disrupted. Speech targeting proceeds using inefficient and error-prone mechanisms not well suited for rapid speech production and the time-sensitive demands of cognitive and linguistic processing. This account is promising but speculative, and further research into computational models of speech processing is needed to evaluate the validity of the model with respect to both typical and disordered human behavior.

Vowel production provides a window on articulatory targeting deficits in apraxia of speech, although vowels are not a major contributing factor to the communicative impairment in the disorder. Continued study of speech motor control abilities in the context of varied motoric, linguistic, and cognitive demands is needed to enhance our understanding of the mechanisms underlying the disorder. Improved understanding of the behavioral characteristics and the theoretical and etiological underpinnings of AOS will lead to more effective approaches for repairing or circumventing the deficient mechanisms and eventually result in improved communication outcomes.

APPENDIX A

VOWEL SCREENING WORDS

heat

head

hat

hot

hoot

hub

hid

head

had

pin

pen

pan

bin

ben

ban

mitt

met

mat

APPENDIX B

SINGLE-WORD INTELLIGIBILITY TEST WORDS

bad	read	lip
sip	sell	reap
spit	blend	rise
knot	shoot	row
sigh	see	wax
sheet	slip	dock
sticks	steak	cheer
knew	blow	hash
leak	beat	tile
chair	sin	bunch
nice	rock	ease
write	geese	seed
side	chop	sink
pat	ship	harm
hand	feet	cake
ate	coat	meat
witch	dug	had
much	cash	hail
sew	fill	hall
feed	hat	fork
him	hold	rake
at	heat	leak
air	bill	
pit	ache	

APPENDIX C

RHYME PROCESSING TASK WORDS

Table C.1.
Rhyme generation stimulus words

cap
shed
kick
suit
lock

Table C.2.
Auditory rhyme judgment stimulus pairs

/ɪ/	bid - rid
	pig - dig
	rib - hid
	fed - kid
/ɛ/	pet - jet
	bed - led
	web - peg
	beg - tag
/æ/	rag - lag
	hat - vat
	lab - rack
	pack - luck
/a/	knob - sob
	knock - dock
	rot - hop
	dock - sack
/u/	loop - soup
	root - shoot
	mood - tube
	boot - dot

Table C.3.
Written rhyme judgment stimulus pairs

/ɪ/	myth - kith
	Wayne - Lynn
	hymn - gym
	nip - nape
/ɛ/	dead - bed
	head - beat
	led - red
	get - take
/æ/	laugh - staff
	laugh - rough
	bat - cat
	cap - tape
/a/	watt - cot
	wad - sad
	rock - shock
	dock - coat
/u/	rude - sued
	food - hood
	loot - hoot
	suit - cop

APPENDIX D

INDIVIDUAL DISCRIMINATION RESULTS

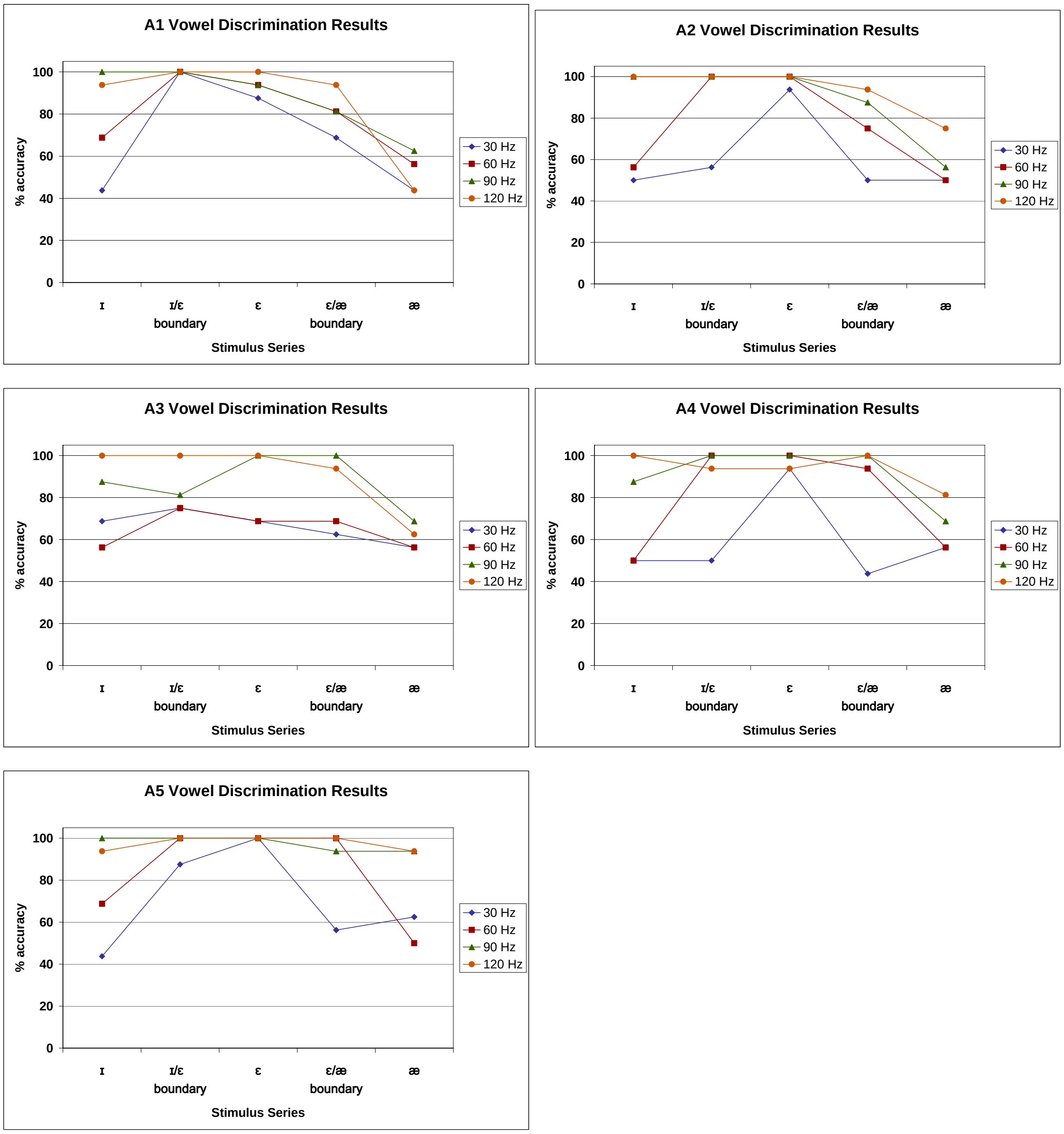


Figure D1. Individual discrimination accuracy results by stimulus series and step size for AOS participants.

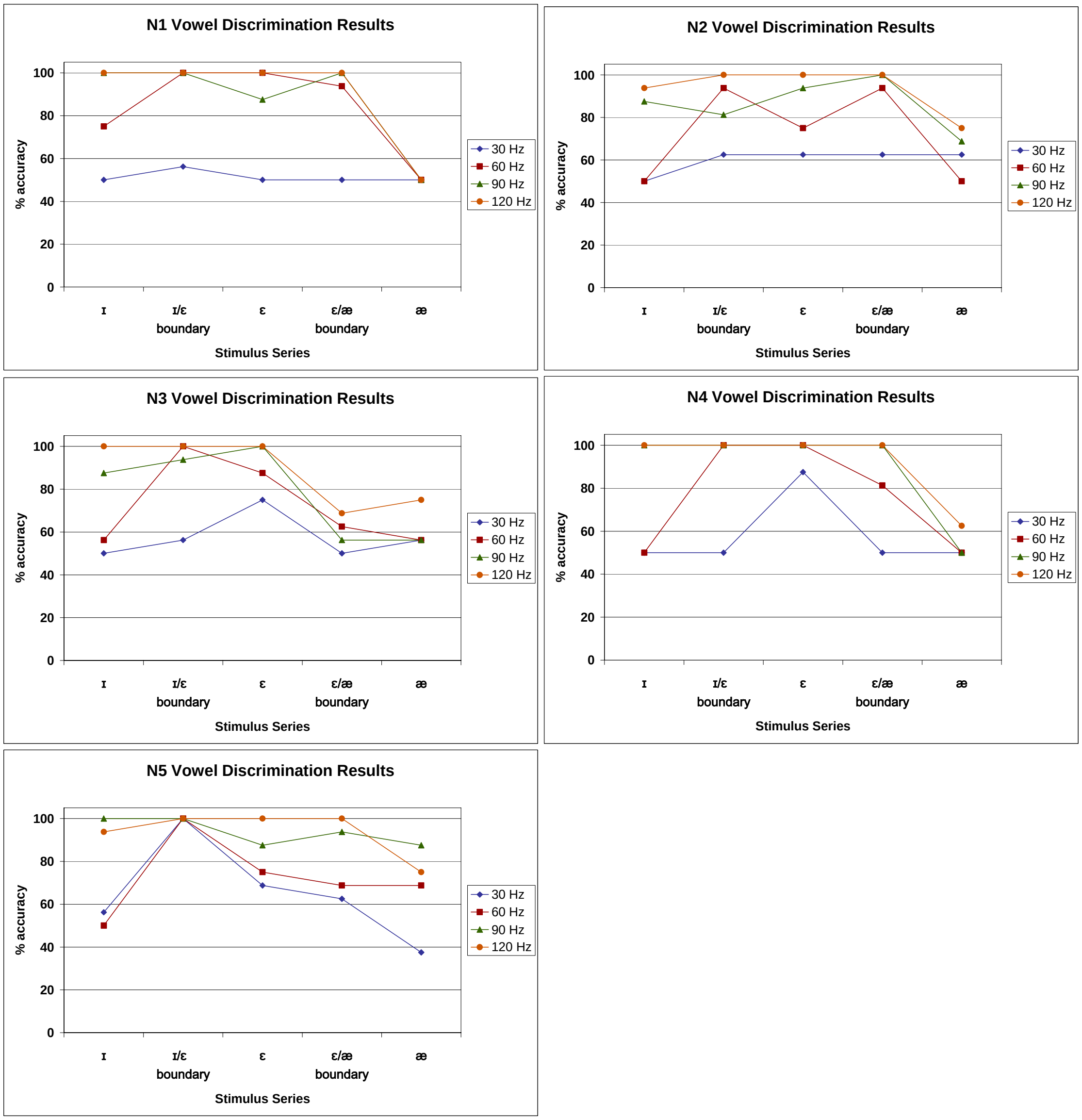
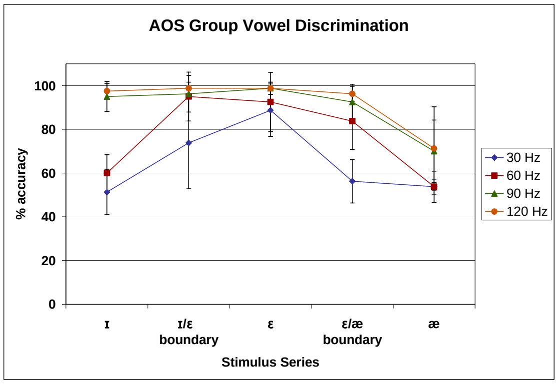


Figure D2. Individual discrimination accuracy results by stimulus series and step size for NBD participants.



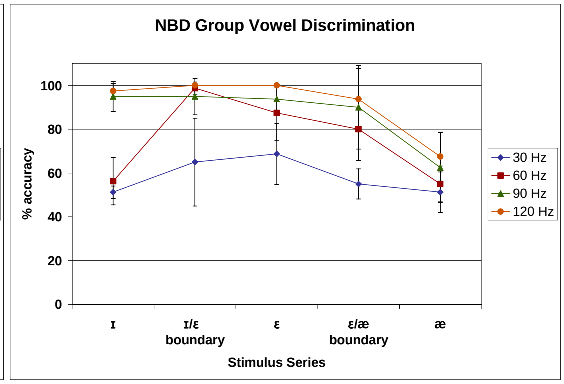


Figure D3. AOS group vowel discrimination results by stimulus series and step size. Standard deviation of individual results are shown as error bars.

Figure D4. NBD group vowel discrimination results by stimulus series and step size. Standard deviation of individual results are shown as error bars.

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