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Anticipatory Coarticulation and Stability of Speech in Typically Fluent Speakers and People Who Stutter Across the Lifespan: An Ultrasound Study

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Anticipatory Coarticulation and Stability of Speech in Typically Fluent Speakers and People Who Stutter Across the Lifespan: An Ultrasound Study

by

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science Department of Communication Sciences and Disorders with a Concentration in Speech-Language Pathology College of Behavioral and Community Sciences University of South Florida

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Abstract

This study uses ultrasound to image onset velar stop consonant articulation in words. By examining tongue body placement, the extent of velar closure variation across vowel contexts provides for the measurement of anticipatory coarticulation while productions within the same vowel context provide measurement of extent of token-to-token variation. Articulate Assistant Advanced 2.0 software was used to semi-automatically generate midsagittal tongue contours at the initial point of maximum velar closure and was used to fit each contour to a curved spline. Patterns of lingual coarticulation and measures of speech motor stability, based on curve-to-curve distance (Zharkova, Hewlett, & Hardcastle, 2011), are investigated to compare the speech of typically fluent speakers to the speech of people who stutter. Anticipatory coarticulation can be interpreted as a quantitative measure indicating the maturity of the speech motor system and its planning abilities. Token-to-token variability is examined from multiple velar vowel productions within the same vowel context, describing the accuracy of control, or stability, of velar closure gestures. Measures for both speaking groups are examined across the lifespan at stages during speech development, maturation, and aging. Results indicate an overall age effect, interpreted as refinement, with increased speech stability and progressively more segmental (less coarticulated) productions across the lifespan. A tendency toward decreased stability and more coarticulated speech was found for younger people who stutter, but this difference was small and absent among older adults. Outcomes of this study suggest the articulatory maturation trajectories of people who stutter may be delayed, but overall maturation of the speech
mechanism is evident by older adulthood for typically fluent speakers and those who stutter. Applications to intervention are discussed in closing.
1.0 Introduction

In this study, speech movement is examined through use of ultrasound imaging, which offers a safe, noninvasive (Wiethan, Ceron, Marchetti, Giacchini, & Mota, 2013; Zharkova, 2011), means for investigating anticipatory velar-vowel coarticulation and stability of speech in speakers who do and do not stutter across the lifespan. Ultrasound provides the ability to examine midsagittal contours of the tongue at the point of velar stop closure (Epstein & Stone, 2005), reflecting both the virtual target for the stop consonant beyond the palate as well as the advancement of the tongue body for the upcoming vowel (Frisch, Wodzinski, & Maxfield, submitted). These measures are clinically and developmentally relevant because the tongue is central to all vowel and most consonant productions and therefore much can be learned from the maturation trajectory as it relates to coarticulation and speech stability (Noiary, Ménard, & Iskarous, 2013). Furthermore, these measures are assumed to provide insight to the maturity of cognitive processes at the level of speech motor planning (assumed to be a linguistic function), necessary for fluent speech production (Barbier, Perrier, Menard, Tiede, & Perkell 2013; Van der Merwe, 1997).

In the current study, measures of velar vowel coarticulation and speech stability are compared across age ranges for both typically fluent speakers and people who stutter. Little is known about how aspects of lingual speech articulation, such as coarticulation and speech stability, vary between people who stutter in comparison to typically fluent speakers. Similarly, little is known about how the speech mechanism develops, matures, and ages when compared
between these populations. Information on the capabilities and constraints of speakers across the lifespan, and those with motor speech disorders, can provide a framework for treatment planning.

1.1 Theoretical Considerations

1.1.a Speech Production Models. Current theoretical frameworks from which fluent speech production may be analyzed provide a wide variety of models. In all models, there are a multitude of processes involved from language formulation to speech production. As applied to stuttering, it is suggested that speakers who stutter have impairment in the functioning of speech planning for production (Peters, Hulstijn, & Starkweather, 1989; Postma, Kolk, & Povel, 1990). Available models emphasize processes from the central nervous system’s efferent system, to lexical selection itself, having underlying involvement in moments of disfluency (Daliri, Prokopenko, Flanagan, & Max, 2014; Max, Guenther, Gracco, Ghosh, & Wallace, 2004; Smith, 2006). Some theorists propose that breakdowns in speech fluency may be influenced by linguistic, cognitive, and emotional factors in addition to the speech motor system itself (Smith, Sadagopan, Walsh, & Weber-Fox, 2010). Of interest to the present study are theories able to address both linguistic and speech motor deficiencies to explain hypothesized speech motor coordination and control differences in the speech of people who stutter. Also relevant, are theories illustrating the development and maturation of typically fluent speech motor control.

In one view, Smith et al. (2010) suggest that complex mappings of dynamical linguistic and speech motor commands are developed bi-directionally over time; meaning, “not only do linguistic goals shape motor commands, but preferences and features of the motor system shape linguistic processes” (Smith, 2006 p. 346). Due to limited language exposure and speech motor practice, neural maps of younger speakers are less developed and result in syllable and word
level production units. With increasing motoric and linguistic maturity, the mapping systems of adult speakers are more highly developed, and able to produce more stable and segmental speech patterns. This view maintains that the language and speech motor systems are developed over time, requiring years, possibly even into young adulthood before speakers reach adult-like levels of speech motor coordination. The idea of a complex mapping process provides rationale for the observed variance in patterns of speech production across the lifespan. Also, due to the linguistic-motoric involvement hypothesized to underlie moments of stuttering, the idea of a bi-directional mapping between these two possibly deficient processes provides a relevant framework for interpretation.

Inverse internal models of speech production are especially useful for interpreting differences in both speech motor control of stutterers as well as developmental differences in control of young children still acquiring mature production skills. Development of internal modeling is explained simply by Guitar (2014), who describes the process of speech production under this model as beginning with infant exposure to sounds in the environment. Sounds are stored as auditory targets and as children begin vocalizing, aiming to produce targets, “a mental model [is developed] of the relationship between their speech movements and the sounds they hear” (Guitar, 2014 p.92). The mental model grows and is continuously refined, containing the relation between speech sounds and motor commands. The model is said to be “inverse” since it involves the inversion of sensory targets to motor commands. During production, speakers rely on their internal (sensory-motor) model to plan and form the motor commands needed to produce the auditory targets necessary for carrying out intended speech (Guitar, 2014). Similar to this theory, as it applies to development, the Directions into Velocities of Articulation (DIVA) model suggests that children are less mature speakers due to their inexperience with “sensory
consequences of speech motor acts and still-developing forward models for the control of those acts. In other words, children do not have the same dexterity as adults because they do not have robust enough neural representations of their speech motor systems (internal models), particularly in terms of the amount of produced variability that is compatible with correct perception of the sound by listeners” (Barbier et al., 2013 p.2). Additionally, theories of aging suggest that general motor slowing may be attributable to “decrements in the efficiency of feedback mechanisms” (Sadagopan & Smith, 2013 p. 1562; Walker, Philbin, & Fisk, 1997). In this way, a theoretical model that credits fluent, mature speech motor control to efficiently working internal models (including feedback and feedforward systems) explains why underdeveloped or atypical control may be observed in the speech of children, aging adults, or disordered populations.

Similarly, inverse internal models have been applied to explain the speech movement patterns characteristic of stuttering disorders. Neilson & Neilson (1987) proposed that repetitions in speech production of young stutterers initially might be attributed to difficulty with creating and using the inverse internal model. Updated hypotheses suggest sensory-motor difficulty underlying stuttering disorders may provide a basis for differences observed in speech movement not explained by coordinative timing of articulators. Integrative feedforward/feedback models such as the DIVA model, propose stutterers have “unstable or insufficiently activated internal models” (Max et al., 2004 p. 105). People who stutter are hypothesized to have impairments to the working of both feedforward and feedback systems, with overreliance on sensory feedback and impaired readout of feedforward commands for speech (Max et al., 2004). The theme of overreliance on sensory feedback in speech production may play a role in explaining why speech motor control differs in those with fluency disorders. This claim is supported by results from
both kinematic and brain imaging studies, suggesting that stuttering breakdowns arise from problems with “movement preparation, sensory monitoring, and sensorimotor integration” (Max et al., 2004 p. 109). As Feng (2008, p.1) states, “accuracy of most motor tasks depends strongly on sensory feedback.” Since speech motor skill for fluent speech production involves transitioning from feedback to feedforward control, the supposed impairments in those specific control systems provides subsequent rationale for why speech motor control differences are hypothesized to exist in disfluent speakers.

1.1.b Articulatory Organization. Anticipatory coarticulation, specifically, is assumed to provide evidence of gestural planning; thus, variance in patterns of coarticulation across the lifespan at the physical level of articulation may provide information on plasticity of the speech mechanism itself. However, uncertainty regarding the neural representations for units of phonology and their organization hinder the ability to accurately define and generalize articulatory movement data from speech planning to speech production. Problematic to the study of speech motor production, there is a “significant gap between models of language processing and production models of speech motor control” (Smith, 2006; Smith & Goffman, 2004 p.332). As Sussman, Duder, Dalston, & Cacciatore (1999, p.1080) state, “very little is known about the developmental pattern underlying the emergence of segmental autonomy.” Theories of coordinative structures demonstrate that despite their differences, the continuous, context-dependent nature of articulation and the discrete, qualitative, context-invariant features of phonological representations can be collectively interpreted (Gafos & Goldstein, 2012; Kelso, Saltzman, & Tuller (1986); Saltzman, 1986; Saltzman & Munhall, 1989). Although there is existing evidence
that phonemic organization underlies speech production, little is known about its course of establishment (Nittrouer, Studdert-Kennedy, & McGowan, 1989).

In reference to coarticulatory unit sizes for speech planning and production current literature on linguistic representation suggests a developmental progression may exist (Goodell & Studdert-Kennedy, 1993; Nittrouer, Studdert-Kennedy, & Neely, 1996; Sussman et al., 1999). For example, children are proposed to utilize larger, less specified linguistic units (Kent, 1996). Perceptual studies provide evidence for syllabic organization of gestures in young children, with gradual reorganization to more segmental phoneme-sized phonetic units throughout development (Nittrouer, Studdert-Kennedy, & McGowan, 1989). As Goodell & Studdert-Kennedy describe children either acquire a repertoire of phonemes from which they then build their lexicon, or children build a repertoire of words and then “gradually differentiate the sequences into gestural and segmental components” (1993 p.707). The process of gradual differentiation into smaller articulatory units is also supported by evidence from speech error research (Goodell & Studdert-Kennedy, 1993).

Results of an in-depth case study supporting a progression from syllabic to segmental coarticulatory units focused on CV acquisition as measured through acoustic analysis of speech production with coarticulatory patterns maturing distinctly with time (Sussman et al., 1999). In this view, through a process of refinement of articulatory organization and improvement in coordination of articulatory gestures, adult speakers display more segmental, less coarticulated patterns of speech production as compared to children. Upon analysis, group specific coarticulatory patterns of the present study will be indicative, in part, of the underlying phonological representation and organization of gestural units in the speech planning stages prior to execution. Understanding organization of the speech motor system and its underlying
phonological representation is of clinical relevance since treatment may aim to enhance phonemic organization, if as a consequence speakers would improve in speech motor skill (Maas et al., 2008).

1.2 Stuttering. This study investigates speech stability and coarticulation in people with fluency disorders. Prevalence of fluency disorders, or stuttering, ranges from approximately 1.4% in children 2-10 years old to less than 1% in people 11-51+ years old, with an overall recovery rate of approximately 67% (Craig, Hancock, Tran, Craig, & Peters, 2002). The primary symptom of developmental stuttering involves disruptions of speech articulation, so an improved, comprehensive, understanding of speech production processes at the planning, programming, and execution levels may reveal relevant descriptive insight to the motor aspect of stuttering disorders. It should be noted this study is focused on aspects of speech motor planning and control, but there are many other variables (e.g. temperamentally related emotional reactivity and regulation) that are also hypothesized to contribute to stuttering (Conture et al., 2004). Fluency disorders manifest differently in each individual, but Guitar (2014) proposes “at least some degree of inefficient organization” underlying speech and language production and that “those children who stutter and have poorer sensory-motor skills or other speech and language disorders, may simply have greater anomalies in their neural circuitry functions, which affect fluency, articulation, language, or other sensory-motor tasks” (p. 109). The present study solely investigates speech at the production level, which intrinsically involves interaction between the speech motor and linguistic systems, both hypothesized as deficient to some degree in speakers who stutter.
Stuttering at the production level of speech has been suggested to be influenced by inefficient, slow, or dyssynchronous linguistic planning (Conture, Zackheim, Anderson, & Pellowski, 2004; Maasen, Kent, Peters, van Lieshout, & Hulstijn, 2004). It is suggested that speech motor breakdowns evident at the production level are, “the result of faulty or slowed input from the higher-level networks involved in translating abstract phonological words via a phonetic encoding process to motor programs” (Smith, Sadagopan, Walsh, & Weber-Fox, 2010 p. 2). Thus, measures of anticipatory coarticulation during dynamic speech production are utilized in the present study in order to better understand this proposed link in speech production between the physical level of speech articulation and the interrelated underlying linguistic systems in speakers who stutter.

Recent evidence suggests that people who stutter may differ in the linguistic stages of speech plan assembly (Maxfield, Pizon-Moore, Frisch, & Constantine, 2012), however; physiologic data also suggest those who stutter may have differences in the initiation, coordination, and control of speech movements (Kleinow & Smith, 2000; Peters, Hulstijn, & van Lieshout, 2000; McClean et al., 2004; McClean & Runyan, 2000; Walsh & Smith, 2013). Additionally, people who stutter were found to differ from non-stuttering peers for tasks of movement stability and strength of coordinative patterns (Namasivayam & van Lieshout, 2008). Much current research is focused on comparing speech motor abilities of children who stutter to typically fluent peers (Chang, Ohde, & Conture, 2002; Smith, 2006; Walsh & Smith, 2013). In terms of articulatory stability in lip movement, results of a non-word repetition task indicate preschool age children who stutter are delayed in maturation of speech motor control as compared to typically fluent peers (Smith, Goffman, Sasisekaran, & Weber-Fox, 2012). Further, studies investigating coarticulation and formant transition rate, found “subtle difficulties
learning, retrieving, storing, or executing certain temporal/spatial parameters of speech-language production may be associated with childhood stuttering” (Chang, Ohde, & Conture, 2002 p.687).

Results of acoustic investigations vary greatly, with some studies describing differences in the coarticulation of people who stutter as evidenced by greater formant transition slope coefficients and greater degree of contrast between formant transition rate and place of articulation than for typically fluent speakers (Robb & Blomgren, 1997; Chang, Ohde & Conture, 2002). Other results indicate normal ranges for the extent of anticipatory coarticulation when vowel influence on initial stop consonants was compared between people who stutter and typically fluent speakers (Sussman, Byrd & Guitar, 2011). When anticipatory coarticulation of fluent and disfluent stop + vowel productions were analyzed through the plotting of locus equation (LE) regressions, the slope of the LE regression functions was found to be within the normal range for both speaking groups. These results suggest that those five speakers who stutter do not possess deficits in their motor planning or execution as measured by their stop + vowel coarticulation for [bV], [dV], [gV] sequences (Sussman, Byrd, & Guitar, 2011). Results should be interpreted cautiously, as previous work that has focused on speech motor coordination and stability of people who stutter has mainly done so through acoustic analysis with accompanying video recordings used to identify fluent versus stuttered speech (Chang, Ohde & Conture, 2002; Robb & Blomgren, 1997; Sussman, Byrd & Guitar, 2011). However, studies relying on F2 measurements, or the spectral analysis of formant transitions, have recording limitations providing additional reasoning for caution during interpretation, especially when the overlap of speech articulation is of interest and specifically for populations with immature or disordered patterns of speech (Löfqvist, 1999). Use of ultrasound in the present study will provide a direct measure of lingual articulation during anticipatory coarticulation.
In general, the consensus from literature suggests people who stutter possess speech motor skills more limited than fluent speakers, with “less efficient and less flexible adaptation to lower motor and higher cognitive-linguistic order requirements that impact speech motor functioning” (Namasivayam & van Lieshout, 2011, p.477). Research on motor control in typical and disordered speech claims that lack of coarticulatory cohesion may be attributable to issues with planning and programming speech movements (Ziegler & Maassen, 2007). Subsequently, patterns compared from examining anticipatory coarticulation of stutterers and typically fluent speakers could reveal either similarities or differences in their speech motor abilities. Differences in coarticulatory patterns may be explained by insufficient coordination between stages of planning and execution during speech production (Howell & Dworzynski, 2005; Sussman, Byrd, & Guitar, 2011). Similar patterns of coarticulation between stutterers and non-stutterers may indicate that the breakdown for stuttering occurs elsewhere in the speech language system (Sussman, Byrd, & Guitar, 2011) attributing the disorder to factors other than speech motor coordination.

Research on speech motor ability is essential for gaining a comprehensive understanding of the complexities of speech production in people who stutter. Assuming stuttering to be multifactorial in nature (Smith et al., 2010), then a better understanding of motor speech performance for individuals who stutter will provide insight to one of the many factors involved in the disorder. By applying measures that intrinsically provide insight to higher-order processes underlying production, comparing performance measures to fluently speaking peers helps to explain whether speech motor systems of stutterers are weak or atypical. Stutterers who have disorders with a stronger speech motor basis, might achieve greater gains in fluency when intervention is targeted at improvement in aspects of speech motor ability, specifically. With a
better reference for the expected speech motor control in typical cases of stuttering, clinicians could appropriately plan assessment and treatment to better address deficits. With a complete understanding of acoustic and kinematic characteristics of speech production it may even be possible to reveal differences between those children likely to persist in stuttering versus those who will recover naturally (Smith et al., 2012; Walsh & Smith, 2013). Earlier identification, more accurate prognoses, and appropriate treatment decisions may significantly improve outcomes for young children with fluency disorders.

1.3 Coarticulation. For all speakers, the complex activities of connected speech articulation are highly context-dependent, and multiple speech gestures require coordination, or synergy, to create fluid speech movements (Katz & Bharadwaj, 2001). Coarticulation, or the overlapping of sounds in speech, is a phenomenon that results in measurable differences when sounds are examined in differing surrounding contexts (Zharkova, 2011). These differences are evident at the physical level of articulation and may be influenced by the context either preceding or following phonemes in production. Research on “inertial or mechanic-elastic properties of the articulatory system” tends to utilize measures of perseverative coarticulation whereas studies interested in “higher-level cognitive and linguistic mechanisms” tend to examine anticipatory coarticulation (Katz & Bharadwaj, 2001 p.139). Anticipatory coarticulation necessarily reflects an “adaptive and varying index of the extent of planning units” underlying speech production (Benguerel & Cowan, 1974; Danilof & Moll, 1968; Goffman et al, 2008; Katz & Bharadwaj, 2001 p.139; Nittroser & Whalen, 1989; Recasens, 2002;). Some anticipatory effects attributed to coarticulation can be observed over several intervening segments (Benguerel & Cowan, 1974; Kühner & Nolan, 1999; Sussman & Westbury, 1981). Evidence of coarticulatory influence in or
across words, whether from nearby or distant sounds, discounts the thinking that coarticulation is only the result of the dynamic assembly of gestures (Kühnert & Nolan, 1999). Instead, some forms of coarticulation at the level of speech production can be viewed as the result of an active, higher-level process, as different patterns of coarticulation are observed across different languages (Keating & Lahiri, 1993). Further support of preprogramming of articulation includes work on topics of early lip rounding and jaw height. Anticipatory effects are observed across labial, lingual, and other articulatory movements, providing additional credit to active, higher-order planning and its role in influencing articulation at the execution level. Labial coarticulation, investigated in adults by Daniloff and Moll (1968) and Lubker (1981), shows labial movement present preceding the rounded vowel, /u/ (Sereno et al., 1987). Furthermore, jaw movement has been shown to lower due to anticipation of the following articulatory context (Fujimura, 1961). To gather a sense of speech motor planning, programming, and production the current study specifically examines anticipatory velar-vowel coarticulation within words. In this way, “essential elements of both speech motor planning and execution can be parsimoniously assessed” (Sussman, Byrd, & Guitar, 2011 p. 169).

As previous articulatory and acoustic findings on velar-vowel coarticulation suggest, tongue body position for velar closure location is determined to an extent by phonetic context (Keating & Lahiri, 1993). It has been concluded in similar ultrasound investigations that placement of velar closure location falls along a continuous range where location placement is more front or back in the mouth based on following vowel context (Frisch, et al., submitted). A previous study utilizing a method of magnetic transduction described this same coarticulatory progression along the horizontal plane with velar frontness varying across the vowel contexts /u/, /a/, and /i/ (Löfqvist & Gracco, 1994). Previously demonstrated, closure location is not a fixed
articulatory gesture intrinsic to velar production; rather, it varies more front or back based on the features of the following vowel (Kühnert & Nolan, 1999). For example, the tongue body in a speaker’s mouth comes in contact with the palate more anteriorly (see figure 1) for the initial /k/ production in the word “key” as compared to the more posterior closure location (see figure 2) for the production of /k/ in the word “coo.” Although all speakers coarticulate to some extent in conversational speech, existing literature describes dissimilar patterns regarding coarticulation observed between speakers at different ages, provided many studies varied in their methods and measures; see section 1.5.a. Distances between closure locations are quantified in the present study, by calculating an average nearest neighbor curve-to-curve measure (Zharkova & Hewlett, 2009; Zharkova, Hewlett & Hardcastle, 2011).

**Figure 1.** Front vowel context /i

**Figure 2.** Back vowel context /u/

1.4 Token-to-Token Variability. In the present study, an additional measure of speech control, or stability of speech, is quantified through same-speaker word repetitions (see section: 2.4.b Measurement of Stability). In the present study, word repetitions were obtained concurrently with the coarticulatory measure, as it has been concluded that, “stable coarticulation is indicative of mature control of articulators during speaking” (Zharkova, Hewlett, & Hardcastle, 2012 p.118). Previous research has suggested adults who stutter are less stable even in their fluent productions as compared to typically fluent speakers. Smith et al. (2010) found adults who stutter...
perform less consistently on repeated inter-articulatory coordinative measures of production with distinct differences in coordinative consistency observed with increasing phonological complexity. Patterns of stability investigated for typically fluent speakers have identified stability to be influenced by age. Zharkova, Hewlett, & Hardcastle (2012) reported similar findings when speakers produced /ʃ/+vowel and /s/+vowel sequences multiple times allowing for a comparable measure of within speaker token-to-token variability. In general, the majority of studies focusing on within speaker token-to-token measures for typically fluent speakers have identified speech articulation to be more variable in children, with stability increasing with age (Kent & Forner, 1980; Koenig, Lucero, Perlman, 2008; Lee, Potamianos, & Narayanan, 1999; Nijland et al., 2002; Nittouer, 1993; Nittouer, Estee, Lowenstein, & Smith, 2005; Riely & Smith, 2003; Smith & Goffman, 1998; Walsh & Smith, 2002; Walsh, Smith, & Weber-Fox, 2006). Specifically, it is suggested that acquiring stability of speech is a developmental process, with “children under ten unlikely to reach adult-like capability” (Zharkova, Hewlett, & Hardcastle, 2011 p. 135).

However, some hypothesize that speech motor variability across levels of skill development may be either increased or decreased depending on various articulatory parameters. For example, Bernstein (1967) takes the view that because factors continually cause variance in the organization of coordinative structures, “multiple repetitions of a task are seldom repeated with the same movement parameters” (as cited in Sharkey & Folkins, 1985 p.8). In summary, though an overall consensus suggests speech motor control to increase with age for typically fluent speakers, the rationale provided for the observed increase is inconsistent. It should be noted that although some view an overall increase in stability of the speech motor system with development, not all agree that it is because of refinement in precision, instead offering rationale for decreased flexibility with age, or preference for habitual patterns (Sharkey & Folkins, 1985).
In general, those in support of a speech-motor approach suggest the increased stability is due to fine-tuning of the underlying motor processes for speech. For example, Bruner (1973) suggests that as children execute speech, their movement schemes are refined and stabilized over time based on perceptual output. In the present study, decreased token-to-token variability is interpreted as an indication of refinement of speech motor control.

1.5 Development and Maturation. Previous studies, including those on speech stability, demonstrate the occurrence of articulatory change even after young adulthood (Dromey et al., 2014). Even once phonemes produced by children are subjectively judged to be correct and similar to that of adult speech, numerous studies on the topics of duration, coordination, and intra-speaker variability in children’s speech reveal that measurable differences still persist (Munson, 2004). Once a child demonstrates coarticulation of speech sounds, they may overshoot mature target patterns before stabilizing (Noiray, Ménard, & Iskarous, 2013). However, relatively little is known about linguistic and articulatory changes as related to typical childhood development into adulthood and beyond in older aging populations.

Much literature associating articulatory control with age involves children or young adults; details relevant to the speech motor performance abilities of healthy aging adults are largely unexplained. Broadly speaking, in regard to performance on motor tasks, generalized slowness, decreased coordination, and lower performance levels are exhibited by older adults (Sadagopan & Smith, 2013; (Seidler, Albers & Stelmach, 2002; Stelmach, Amrhein & Goggin, 1988). An overall decrease in motor control abilities (Benjamin, 1997; Harnsberger et al., 2008; Mefferd & Corder, 2014) and less precise fine force control with increasing age have also been found (Mefferd & Corder, 2014). Due to the numerous declines associated with aging it can be
speculated that decline in speech motor functioning may also exist. As Levelt (1999) points out, “there is virtually no other skill we exercise as much as word production” (p.223). Taking this into consideration, when investigating speech motor control across the lifespan it would be reasonable to expect either evidence in refinement as reflected by increased stability, or age related declines as evidenced by decreased stability, possibly because of the complex nature of this skill. Previous literature specific to aging and speech production, evidences decreased spatiotemporal consistency with increasing age, observed for same sentence repetitions (Wohlert & Smith, 1998). As Sadagopan & Smith emphasize, additional study of speech motor skill as it relates to older individuals is necessary, “given the importance of speaking clearly and fluently over the lifespan” (2013 p. 1553). Stability and coarticulatory control are aspects of speech that help to make production fluent in conversation for listeners. Investigating these topics across the lifespan may aid in understanding the aging process as it relates to both fluent and disordered speech production. In terms of clinical implications, results may provide recommendations to guide treatment planning. See section 4.1 Treatment Implications.

1.5.a Coarticulatory Differences Across the Lifespan. Just as speech articulation is a developmentally changing process, the nature of coarticulation may also change throughout the lifespan. Differences in patterns of coarticulation produced by children and adults are “not attributable to age-related differences in vocal-tract anatomy”; rather, they may reflect different planning strategies (holistic or segmental) utilized by speakers for speech production (Munson, 2004 p. 59). Since underlying motor processes for anticipatory coarticulation are not believed to be innate, with gradual development instead implied, differences between adults and children,
who are still developing speech motor control skills, are to be expected (Sereno & Lieberman, 1987).

Previous studies describe differing amounts of coarticulation present in child versus adult speech (Sereno & Lieberman, 1987; Goodell & Studdert-Kennedy, 1993; Siren & Wilcox, 1995; Nittrouer, Studdert-Kennedy, & Neely, 1996; Zharkova, Hewlett, & Hardcastle, 2011; Zharkova, Hewlett & Hardcastle, 2012; Barbier et al., 2013; Noiray, Menard, & Iskarous, 2013). Results from previous investigations should be interpreted cautiously as to take each context and population into consideration when interpreting results (Smith et al., 2010). Additionally, since previous studies incorporate differing theories and models of speech planning and production in their explanations, the interpretation of results is further complicated. Some view the presence of more coarticulation in speech, reflected by observed increasing contextual effect on articulation of speech, as a maturity in the coordination and efficiency of articulators (Katz & Bharadwaj, 2001). Others, who view early speech production to be organized more holistically, tend to view a greater amount of overlap or coarticulation typically observed in child speakers, as an indicator of less mature speech organization (Gibson & Ohde, 2007; Goodell & Studdert-Kennedy, 1993; Nittrouer et al, 1996). What we expect to find may differ depending on whether anticipatory or preserverative coarticulation is measured and whether the coarticulation observed is within words or between words. As Table 1 below illustrates, controversy also currently exists surrounding to what extent coarticulation changes across the lifespan.

It should be noted that the previous literature addresses the topic of coarticulation through various methods of measurement. In the present study, ultrasound is used as a direct means of visualizing articulation and aspects of coarticulation. Previous studies have primarily used acoustic analysis. Acoustic measures may not be as precise of a measurement of velar stop
coarticulation because a portion of the coarticulatory transition occurs during the stop closure, and as a consequence is acoustically silent, unable to be analyzed directly (Zharkova, 2011). Other disadvantages of using acoustic measures to explore coarticulation include ambiguity due to the many-to-one mapping that occurs between articulation and its acoustic result. Also, the high fundamental frequency of speech produced by children makes for challenging estimation of vowel formant frequencies from acoustics alone (Katz & Bharadwaj, 2001).

Some studies suggest that there is no substantial interaction between coarticulation and age (Katz, Kripke, & Tallal, 1991). Alternatively, a study which utilized ultrasound imaging with a focus on articulatory synergy of the tongue tip and tongue body comparing children age 4-5 and adults found patterns of coarticulatory magnitude to be similar between the age groups (Noiray, Ménard, & Iskarous, 2013). Sereno & Lieberman (1987) found similar coarticulatory effects to be observed in an analysis of anticipatory labial coarticulation between children age 3-7 and adults, though children were found to be more variable in production. Other studies show results indicating a greater amount of coarticulation in children than adults (Nittrouer, Studdert-Kennedy, & Neely, 1996; Nittrouer & Whalen, 1989; Studdert-Kennedy, 1987; Zharkova, Hewlett, & Hardcastle, 2011). In contrast, some results show a lesser extent of coarticulation in children (Green, Moore, & Reilly, 2002; Kent, 1983).

Overall, a consensus subscribes to the view that coarticulation is more variable in the speech of young children. Evidence supports that motor planning involved in the production of anticipatory coarticulation is not innate; instead, is “gradually acquired with fine tuning of speech motor patterns” throughout childhood (Sereno, Baum, Marean, & Lieberman, 1987 p. 518). Results imply maturation of speech motor coordination is developmental skill (Robb &

**Table 1. Summary of recent coarticulatory research**

<table>
<thead>
<tr>
<th>Study</th>
<th>Country/Language</th>
<th>Sample Size</th>
<th>Age</th>
<th>Focus</th>
<th>Method</th>
<th>Stimuli</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barbier et al., 2013</td>
<td>Canada/French</td>
<td>30</td>
<td>Children 4 years old &amp; adults</td>
<td>Trans-syllabic anticipatory coarticulation &amp; speech motor control</td>
<td>Ultrasound</td>
<td>VCV sequences</td>
<td>Children showed more token-to-token variability</td>
</tr>
<tr>
<td>Gibson &amp; Ohde, 2007</td>
<td>USA</td>
<td>10</td>
<td>Children 17-22 months</td>
<td>Coarticulation of voiced stops</td>
<td>Acoustic Analysis</td>
<td>CV syllables: bV, dV, gV</td>
<td>Early coarticulation patterns are phoneme specific</td>
</tr>
<tr>
<td>Goffman et al., 2008</td>
<td>USA</td>
<td>16</td>
<td>Young adults &amp; children 4-5 years</td>
<td>Labial coarticulation</td>
<td>Kinematic Analysis</td>
<td>Stimuli pairs differing by rounded/unrounded vowel</td>
<td>No difference in extent of coarticulation, but lip rounding of children more variable than young adults</td>
</tr>
<tr>
<td>Katz &amp; Bharadwaj, 2001</td>
<td>USA</td>
<td>14</td>
<td>Adults &amp; children 7 and 5 years</td>
<td>Anticipatory coarticulation</td>
<td>EMA</td>
<td>CV syllables (fricative (s &amp; sh)-vowel)</td>
<td>Children as a group showed more extensive coarticulation than adults</td>
</tr>
<tr>
<td>Nijland et al., 2002</td>
<td>Dutch Speaking</td>
<td>15</td>
<td>Children 5-7 years</td>
<td>Anticipatory coarticulation</td>
<td>Acoustic Analysis</td>
<td>Schwa, C, V sequences (fricative &amp; stop)</td>
<td>Children exhibit more coarticulation than adults</td>
</tr>
<tr>
<td>Nittrouer et al., 1996</td>
<td>USA</td>
<td>40</td>
<td>Adults &amp; children 3, 5, and 7 years</td>
<td>Lingual coarticulation</td>
<td>Acoustic Analysis</td>
<td>CV syllables (fricative-vowel)</td>
<td>Children exhibit more coarticulation than adults</td>
</tr>
<tr>
<td>Noiray et al., 2013</td>
<td>French Speaking</td>
<td>11</td>
<td>Adults &amp; children 4-5 years</td>
<td>Coarticulation</td>
<td>Ultrasound &amp; Acoustic Analysis</td>
<td>VCV sequences differing by alveolar and non alveolar consonants</td>
<td>Similar coarticulatory magnitude/slope patterns between children and adults</td>
</tr>
<tr>
<td>Study</td>
<td>Country/Language</td>
<td>Sample Size</td>
<td>Age</td>
<td>Focus</td>
<td>Method</td>
<td>Stimuli</td>
<td>Results</td>
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<tr>
<td>Robb &amp; Blomgren, 1997</td>
<td>USA; English</td>
<td>5 PWS</td>
<td>Average 28 years PWS, Average 35 years PWNS</td>
<td>Lingual coarticulation</td>
<td>Acoustic Analysis</td>
<td>CVt syllables</td>
<td>PWS differ from PWNS in their coarticulation of speech sounds</td>
</tr>
<tr>
<td></td>
<td>Speaking</td>
<td>&amp; 5 PWNS</td>
<td></td>
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<tr>
<td>Sussman, Byrd, &amp; Guitar, 2011</td>
<td>USA; English</td>
<td>5 PWS</td>
<td>21-41 years</td>
<td>Anticipatory lingual</td>
<td>Acoustic Analysis</td>
<td>CV syllables (stop-vowel)</td>
<td>Extent of CV coarticulation does not significantly differ for PWS from PWNS</td>
</tr>
<tr>
<td></td>
<td>speaking</td>
<td>&amp; PWNS</td>
<td></td>
<td>coarticulation</td>
<td></td>
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<tr>
<td>Zharkova, 2008</td>
<td>UK; Standard</td>
<td>4</td>
<td>6-9 years</td>
<td>Anticipatory lingual</td>
<td>Ultrasound &amp; Acoustic</td>
<td>CV syllables</td>
<td>Children significantly greater amount of anticipatory lingual coarticulation than adults</td>
</tr>
<tr>
<td></td>
<td>Scottish English</td>
<td></td>
<td></td>
<td>coarticulation</td>
<td>Analysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zharkova et al., 2011</td>
<td>UK; Standard</td>
<td>10</td>
<td>6-9 years</td>
<td>Anticipatory lingual</td>
<td>Ultrasound</td>
<td>CV syllables</td>
<td>Greater amount of coarticulation in children &amp; Greater within-speaker variability in children than adults</td>
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<tr>
<td></td>
<td>Scottish English</td>
<td></td>
<td></td>
<td>coarticulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zharkova, 2012</td>
<td>UK; Standard</td>
<td>20</td>
<td>Children 6-9 years; Adults 27-46 years</td>
<td>Coarticulatory stability</td>
<td>Ultrasound</td>
<td>CV syllables</td>
<td>Greater within-speaker variability in children than adults</td>
</tr>
<tr>
<td></td>
<td>Scottish English</td>
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</table>

PWS = People who stutter; PWNS = People who do not stutter

**1.6 Purpose.** Articulation in the present study requires anticipatory planning of velar-vowel gestures, which is measured with a focus on contextual variability (coarticulation) and variability across repetitions (stability). These measures are obtained to provide insight for the speech planning and production of both typically fluent speakers and those who stutter, across three age
ranges: children 8-12, adults 18-40, and older adults 50-70. The purpose of this research project is to replicate previously studied topics of speech motor coordination and control and expand these measures to topic areas (stuttering and typical aging) where current literature is lacking.
2.0 Methods

2.1 Participants. 122 speakers participated in this stimulus reading task: 36 children (15 who stutter and 21 typically fluent) between the ages of 8-12, 46 young adults (23 who stutter, 23 typically fluent) between the ages of 18-29, and 40 older adults (11 who stutter and 29 typically fluent) between the ages of 50-65 were recruited from the community and were paid for their participation. All participants reported English to be their first language. The typically fluent speakers reported no history of speech, language, or hearing disorders. The people who stutter all self reported a history of developmental stuttering with no other speech, language, or hearing disorders.

2.2 Stimuli. 18 monosyllabic (CVC or CV) words embedded in a carrier phrase were presented one at a time through a computer-displayed script. All stimulus words were provided on a paper list to familiarize subjects before the recording. The stimuli consisted of the initial velar stop /k/ followed by one of nine Standard American English vowels: /i e æ ø æ ø u/. These vowels account for the entire continuum of possibilities for English vowel placement, front-to-back. Each vowel was used in two different words presented in a pseudo-randomized order ensuring identical vowel contexts were not repeated back to back. In the case of CVC words, the coda was either a bilabial (/p/ or /b/), or labiodental (/f/ or /v). Labial codas were used to reduce the influence of additional lingual coarticulation within words (Pouplier & Goldstein, 2005). The word stimuli were: /i/ key, keep, /e/ cay, cape, /æ/ cap, cab, /ø/ cup, cub, /ø/ curb, curve, /ʌ/ cop,
Word stimuli were produced in the phonetically neutral carrier phrase: “Say a ____ again”, which provides a stable coarticulatory environment between schwa vowels and aims for optimal imaging of the onset velar closure. Each stimulus phrase was produced three times in a row, for a total of 6 productions of /k/ for each vowel context.

2.3 Procedure. The stimulus script was displayed one line at a time on a computer monitor screen, using Articulate Assistant Advanced, 2.0 software (Articulate Instruments, 2007). The participant was seated in a steady chair in front of the computer screen. Measuring dynamic speech production requires stabilization of the ultrasound transducer beneath the tongue in order to obtain quality imaging for research purposes (Stone & Davis, 1995). Participants wore an adjustable head stabilization unit, shown in Figure 3, designed by Articulate Instruments for the purpose of holding the ultrasound transducer beneath the chin (Articulate Instruments, 2008). The ultrasound transducer was adjusted before recording for a centered midsagittal view of the tongue body between hyoid and sublingual shadows. An Aloka SSD1000 with 90-degree convex probe was used to generate the midsagittal ultrasound image. Video was monitored by research assistants from the ultrasound unit itself, set up to project behind the seated participant in order to minimize participant distraction. To control for rate of speech, participants wore a digital metronome over their ear in order to meter speech at the target tempo of 90 BPM. A microphone placed in front of the participant was connected through the synchronization unit, Sync BrightUp, to simultaneously record ultrasound video and acoustic data with a synchronization marker in the audio and video. Phrases were presented in a single fixed order across all
participants. Participants read each stimulus phrase three times in a row to the pace of the metronome.

![Ultrasound head stabilization unit](image)

**Figure 3.** Ultrasound head stabilization unit

### 2.4 Measurement

Continuous ultrasound video recording was obtained throughout the experiment in combination with acoustic and spectrographic data for articulatory analysis. Frames from the continuous recording displaying velar closure were identified manually following procedures from Frisch, et al., (submitted) and tongue traces from these frames were quantified as a set of points. Articulate Assistant Advanced was used to semi-automatically fit each velar vowel production to a spline using the midsagittal tongue trace on the ultrasound image, based on a fixed fan of 42 measurement angles from the virtual probe center. Although these splines contained points along the tongue and area of velar closure necessary for comparative analysis, the full spline also included points outlying the extent of the tongue’s sagittal length due to shadows created by the hyoid bone and visible sublingual space when using a 90-degree probe. Initial and final boundaries of each speaker’s tongue contour were marked manually, to exclude any anterior and posterior shadows since the primary area of interest is the
velar closure itself and the extent of the visible midsagittal tongue surrounding this area. As a result of data trimming, splines for each production varied in the number of points they contained. Measures were normalized to account for across-speaker differences in vocal tract size. Since participants were not balanced for age or gender, data were normalized by height of closure across participants as a proxy for vocal tract size. The average of the greatest y-axis value for each production was used as a normalizing coefficient. Although data normalization introduces additional analytic complexity, it helps to equate groups across the lifespan and reduce gender as a confounding variable in the present study.

2.4.a Measurement of Coarticulation. Coarticulation was determined through curve-to-curve distance comparison between tongue contours across the variety of all vowel contexts for each speaker following Zharkova, Hewlett, & Hardcastle (2011). See Figures 4 and 5 below. Average measures of coarticulation obtained from each speaker were then used in statistical analysis for age groups (children, young adults, and older adults) and speaking groups (i.e. typically fluent speakers and people who stutter) to compare overall patterns of coarticulation.

2.4.b Measurement of Stability. Data were quantified by distance between tongue splines using the mean nearest-neighbor point-to-point distance as proposed by Zharkova, Hewlett, & Hardcastle (2012). See Figure 6 below. For speech stability, average curve distance was obtained for stimuli with the same vowel context (e.g., a speaker’s production of /ki/ compared to the speaker’s other productions of /ki/). This average distance between curves within the same vowel context can be interpreted as a measure of speech motor stability for individual speakers. Effectively, the consistency of each stimulus repetition was quantified by the average curve-
distance between each pair of curves. Speech motor stability was determined within each individual and then used in statistical analyses of differences according to age groups (children, young adults, and older adults) and speaking groups (i.e. typically fluent speakers and people who stutter).

*Figure 4.* Ultrasound images depict a typically fluent young adult’s velar closure production of /k/ + vowel in nine contexts. Target words produced as follows: 1. key, 2. coop, 3. cape, 4. curve, 5. cope, 6. cup, 7. cap, 8. cop, 9. cough. Each picture is an example of one velar closure for one repetition of the target word listed. In total, the speaker repeated each of these and an additional nine words containing the same velar-vowel context, three times each.
Figure 5. Average velar vowel closures across 9 differing vowel contexts, within one speaker. For each speaker, the 6 velar closures identified for all same vowel context items were averaged. A spline contour was generated through Articulate Assistant Advanced, 2.0 representing the speaker’s average velar closure location for that vowel context. The average spline contours for each of the 9 target vowel contexts in this study are overlaid to visually demonstrate the extent of coarticulatory variability for a typically fluent young adult speaker.

Figure 6. Curve-to-cure comparison adopted from Zharkova et al. (2012 p. 197).
3.0 Results

Based on curve-to-curve distance calculations after data trimming and normalization, two-way analysis of variance of the between-context measure of coarticulation revealed the speaking groups differed significantly by age, \( F (2, 116) = 4.8, p = .01 \). This represents a small to medium effect size for age, \( (\eta^2 = .08, \text{Cohen, 1988}) \). Post-hoc comparison using the Tukey procedure for analysis of articulation of velar-vowel production between-context found the mean difference between children and older adults to be significantly different but for younger adults to not be significantly different from either children or older adults. There was no significant difference for the measure of coarticulation in people who stutter and typically fluent speakers, \( F (1, 116) = .53, p = .467 \). See Figure 7 for average measure comparisons. It should also be noted that the measure of coarticulation was larger than the measure of stability for all subjects, replicating the findings of Zharkova et al. (2011) with different segmental material.

![Figure 7. Average measures for between-context measure, demonstrating the extent of coarticulation due to vowel context, (C=Child, YA=Young Adult, OA=Older Adult).](image)
Two-way analysis of variance of the within-context measure of speech stability for both speaking groups revealed a main effect of age, $F(2, 116) = 20.4, p < .001$. This represents a relatively large effect size for age ($\eta^2 = .26$, Cohen 1988). As a whole, people who stutter did not differ significantly from typically fluent peers on within-context measures of speech stability $F(1, 116) = 1.1, p < .289$. See Figure 8 for average measure comparison. However, for the young adult group, an F-test for variance differences shows significant group differences between typically fluent young adults and young adults who stutter ($F(22, 22) = 0.19, p < .001$). Similarly, statistically significant difference in variance of within-context values was found between typically fluent children and children who stutter ($F(20,14) = 0.41, p < .05$). Post-hoc comparison using the Tukey procedure revealed the mean difference of within context values to be significantly different across all age groups: children, younger adults, and older adults, with the same trend here as was found in the coarticulatory measure.

![Within Context](image)

**Figure 8.** Average measures for within-context measure, demonstrating the speech stability within same vowel context repetitions, (C=Child, YA=Young Adult, OA=Older Adult).

Significant difference in variability of the within context measure was found between the typically fluent young adult group and the group of young adults who stutter ($t(30) = 2.1, p =$
while children groups had a non-significant trend in the same direction (t (22) = 0.41, p = .34). This difference completely disappears in the older adult groups. The findings of this measure of articulatory stability suggest that people who stutter may have less accuracy of control when compared to the typically fluent peer group. Given that stability increases with age, it is uncertain whether this difference reflects the people with stuttering as developmentally delayed compared to their fluent peers or whether there is a qualitative difference in the articulatory ability of people who stutter. Fluent children had more observed velar-vowel coarticulation, revealed by more variance in closure locations due to vowel presence, compared to children who stutter, suggesting that a developmental delay is not the appropriate explanation of the findings (cf. Zharkova, Hewlett, & Hardcastle, 2011). In all, children—both fluent and disfluent, had more observable coarticulation than younger and older aged adults, as expected.

Grouped patterns within individual speakers were analyzed to determine the correlation between the two performance measures under investigation, see Table 2 below. Positive correlations were found in all groups, indicating that speech stability performance is correlated with the extent of velar vowel coarticulation across individuals within groups. These findings further support the connection between a lifespan increase in speech stability and a development of segmental representation (reduced extent of anticipatory coarticulation) within the individual participants. Statistically significant were the correlations found for older adults (r (29) = 0.58, p < .001), typically fluent children (r (19) = 0.59, p <.01), children who stutter (r (13) = 0.65, p <.01), and young adults who stutter (r (21)= 0.63, p <.01). The presence of a statistically significant correlation for young adults who stutter, while no significant findings in typically fluent young adults, suggests these speakers who stutter may vary to a greater extent in the developmental maturity of their articulatory motor processes compared to typical speakers. One
question raised here is, why are young speakers who stutter more variable in their correlative measures? Possibly, the less refined speech of young speakers who stutter could be attributed to the chance that these individuals have a more limited amount of practice speaking. Other possibilities offered, in explanation of the more variable individuals who stutter, could be that these are the individuals who have a larger speech motor component to their disorder.

**Table 2. Correlations**

<table>
<thead>
<tr>
<th>Correlations for:</th>
<th>Typically Fluent</th>
<th>Stuttering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Children</td>
<td>0.59 *</td>
<td>0.65 *</td>
</tr>
<tr>
<td>Young Adults</td>
<td>0.32 +</td>
<td>0.63 *</td>
</tr>
<tr>
<td>Older Adults</td>
<td>0.58 **</td>
<td>0.36</td>
</tr>
</tbody>
</table>

**p < .001; * p < .01; + p = 0.14**
4.0 General Discussion

4.1 Treatment Implications. The scope of research in the present study, although distinguished as speech science, has valuable potential to inform intervention. The outcomes from speakers on the descriptive performance measures used in the present study are able to be bridged over to practical, clinical, use by interpreting the results of anticipatory coarticulation and token-to-token variability as a reflection of mature control of articulators, and aligning the results to specific existing approaches for treatment. Most work on these topics suggests either a linguistic-motor or motor-speech approach to intervention. Under a linguistic-motor approach clinicians target both language and phonology with rationale that speech motor control would improve as a result. A speech-motor approach focuses more exclusively on practicing speech production.

In terms of stuttering, a similar extent of coarticulation was revealed between the speakers who stutter and those typically fluent. However, if significant discrepancy in patterns of coarticulation for stutterers as compared to fluent peers had been revealed in the present study, then differences at the cognitive-linguistic level would have been implied, suggesting a more phonemically based treatment may be effective, clinically. If that had been the case, intervention aimed at decreasing overall cognitive demands (Sasisekaran, 2014) and strengthening organization of phonological representations in speakers with less mature or atypical articulatory abilities would be appropriate. Treatments aiming to improve efficient phonological encoding often involve “chunking” sentence components during speech planning and production to better facilitate fluency (Sasisekaran, 2014).
Since a similar degree of coarticulation was observed between speaking groups, then a speech-motor based framework to speech treatment for those with fluency disorders may be more appropriate for targeting the less refined aspects of speech production. Under a speech motor approach to therapy, clinicians presume increasing production, so simply practice, will best aim to improve speech motor skill. While practice may not necessarily directly decrease moments of stuttering, the aim is to refine the underlying components of the speech motor system. Since fluent, efficient, speech production relies on underlying coordination and control of articulators, the aim is to improve the production skills of stutterers to be as coordinated and controlled as that of fluent peers. Of course much current evidence for fluency disorders advises the use of an integrated approach to treatment where clinicians aim therapy to be all encompassing. So, the results of the present study do support use of a speech-motor based framework, but we promote this to simply be one aspect of an all-encompassing, integrated, approach to intervention. Recommendations for stuttering should focus on many evidence based suggestions including but not limited to: fluency shaping or stuttering modification, cognitive behavioral therapy, the targeting of language, social, and emotional factors- but, should not neglect the speech-motor practice aspect. Intervention recommendations for incorporating articulatory practice promote using an intensive service delivery model (Blomgren et al., 2005; Fry et al., 2009) based on the theory that “principles of speech motor learning parallel those of motor learning in general” (Kent, 2004 p. 19). Practice, especially early in development, is proven to help better define motor plans for speech movement (Sasisekaran, 2014). In addition, principles of motor learning described by Verdolini & Lee (2004) explain clinicians should encourage clients to facilitate their own feedback by providing questioning techniques suggested by Williams (2004) such as, “what were you doing?” as the client speaks a word fluently, or
“how does that feel?” to encourage the formation of new sensory habits. This recommendation especially applies to stuttering treatment for individuals who are practicing new modified speech behaviors.

Similarly, results from performance on the measures discussed across the lifespan may also align with either a linguistic-motor or motor-speech approach to treatment. If age effects were interpreted to be an indication of continuous refinement of the planning units for speech production, then clinical intervention recommendations for those with less stable abilities may target phonology. For example, treatment might take a linguistic-motor approach with a rationale such as that suggested by Smith & Zelaznik (2004) stating that the “developmental course for speech motor control reflects the continuing, growing interaction of the speech motor system with the developing language systems of the brain” (as cited in Smith, 2006 p. 339). According to this view treatment for speech motor control in children should support the development of both speech and language concurrently. In contrast, if stability were explained from a speech motor perspective where stability follows a developmental sequence across the lifespan, treatment would emphasize increasing productions during therapy without a particular need for a language component. Rationale for treatment recommendations targeting increased motor practice are derived from motor theories at large that have shown performance accuracy to improve with practice (Kelso & Norman, 1978; Kerr & Booth, 1978; Moxley, 1979; Sharkey & Folkins, 1985). The hypothesis here is that the speech motor practice would improve stability over time.

Does practice make perfect? Well, in terms of speech, the refinement in stability of speech observed across the lifespan may in fact be attributed to practice. Principles of motor learning support the recommendation that practicing speech may help to facilitate refinement in
control. This conclusion applies to speakers with speech motor disorders as well as typically developing children who have not yet mastered mature control of speech production. Taking into account that “sensory information plays a more important role in processes of motor learning than in performance of highly learned tasks,” treatment should emphasize practice beginning in the early learning stages of speech production (Hoyle, 1979; Sharkey & Folkins, 1985 p. 9). Still to be determined are specific clinical procedures for enhancing speech motor control, such as the recommended frequency and duration of sessions, scaffolding suggested, and appropriate stimuli for articulatory practice. As Maas et al. (2008) notes, the “optimal conditions of practice and feedback likely depend in part on the nature and severity of the underlying impairment.”

4.2 Limitations and Future Directions. In the present study, ultrasound was used effectively as a tool to investigate the velar vowel productions of 122 speakers including those who stutter across three age ranges. Data analysis was completed within and across speakers to investigate individual and group differences. Previous literature has not addressed speech motor stability and coarticulation using articulatory measures in typical and disordered populations with large enough samples to establish normative performance. In fact, a large sample size “is still rare in most speech production experiments” (Kühnert & Nolan, 1999 p 71). In the future, use of ultrasound with similar methodology may expand upon the development and refinement of speech motor coordination and control across the lifespan, in ways suggested below.

It should be emphasized that the results of the present study describe the metronome-metered speech of participants. Although a metronome played a crucial role in controlling for speaking rate, which is important in studying control and coarticulation, it is hypothesized that metronomes may have fluency-enhancing effects and reduce the demands of the speech motor
control system in all speakers, both typically fluent and stuttering (Namasivayam & Van Lieshout, 2011). Other limitations to be acknowledged in the current study include that the speech productions obtained were elicited from a script read aloud by participants. Results may be more representative of online formulation if spontaneous speech production was measured rather than scripted reading (Goffman, Smith, Heisler, & Ho, 2008). Future research should examine spontaneous, unmetered speech for both typical and disordered populations. Another limitation involves there being a target phoneme under investigation for coarticulation in this study: /k/, however; coarticulatory patterns may differ for other phonemes (or classes of phonemes such as fricative-vowel or stop-vowel). Consequently, it is suggested future research additionally explore other phonemes. Since it is also unknown if similar findings would be replicated for different phonetic contexts such as coarticulation of consonant clusters or different word positions (e.g. medial, final), a variety of contexts should be further investigated in future research. Studies focused on the development of coarticulation in young children should especially consider comparing a variety of phonemes seeing that Gibson & Ohde (2007) suggest coarticulatory patterns may be phoneme specific with extent of coarticulation greater in /gV/ than /bV/ or /dV/ syllables. Furthermore, results of cross-syllabic anticipatory coarticulation (e.g. measuring the anticipatory influence of V2 in V1 for V1-C-V2 syllables) may be more representative of speech motor planning processes, because coarticulation is even less likely affected by physical articulatory constraints (Barbier, et al., 2013).

Presently, literature on speech development emphasizes psycholinguistic processes with an abundance of research involving linguistic development and aspects of phonological and phonetic development. Lacking are studies focused on the speech motor system itself and its development (Kent, 1981; Sharkey & Folkins, 1985). Future research may consider investigating
speech motor coordination and control in the context of a broader age range, especially for children younger than 8 years to obtain more information on development, and for older adolescent aged speakers since it has been suggested consistency of speech is still improving significantly even after 14 years (Smith, 2006). In addition, longitudinal study of the topics discussed would greatly be of benefit to understanding typical and disordered speech development.

Given that perceptual organization of children is less segmental than adults (Nittrouer & Studdert-Kennedy, 1987), future research may additionally incorporate measures of speech production with measures of perception within speakers investigating how patterns evidenced by production (syllabic vs. segmental) correlate with perceptual organization. Better-defined developmental trajectories (involving perception and production) may eventually lead to helpful intervention recommendations. For example, if it is determined production and perception interact; treatment could aim to improve overall articulatory organization by targeting just one of the modalities heavily. Additionally, prospective studies on these topics may incorporate similar measures of articulatory coordination and control in combination with more global measures of other cognitive and linguistic abilities to investigate descriptively, how aspects of speech and language as a whole change, or adapt, as a function of development, maturation, and aging. Additional measures might be helpful in describing the performance of stutterers across the lifespan. For example, scores from the Stuttering Severity Instrument (SSI), could be collected to look more holistically at each participant who stutters’ overall performance and abilities not just on speech motor control and coordination but on a collection of descriptive measures across the lifespan.
In terms of velar vowel coarticulation, the extent of coarticulation observed for people who stutter did not significantly differ from typically fluent peers, consistent with findings from Sussman, Byrd, and Guitar (2011). The extent of inter-speaker variability was similar between groups. Since people who stutter performed similarly to typical fluent speakers on this measure of anticipatory coarticulation, it can be assumed that disfluencies are not attributable to poor speech motor planning and execution as measured by velar vowel coarticulation in this script-reading task. It should be noted though that all individuals who stutter may be influenced to a different extent by various underlying factors with some individuals having more or less of a sensory motor basis to their disorder, possibly confounding group comparison results. Although this study’s stability of speech measurements demonstrated people who stutter do not differ significantly from typically fluent peers in the production of within-context velar vowel repetitions, there was a trend toward less stability in people who stutter that merits additional investigation. As they stand, these findings are consistent with claims that people who stutter “may be located more toward the unskilled end of a presumed (normal) speech motor skill continuum” (Namasivayam & van Lieshout, 2011 p.477; van Lieshout, Hulstijn, & Peters, 2004). More data regarding the articulatory abilities of people who stutter may still be of benefit clinically, especially as it applies to early identification and prognosis.

A possible future outcome of investigating the coordination of neural to motor execution in young children who stutter could be the development of a predictive measure, able to aid in identification of children who will likely persist in stuttering versus those who will recover (Smith et al., 2012; Walsh & Smith, 2013). In order to determine whether children are at risk for persistence in stuttering, linguistic, motor, and emotional predictors should all be considered. The speech motor aspect of the factors contributing to persistence can be accounted for through
use of stability of speech measures sensitive to speech motor coordination, such as the token-to-
token variability measure used in the present study. Improved knowledge of typical speech motor
functioning would also provide a better means of comparison for other populations whose speech
production skills may be either immature in development or atypical such as in dysarthria or
apraxia of speech.

As far as interpreting results across the lifespan, for both speaking groups, patterns of
coarticulation varied from a greater to a lesser extent of vowel influence on velar closure, with
increasing age. These findings are also consistent with previous studies on the topic of
coarticulation of speech (Green et al., 2002; Kent, 1983; Kent & Forner, 1980; Koenig, Lucero,
Perlman, 2008; Lee, Potamianos, & Narayanan, 1999; Nijland et al., 2002; Nitttrouer, 1993;
Nitttrouer et al., 2005; Riely & Smith, 2003; Sharkey & Folkins, 1985; Smith & Goffman, 1998;
Walsh & Smith, 2002; Walsh, Smith, Weber-Fox, 2006; Zharkova, Hewlett, & Hardcastle,
2011). Since motor programs underlying anticipatory coarticulation are developed gradually,
additional research on the development of coarticulation in children may provide for improved
understanding of “automatized speech motor control patterns” (Sereno et al., 1987).

Similarly, for all speakers, speech stability measures varied from less to more stable with age.
Setting aside the variable of stuttering, the clear age effects show that speech production
becomes increasingly stable and increasingly segmental (less syllabic and coarticulated) over the
course of the lifespan. Notably, production is evidenced to shift from syllabic to more segmental
coarticulatory representation beyond the years typically considered in language acquisition.
These findings are consistent with theories of articulatory refinement, suggesting that articulation
is a skill that becomes increasingly entrenched in stable patterns over the course of the lifespan
through repetition.
Further study of typical development, maturation, and aging of the speech mechanism may be of benefit clinically, as specific speech motor abilities would be better understood across the lifespan. More research on the refining of features associated with coordination and control of speech, from planning to production, should be investigated in order to better understand these aspects across the lifespan. With a better understanding for what specifically leads to refinement, treatment can aim to capitalize on those components of speech production to possibly enhance or expedite these elements of refinement. An improved model of speech production and a more defined maturation trajectory would be advantageous scientifically and clinically to (a) provide framework for typical and disordered speech production abilities, (b) provide insight to developmental phonology, and (c) guide intervention practices appropriately.
5.0 Conclusion

In conclusion, this study expands on topics of speech motor planning, production, and control across the lifespan. Stability of speech posture was found to increase throughout the lifespan; however, this aspect of speech production may be considered delayed in people who stutter. Although no group difference was evident, based on possible delays in refinement of speech production evidenced; it is recommended speech motor abilities continue to be investigated in the stuttering population. Stability of speech was found to correlate with the extent of coarticulatory variation within individuals in every age category within each speaking group. Given these findings we suggest for typical speakers that aspects of phonological organization, speech motor coordination, and speech motor control develop and mature with age, providing evidence to support theories of refinement.
References


Wietlan, F., Ceron, M. I., Marchetti, P., Giacchini, V., & Mota, H. B. (2013). The use of electroglottography, electromyography, spectography and ultrasound in speech research-theoretical review. Revista, CEFAC (Ahead), 0-0.


Appendix: IRB Approval

4/28/2015

Nathan Maxfield, PhD
USF Communication Sciences and Disorders
4202 East Fowler Avenue, PCD1017
Tampa, FL 33620

RE: Expedited Approval for Continuing Review
IRB#: CR5_Pro00001111
Title: Picture Naming Electrified: Brain Electrophysiological Correlates of Psycholinguistic Planning in Adults who Stutter

Study Approval Period: 5/19/2015 to 5/19/2016

Dear Dr. Maxfield:

On 4/28/2015, the Institutional Review Board (IRB) reviewed and APPROVED the above application and all documents outlined below.

Approved Item(s):
Protocol
Document(s):
addendum #1
Maxfield_1_R03_DC011144-01[3].pdf

The IRB determined that your study qualified for expedited review based on federal expedited category number(s):
(4) Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing.

(6) Collection of data from voice, video, digital, or image recordings made for research purposes.

(7) Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

As the principal investigator of this study, it is your responsibility to conduct this study in accordance with IRB policies and procedures and as approved by the IRB. Any changes to the approved research must be submitted to the IRB for review and approval by an amendment.

We appreciate your dedication to the ethical conduct of human subject research at the University of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5638.

Sincerely,

John Schinka, Ph.D., Chairperson
USF Institutional Review Board