ATTENTIONAL FOCUS AND SPEECH MOTOR PERFORMANCE

by

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ABSTRACT

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Attentional Focus and Speech Motor Performance

Thesis directed by Professor Neeraja Sadagopan

Speech production is a fine motor skill that requires formation of muscle movement sequences and synergies that are refined over time through inclusion of cognitive, linguistic and sensory information (Stoel-Gammon & Dunn, 1985). Understanding what factors positively and negatively affect speech motor performance is of clinical relevance. In this study, the effect of an internal and external focus of attention on speech motor coordinative consistency (measured through lip aperture variability [LAVAR] index values), mean duration, duration variability, and behavioral accuracy (% phonemes correct), was investigated. Twenty students (aged 18-25) from the University of Colorado-Boulder, participated in a within-subjects experimental design. Nonwords, Real words, and tongue twisters were produced by each participant in both attentional focus conditions (internal and external), with order of condition counterbalanced across participants. Although overall results did not support higher accuracy or lip aperture trajectory consistency in the external condition as hypothesized, shorter production durations in the external condition were observed, possibly reflecting increased automatic control of speech movements when attention was focused on acoustic output.

Chapter 1. Introduction

Over the past 10-15 years, much has been learned about how the brain accepts and stores new information, retrieves previous memories, and controls our actions based on what we know and perceive. We now have a much more complete idea of the process of motor learning and performance. The central nervous system coordinates the function of many different muscles, incorporating sensory information from the world around us to determine appropriate responses and modify those responses; information such as the amount of pressure exerted by active muscles and the physical location of the body in space, in relation to concrete objects. These sequences of motor movements are also modified according to the environment and the task at hand. Using this complex information, the motor system creates and modifies movement sequences that result in learned, skilled motor behaviors such as playing sports, opening a jar of pickles, or playing the piano.

One such skilled motor behavior of particular interest in the field of Speech, Language, and Hearing Sciences is speech production. Speech production is a fine motor skill, and like learned limb motor movements, requires formation of muscle movement sequences and synergies that are refined over time through inclusion of cognitive, linguistic and sensory information (Stoel-Gammon & Dunn, 1985). Understanding the process by which new motor skills are acquired, and familiar motor skills are re-established is clinically relevant. Researchers studying limb movement, such as swinging a golf club or performing a basketball shot, have spent decades documenting factors that facilitate the acquisition and performance of novel limb motor skills (e.g. Schmidt & Lee, 2005; Wulf, Shea & Lewthwaite, 2010; see Maas et al., 2008 for a review). Application of these factors, often referred to as "principles of motor learning", to

the acquisition (and/or re-learning) of speech motor skills in both healthy and disordered individuals has been recently emphasized (Ludlow et al., 2008; Maas et al., 2008). However, little evidence exists to date on whether and how these principles apply to the speech motor system.

The aim of the current study was to examine the role of one specific principle, that of 'focus of attention', addressed extensively in limb motor learning and performance literature (e.g. Wulf, McNevin & Shea, 2001; Shea & Wulf, 1999; Wulf & Prinz, 2001), on speech motor performance in healthy young adults. In order to address this question, a within-subjects design was employed, wherein each young adult participant engaged in several different speech production tasks, under two different attentional focus conditions (external and internal). In the following sections, a more detailed background relevant to the current project will be provided by reviewing motor learning and performance, principles of motor learning, and the 'focus of attention' principle.

1.1. Motor Skill Acquisition and Performance

Although the current study focused on performance of skilled motor movements (rather than acquisition or learning), it is important to address theories of acquisition in order to provide a background for the reader. Studies examining reorganization in the adult brain during acquisition or adaptation of a motor sequence have provided valuable information about how the brain learns new motor patterns (Doyon & Benali, 2005). Motor learning is defined as "a set of processes associated with practice or experience leading to relatively permanent changes in the capability for movement" (Schmidt & Lee, 2005, as referenced in Maas et al., 2008). Motor learning occurs during practice of an action (acquisition), and proof of learning is measured

during the repetition of the same action at a later time (retention). When novel skills that require coordinated muscular movements are acquired, new motor patterns, or "programs" (Maas et al., 2008) are generated and learned (i.e., improved over time). Maas et al. (2008) define a motor program as a "unit of action that is retrieved from memory and then adapted to a particular situation". In the current study, we refer to performance as the process of retrieving a motor program in order to produce a skilled motor sequence (such as the production of a familiar word). One way to explain motor learning and performance is by considering the Schema Theory, as originally advanced by Schmidt (1975), and refined by Schmidt & Lee (2005). This prominent theory of motor control, learning, and performance states that an individual system selects a particular motor program and the appropriate parameters by integrating sensory information about current conditions with past experiences. In this context, schemas are defined as representations stored in memory of a particular pattern of relationship between stimulus and action (Schmidt & Lee, 2005). For example, consider an individual who has just mastered a particular tennis swing. They have stored a mental schema representing the distance between the ball and the racket when movement must be initiated, the muscle contractions (including timing and force) required to move the racket a particular way and contact the ball, and the outcome of their movement (hitting the ball with a particular directionality and force). When presented with a similar situation at a later time, with a similar ball approaching them at a comparable velocity from the same angle, their system will pull this schema from storage and apply it. Their system will also attempt to continually modify the schema by incorporating any salient novel information (such as particular muscle fatigue or a slightly altered trajectory). Once hitting the ball in this particular context has been mastered, variations of the same motor system and/or completely new schemas related to a different movement can be acquired and effected.

1.2. Principles of Motor Learning and Performance

Motor learning and performance is governed by many established principles that explain how plasticity is promoted in the brain (Shea & Wulf, 1999; Shea et al., 2001; Wright et al., 2004). These principles have been researched as they apply to limb motor movement and learning, and more recently, to oral and speech motor control and learning (Maas et al., 2008; Ludlow et al., 2008). There are two primary categories into which these principles can be divided: practice and feedback. Principles of feedback describe the influence of feedback timing, frequency, and type on an individual's acquisition, adaptation, and retention of a motor sequence. The category of practice relates to the current study, and will be discussed in greater detail below.

The principles of practice detail how practice variables (amount of practice, intensity of practice, practice schedules, attentional focus, etc.) can be manipulated to achieve effective and efficient motor learning and performance. Studies examining practice variables for acquisition and application of nonspeech motor skills have indicated the benefit of larger numbers of trials (Park & Shea, 2003), and that practice spread over a long period of time is more effective ((Shea, Lai, Black, & Park, 2001). Other studies detail the benefits of massed practice (Ramig, Sapir, Countryman, et al., 2001), more variable practice (Adams & Page, 2000), randomized practice (Wright et al., 2004), and the effect of training a complex versus a simple behavior (Morrisette & Gierut, 2003). Several studies examine the effect of attentional focus during acquisition and performance of motor tasks, and will be discussed in the following section.

1.3. The 'Focus of Attention' Principle

The principle of attentional focus as it applies to motor learning and performance was the focus of the current study. Extensive research has been conducted on the relationship between attentional focus and performance on complex limb motor learning tasks (e.g. Wulf, McNevin, & Shea, 2001; Shea & Wulf, 1999; Wulf & Prinz, 2001). Findings indicate that the learning process and performance may be affected by what the learner focuses on. By providing explicit instructions dictating attentional focus, researchers have shown that an external focus of attention results in greater improvements in motor skill acquisition and performance when compared to an internal focus of attention (Wulf, 2007). An external focus of attention may be described as focus on the "intended outcome of the action" (James, 1890, as referenced in Shea & Wulf, 1999), while an internal focus of attention may be described as the coordination of muscle and body movement required to produce the desired outcome (Shea & Wulf, 1999). Take the example of a baseball player attempting to hit a ball. By focusing on the end goal of contacting the ball with the bat and the ball remaining airborne for a certain period of time, the player is utilizing an external focus of attention. The goal, in this case, is to contact the ball with the bat, causing it to soar along a certain trajectory over the field (and not on the specific muscles that are contracted in order to swing the bat or maintain a particular posture). If the player were, instead, to think about specific muscles, and the order and strength of contraction required to produce the desired results, an internal focus of attention would be applied.

Findings from studies such as that carried out by Wulf, Lauterbach, and Toole (1999) provide support for the benefits of an external focus of attention during the acquisition and performance of a novel limb motor task. During this experiment, participants without experience in golf performed 80 practice trials of pitch shots (a shot produced with a highly lofted club

designed to go a short distance). Participants were randomly assigned to one of two equal-numbered groups (internal-focus and external-focus). All participants were given the same grip, stance, and postural instructions. Participants in the internal-focus group were directed during practice and performance to focus on the changing positions of the left and right arm throughout performance of the pitch shot (left arm initially straight and right arm bent, both straight, right arm straight and left arm bent). Participants in the external-focus group were directed to focus on the pendulum-like motion of the club, the weight of the club-head, the straight-line direction of the intended path, and the acceleration of the club-head moving toward the bottom of the swing. Performance was scored based on location of ball landing, with points allotted according to distance from intended target. Results indicate a significant group effect. Both groups improved in accuracy, but the external-focus group achieved overall higher scores and demonstrated fewer instances of error (missing the shot entirely or failing to land within the designated zones). These findings support the benefit of adopting an external focus of attention during acquisition and performance of a skilled limb motor task.

Zachary et al. (2005) provide additional support in favor of adopting an external focus of attention during a motor task using electromyography (EMG). Fourteen young adults (6 females, 8 males) with at least one year of prior basketball experience performed a total of forty trials each (20 under external focus conditions, 20 under internal focus conditions) with EMG electrodes located in pairs over the medial biceps brachii, the long head of the medial triceps brachii, the medial deltoid, and the medial flexor carpi radialis of each participants' preferred shooting arm. Participant movements were also video-recorded. The order in which external and internal focus trials were completed was varied between participants. Participants performing under the internal-focus condition were instructed to "concentrate on the 'snapping'

motion of their wrist during the follow-through of the free-throw shot" (Zachary et al., 2005). Participants performing under the external-focus condition were instructed to "concentrate on the center of the rear of the basketball hoop" (Zachary et al., 2005). Focus of attention instructions were repeated after each of the first three throws, and then after every other throw for the extent of the experiment. Accuracy was scored based on proximity to target, and errors (missed shots) noted. The authors reported a significant difference between accuracy scores for the external and internal conditions. Average EMG activity for the deltoid and flexor carpi radialis muscles did not differ significantly between the two conditions. Average EMG activity for the biceps and triceps muscles was lower under the external relative to the internal condition. The authors suggest that the reduced EMG activity observed under the external-focus condition might be viewed as reflective of increased efficiency in movement production.

A possible explanation of this relationship between attention and motor learning is provided by the *constrained action hypothesis* posited by McNevin and Wulf (2001). This hypothesis equates a 'skilled' performance with unconscious, automated control of movements, and suggests that a focus on the movements themselves (internal focus of attention) results in the attempt to consciously control processes that are naturally automatic, thereby disrupting 'skilled' performance and learning (Wulf, 2001). In other words, the imposition of conscious control over an inherently automated motor control mechanism only derails the process of developing automaticity. When left to its own devices, the human motor system integrates reflexive and voluntary control mechanisms fluidly, with a natural tendency to adopt an external focus of attention, resulting in more successful and efficient movements. Wulf, McNevin, and Shea (2001) tested this hypothesis during performance of a dynamic balance task. Twenty-eight young adult participants with no prior experience with the task were asked to balance on a

stabilometer and also to respond as quickly as possible to randomly presented stimuli with a hand-held response button. Addition of the secondary task allowed the researchers to more clearly assess the attentional demands of the primary (stabilometer) task. Participants were randomly assigned to an internal-focus or an external-focus group. Participants in the internal-focus group were instructed to focus their attention on their feet and attempt to keep them horizontal, while participants in the external-focus group were instructed to focus on markers attached to the platform at a distance of 22 cm. from the participants' feet. Trials continued for 90 seconds for each practice and retention session, and seven trials were performed by each participant per session. The experiment consisted of 2 days of practice and one of retention. Findings from this study indicate that an external focus of attention resulted in decreased primary task attentional demands and improved reaction times for the secondary task. Additionally, the external focus group demonstrated more frequent but smaller amplitude adjustments when compared to the internal-focus group. These smaller amplitude adjustments may be interpreted as improved muscular performance, as smaller amplitude response results in improved balance (as measured by root-mean-square error), requires less energy, and is therefore more efficient. This interpretation supports the *constrained action hypothesis*, which claims that an external focus of attention allows for implementation of automatic responses (contrasted to an internal focus of attention interrupting automaticity by imposing conscious control), resulting in more efficient, accurate, and less variable performance.

Although limited research has been conducted to examine the relationship between attention and oral-motor movement, preliminary data is promising. Freedman et al. (2007) conducted a study comparing the accuracy and stability of participant performance on an oral-motor task under both external and internal attentional focus conditions. Forty-six participants

(44 female, 2 male) were randomly assigned to either the internal focus group or the external focus group. They were given the tasks of rapidly exerting force with the tongue on the alveolar ridge and by squeezing the pressure transducer bulb with their hands. Performance was measured by a pressure transducer, the Iowa Oral Performance Instrument (IOPI), placed on the alveolar ridge of each participant or held in the participant's hand. Participants were given instructions according to their group assignment. Those assigned to the internal-focus group were instructed to "focus on the pressures they exerted with their tongues or hands", while those in the external focus group were instructed to "focus on the pressure they exerted on the IOPI's rubber bulbs" (Freedman, 2007). Absolute error and variable error of the peaks of each pressure burst were analyzed, and ANOVA results revealed significant main effects for group for both between and within-participant factors. This study provides us with the first step towards investigating the role of attention in the speech-motor system. Although the study utilized a non-speech task, the movement analyzed shares properties with several speech sounds, namely production of alveolar stops (/t/, /d/). These findings suggest that focus of attention plays a role in oral-motor performance, and generates the question of whether similar effects of attentional focus would be observed in the speech motor system.

The Lee Silverman Voice Treatment (LSVT) program provides some evidence suggesting that an external focus of attention results in improved performance during sustained phonation and various speech tasks (Ramig et al., 2001). Participants in LSVT programs are directed to focus their attention externally through use of visual displays correlating with the loudness of their productions and a visual and auditory model provided by the clinician. However, participant performance during LSVT therapy has never been compared to performance under an internal-focus condition.

The current study was designed to begin to examine the role attentional focus plays in speech production. An experimental protocol including multiple repetitions of words, nonsense words, and tongue twisters was used. A within subject paradigm was used such that each participant performed all tasks under the external and internal conditions (counterbalanced across participants). An external focus of attention during a speech task involves focusing on the acoustic result of speech production, while an internal focus involves focusing on manipulation of the articulators. Inclusion of nonsense words allowed for examination of participant performance on a novel task, for which existing motor programs were likely not already present or established. Participant production of familiar words under varied attentional focus conditions provided information about the effects of focus conditions on the production of utterances with established motor representations.

Inclusion of tongue twisters is supported by research by Keller, Carpenter, and Just (2002), findings of which describe complex patterns of brain activation recorded using functional magnetic resonance imaging (fMRI). Increased activation was noted in the inferior frontal gyrus and interior insula (known to be involved in articulatory speech programming and performance), as well as the inferior parietal cortex (associated with phonological processing and storage) during silent reading of sentences where the proportion of words with similar initial phonemes (a common component of tongue-twisters) is varied. Production of tongue twisters places increased demands on phonological processes, and analysis of participant performance under varied conditions provided information on the effects of attentional focus during a complex speech production task.

Kinematic and behavioral measurements were utilized to examine the effects of attentional focus on motor speech performance in the present study. Kinematic measures, such

as the LAVAR index (discussed in greater detail in Ch. 2), are an effective means of documenting between-trial variability of repeated productions. As the LAVAR index sums trial-to-trial deviations, they are utterance-specific. A low index score is associated with reduced variability, as this demonstrates a similar spatiotemporal pattern for each trial. Research into the development of speech coordination by Smith and Zelaznik (2004) indicates that in typical adult speakers, the variability of a set of multiple-effector, interrelated movement sequences is low for typical speech production when compared to immature systems. This decreased variability in mature systems is thought to be associated with increased automaticity in the execution of complex movement sequences. In the current study, increased variability of production observed under a specific attentional focus condition might suggest increased conscious interference resulting in reduced automaticity.

The following hypotheses will be tested in the current study:

- H0 (Null hypothesis): There will be no difference between the external and internal focus conditions on the production of nonwords, familiar words and tongue twisters.
- H1 (Expected Alternate Hypotheses):

1) <u>Differences between focus conditions:</u>

Maintaining an external focus of attention during a speech performance task results in (a) more highly coordinated lip aperture trajectories (lower LAVAR values), (b) increased accuracy (% phonemes correct), (c) shorter production durations, and (d) lower durational variability than the internal focus condition for all the novel and familiar words. This was expected because normal speech acquisition is highly reliant on an external focus of attention, namely auditory feedback (e.g., Perkell et al., 2000). Since the novel nonwords used in the experiment consist of phonemes used in the English language in allowable combinations, it was expected that during

production of accurate novel words, the same strategy would be preferred as for the production of familiar words.

An internal focus, on the other hand, was expected to disrupt automatic mechanisms of speech motor control, thereby introducing variability in the production of otherwise automated utterances (familiar words) and utterances that rely on existing automated representation of speech production and coarticulatory patterns (novel nonwords).

A secondary goal of this study was to provide pilot data for future studies investigating the role of attentional focus applied to oral-motor learning in speech production. The positive effect of an external focus of attention during limb motor learning and performance has been well documented. Although few in number, studies examining the effects of an external versus an internal focus of attention on oral-motor performance and learning support the application of the 'focus of attention' principle to the oral-motor system. Determining whether this principle remains true for the speech motor system is valuable to the field of speech-language pathology. If manipulation of attentional focus is shown to have an effect on normally functioning young adult speakers, then the possibility arises that it may also affect speech motor performance in disordered individuals.

Chapter 2. Methods

2.1. Participants

There were 20 participants, all young adult undergraduate and graduate students at the University of Colorado at Boulder. For the purposes of this study, an equal numbers of males and females were enrolled. Participants ranged in age from 18 - 25 years (mean age: 20.7 years; SD: 1.6). They were recruited through newspaper and online advertisements, fliers placed in public sites, the Buff Bulletin, a twice-weekly digest delivered electronically to faculty and students of the University of Colorado at Boulder, and word-of-mouth. Additional participants were recruited through messages to participants from previous research studies who signed a form indicating interest in future studies. Students interested in participating were given an initial screening through email or over the phone. Students considered eligible for this study did not have a history of neurological problems or speech, language, of hearing disorders. They did not have lip or tongue piercings unless they were willing to remove the piercing for the duration of data collection. Participants for this study were monolingual English speakers. They were not taking medication for depression or an attention disorder. Additionally, students with a major of speech pathology or linguistics were disqualified on the grounds that their experience might affect their performance on speech tasks. Once eligibility was established, participants agreed to attend one data collection session lasting 2-3 hours. Upon acceptance into the study, participants were given a list of instructions to be followed. These instructions included no alcohol for at least 24 hours immediately prior to data collection (McKinney & Coyle, 2004), no exposure to extremely loud noise for at least 24 hours prior to data collection (Danenberg, Loos-Cosgrove, & LoVerde, 1987), and a good night's sleep prior to the day of data collection (e.g., Walker &

Stickgold, 2006). These instructions ensured that possible threats to the internal validity of findings in this study were controlled for to as great an extent as possible. Each session consisted of screening and/or behavioral testing, and data collection, and did not exceed 3 hours in length. Participants were compensated for their time. The Institutional Review Board at the University of Colorado, Boulder approved all procedures used in the present study (protocol # 10-0192).

On the day of the experiment, participants were administered an oral mechanism screening checklist to verify intact function of oral structures. Participants also passed an audiological screening of a 25 dB HL pure tone presented at 500, 1000, 2000, 3000, 4000, and 6000 Hz in each ear. In addition, they completed a checklist verifying that they followed the instructions given when they were enrolled in the study. If any of the three above criteria were not met, participants were not eligible to begin the study. Participants' cognitive and language abilities were documented through behavioral testing. The Vocabulary subtest of the Wechsler Adult Intelligence Scale (WAIS-III, Wechsler, 1997) was used to estimate general language ability, the Digit Span subtest of the Wechsler Adult Intelligence Scale (WAIS-III) was used to assess auditory short-term memory, the Wisconsin Card-Sorting Test (WCST, Grant & Berg, 2003) was used to estimate general executive function, a Nonword Repetition Task (Dollaghan & Campbell, 1998) was used to measure nonword repetition ability (reflective of phonological skills and phonological working memory), and the Brief Test of Attention (BTA; Schretlen, 1996) was used to assess auditory and visual attention. These tests were not used for exclusionary purposes, but to catalog potential discrepancies that might contribute to results in order to preserve internal validity to as great an extent as possible. All participants performed

within normal limits for their age on each of the above tests. Mean total % phonemes on the Nonword Repetition Task was 95.33 % (SD =2.66).

2.2. Procedure

The methods used for kinematic data collection and analysis were similar to those described by Sadagopan and Smith (2008) in their study describing speech movement variability relative to age and utterance length and complexity. A Northern Digital Optotrak Certus camera system (NDI; Waterloo, Ontario, Canada) was used to record kinematic data. Participants wore a pair of plexiglass goggles with an elastic strap and a splint attached to the outer edge of the goggles extending downwards on both sides. Three small infrared light emitting diode markers (IREDs) were placed on the participant's upper lip, lower lip, and a jaw splint. One additional marker was placed on the forehead and four on splints attached to the plexiglass goggles. The IRED markers were placed as close to midline of the forehead and chin as possible, approximately at the corners of both eyes and at both corners of the mouth on the goggle splints, and at midline on the vermilion border of the participants' upper and lower lips. The IREDs on the goggles and forehead formed a dynamic "rigid body" reference system that was tracked in order to record head motion. The motion of lower lip, upper lip, and jaw markers was then analyzed relative to the position of the rigid body, allowing for participant's postural adjustments. The IRED markers were attached to the participant's skin and goggles using small rings of double-sided adhesive. The chin splint was secured in place with surgical tape.

Kinematic data for each production was drawn from the superior-inferior movement of the IRED markers on the upper and lower lip and the chin. Displacement during production was tracked and recorded by the Optotrak camera system. Each IRED marker was sampled at the

rate of 250 samples/s. An audio signal was also digitized by the Optotrak Data Acquisition Unit (ODAU) at the rate of 16,000 samples/s. This audio signal was digitized by an A/D converter on the Optotrak equipment, integrating the audio signal to the movement for each production, and thereby allowing the experimenter to listen to each signal being analyzed during data analysis. A separate high-quality acoustic signal recording was made using a Marantz PMD 670 digital recorder, sampled at 48 KHz and with 16 bit resolutions. This recording served two purposes: (a) it was used by the experimenter to make perceptual judgments of utterances during behavioral analysis, (b) and the audio recording was downloaded into PRAAT (Boersma, Paul & Weenink, David (2010). Praat: doing phonetics by computer [Computer program]. Version 5.1.43, retrieved 11, September 2010 from http://www.praat.org/) in order to analyze acoustic components of the production when necessary to verify perceptual analysis of phoneme error.

2.3. Experimental task

The stimuli used in this experiment included two 2-syllable nonsense words, two 3-syllable nonsense words, two 2-syllable words, two 3-syllable words, and two tongue twisters. All words and nonsense words used were phonotactically comparable, based on measures of biphone probability. Biphone probability refers to the frequency with which phonemes occur coupled with either their left or right neighbor in the target language. A list of stimuli and phonotactic details (Vitevich & Luce, 2004) are provided in Tables 1, 2, & 3. The average biphone frequencies detailed in Tables 1 & 2 refer to the averaged probability of each phoneme in a word or nonword occurring in conjunction with the phoneme to the left or right. Biphone frequencies were not computed for tongue twisters; however, comparable complexity is likely based on word and syllable count. All words, nonwords, and tongue twisters chosen as stimuli were selected to

include bilabials at the beginnings and ends of each production to allow for segmenting of Optotrak data. Stimuli were chosen to include kinesthetically salient phonemes such as labiodental and interdental fricatives (/f,v,θ/), or the rounded vowel (/u/). Tongue twisters of only a sentence in length were selected so as to avoid very high processing demands.

Once participants were comfortably seated in front of the Northern Digital Optotrak system, practice was completed. Up to five practice trials (depending on individual performance) verified that each participant was able to produce the specific familiar words, nonsense words, and sentences used in this experiment. During practice, all nonsense words were auditorily presented using stimuli models pre-recorded by a native speaker of American English. Participants were allowed to repeat each nonword up to five times, and criterion was met when three practice trials in a row were accurate. Familiar words were not practiced. Tongue twisters were elicited using a written model during practice and the experiment. During practice, participants read the tongue twister silently to familiarize themselves with the sentence(s) and then repeated it twice (without reading) to ensure accuracy of production. No focus of attention directions were given to participants during practice.

All participants completed the experimental tasks under both internal and external focus conditions and the order of conditions was counterbalanced across participants. Under the internal focus condition, participants received instructions intended to direct attention to the speech production mechanism. They were explicitly told that the words and sentences that they would produce had lots of highly kinesthetically salient phonemes such as /p,b,f,v,i,u/; “sounds you can feel”. They were told that, for example, /u/ is produced by rounding the lips, /f/ is

Table 1

Number of Syllables, Phonemes, and Average Biphone Frequency for Nonword Stimuli

Nonword	# of Syllables	# of Phonemes	Average Biphone Frequency
/mipvub/	2	6	1.0040
/puθfaum/	2	6	1.0010
/pimvuθæm/	3	8	1.0043
/bufmɔɪvop/	3	8	1.0026

Table 2

Number of Syllables, Phonemes, and Average Biphone Frequency for Real Word Stimuli

Word	# of Syllables	# of Phonemes	Average Biphone Frequency
/pʊʃʌp/	2	5	1.0019
/bæθtʌb/	2	6	1.0069
/pæpɝklɪp/	3	8	1.0092
/bʌtɝkʌp/	3	7	1.0095

Table 3

Number of Syllables and Phonemes for Tongue Twister Stimuli

Tongue Twisters	# of Syllables	# of Phonemes
Bake big batches of bitter brown bread.	9	25
Four furious friends fought for the phone.	9	23

produced by touching the top teeth to the bottom lip. Participants were then instructed to "focus on how their lips, teeth, and tongue are used to produce each sound", like the examples described above. Participants in the external attention condition were instructed to listen to their voice and their production of the words and sentences and "make sure that the way you said it matches the auditory model" (for words and nonwords), and "sounds accurate" for the tongue twisters. Under both conditions, participants were instructed to produce each word, nonword, or tongue twister 'as quickly and accurately as you can'. Participants were also told that only certain data was being recorded at a given time (i.e. "we are recording only the Optotrak data now", or "we are recording only the microphone signal now"). This deception was included as a means to direct participant attention more specifically to the intended condition.

Twenty productions of each word, nonword, and tongue twister were elicited under each focus condition. Within a focus condition (e.g. internal focus), the order of tasks was random (e.g., tongue twisters, nonwords, words). Real words and nonwords, elicited through pre-recorded auditory models, were produced in twenty blocks with each of the four words (or nonwords) pseudo-randomized within a block. Tongue twisters were elicited through presentation of the written sentence (in order to allow participants to re-familiarize themselves with the production that was practiced earlier). Once participants were ready to produce the tongue twister, the written referent was taken away, and participants were instructed to produce the sentence twenty times, in blocked fashion (i.e, repeated 5 times in succession, in 4 blocks). Instructions appropriate to the desired focus condition were repeated at intervals and throughout each part of the experiment. Participants were asked to rate how well they felt they had followed the instructions given after every 5 blocks (totaling 4 ratings per stimuli per condition). This

self-rating was included to provide a gauge for the researcher of how well participants were complying with the instructions given, as well as redirecting their attention to the given set of instructions. Descriptive statistics were obtained on the ratings for the external condition (M =4.6792, SD =0.47359) and the internal condition (M=4.544, SD =0.42543), [scale of 1-5, with 5 representing best performance (followed instructions exactly) and 1 representing worst performance (did not follow instructions)].

2.4. Data Analysis

Participant productions of all words and nonsense words were judged for accuracy and fluency by replaying the digitized audio signals using a MATLAB (The MathWorks®, Natick, MA, 2001) program. Utterances were judged by the experimenter for incorrect phonemes or phoneme order, atypical rate of production, and misarticulations. Twenty-five percent of all participants were also judged for behavioral accuracy by a blind, independent listener-a trained undergraduate employee of the speech lab-and an interrater reliability analysis using correlation was performed to determine consistency between raters ($r=0.9892$, $p<0.01$). Twenty percent of all participants were randomly selected and reanalyzed, blind, by the experimenter, and an intrarater reliability analysis using correlation was performed to establish rater consistency ($r=0.9023$, $p<0.01$). The percent of phonemes correct was calculated for all 20 productions of each stimulus in each condition. This information was used to decide which kinematic signals (only fluent, error-free productions) could be included in the analyses . Because of an insufficient number of accurate productions of particular nonwords, real words, and tongue twisters, kinematic data analysis could not be completed for certain participants. Table 4 details

the total percent of data included in computing kinematic measures for the participants used (reflecting the number of fluent, error-free productions).

Table 4

Percent Data Included in Kinematic Analysis by Stimulus

Stimulus	Nonwords: Internal	Nonwords: External	Real Words: Internal	Real Words: External	Tongue Twisters: Internal	Tongue Twisters: External
% Data Included	95.6	95.9	96.5	97.5	99.9	98.8

If 20 fluent, accurate productions were not available for the computation of kinematic measures, a particular participant's productions for each stimulus in both conditions were only included in kinematic analysis if at least 10 error-free, fluent productions were available, based on the procedures of multiple studies using the same kinematic analysis techniques (Sadagopan & Smith, 2008; Maner et al., 2000; Smith & Zelaznik, 2004). Table 5 details the exact percentage of data by stimulus for which only 10-15 accurate productions were available, and the percentage of data obtained from 16-20 accurate productions.

The lower lip signal was used to segment movement data. First, a three-point difference method was used to compute velocity from filtered displacement data from the lower lip IRED marker. Continuous displacement and the lower lip velocity signals were then displayed using an interactive program, and the computed velocity signal was used to segment displacement data. Lower lip movement trajectories for each word and nonsense word were extracted using the methods described by Maner, Smith, and Grayson (2000). The words and nonsense words were

Table 5

Number of Productions Summarized for Kinematic Analysis by Stimulus and Condition (percent of participants with 10-15 error-free productions, and percent of participants with 16-20 error-free productions)

Stimulus	% Data: 10-15 Accurate Productions	% Data: 16-20 Accurate Productions
N1: Internal	5	95
N1: External	5	95
N3: Internal	12	88
N3: External	-	100
R1: Internal	16	84
R1: External	-	100
R2: Internal	10	90
R2: External	-	100
R3: Internal	5	95
R3: External	-	100
R4: Internal	10	90
R4: External	-	100
T1: Internal	5	95
T1: External	-	100
T2: Internal	5	95
T2: External	-	100

trimmed using the peak velocity for the opening movement of the initial bilabial and the last opening movement preceding the final bilabial consonants (Figures 1 and 2). Figure 1 shows the velocity waveform of one production of a novel nonword, N3 (‘peemvootham’). The first dotted red line indicates peak velocity for the opening movement of the initial bilabial (the /pi/ of ‘peem’), and the second red line indicates peak velocity for the last opening movement preceding the final bilabial consonant (/thæ/ in the final syllable ‘tham’).

Figure 2 shows the velocity waveform of one production of a real word, R2 (‘bathtub’). The first dotted red line indicates peak velocity for the opening movement of the initial bilabial

(the /bæ/ of ‘bath’), and the second red line indicates peak velocity for the last opening movement preceding the final bilabial consonant (the vowel /tʌ/ in the final syllable ‘tub’).

The tongue twisters were trimmed using the peak velocity for the opening movement of the initial consonant and the peak velocity preceding the final consonant (Figure 3). Figure 3 shows the velocity waveform of one production of T1 (‘bake big batches of bitter brown bread’). The first dotted red line marks the peak velocity for the opening movement of the initial consonant (the /beI/ of ‘bake’), and the second red line indicates peak velocity preceding the final consonant (the /brɛ/ of ‘bread’).

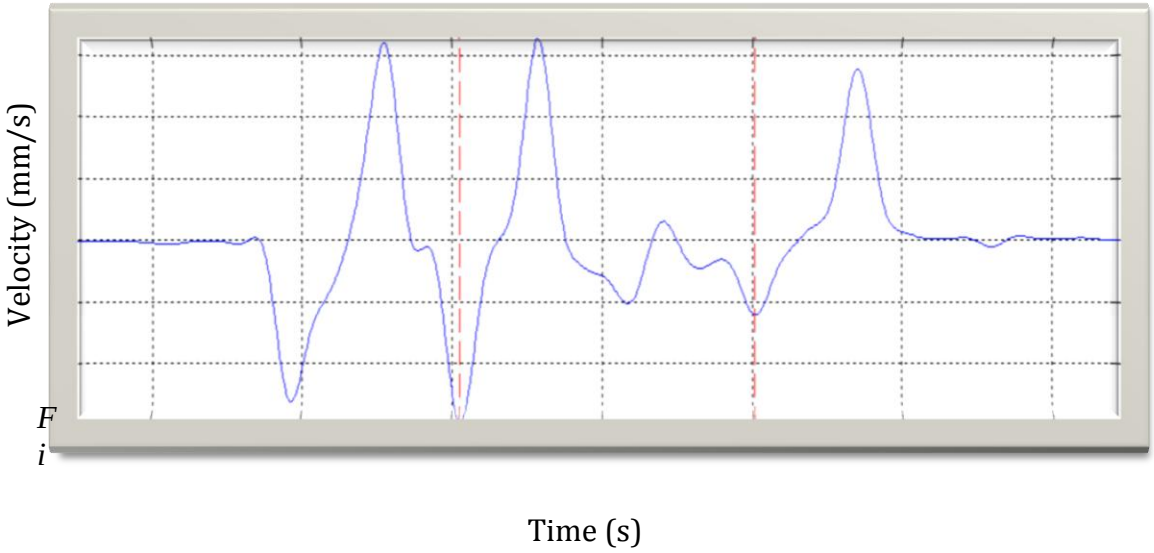

Figure 1. Velocity waveform of N3 (‘peemvootham’), showing peak velocity markers for segmentation.

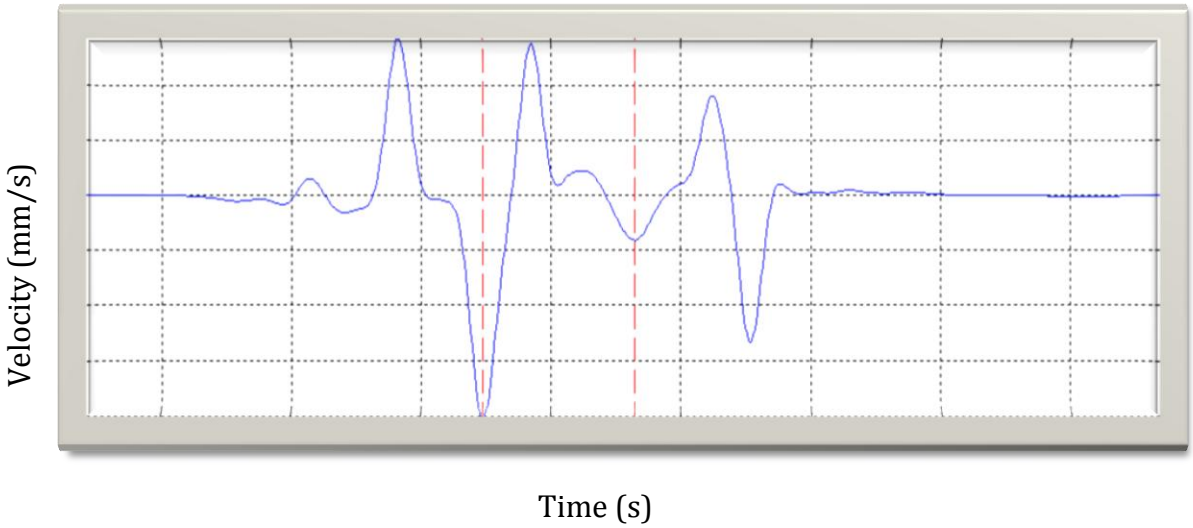

Figure 2. Velocity waveform of R2 (‘bathtub’), showing peak velocity markers for segmentation.

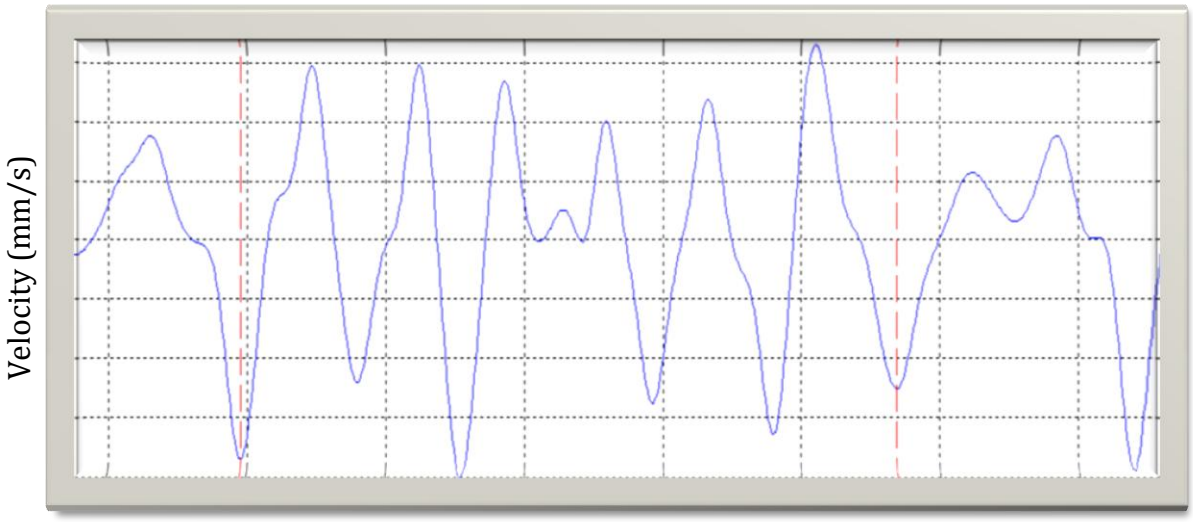

Figure 3. Velocity waveform of T1 (bake big batches of bitter brown bread), showing peak velocity markers.

The corresponding upper lip and jaw signals were simultaneously extracted by a custom-designed MATLAB ® program. For this study, a lip aperture signal was computed using a point-by-point subtraction of the upper lip from the lower lip signal. In their paper on functional synergies for speech motor coordination, Smith and Zelaznik (2004) reveal that measurements of lip aperture result in lower between-trial variability when compared to the independent motion of the upper and lower lip. They discuss the control of lip aperture as a higher-order coordinative structure than that of lower lip and jaw action. The higher order system (lip aperture) relates directly to the overall target of the system for speech, while the lower order system (lip and jaw relationships) subordinates to achieving the speech target. Lip-jaw difference trajectories show greater between-trial variability than lip aperture trajectories. Therefore, measurement of lip aperture variability provides a more meaningful measure of production variability for a single speech target. The lip aperture variability index (LAVAR) was computed by first time and amplitude normalizing the movement signals. Then, standard deviations from the mean of the selected movement patterns at 2% intervals were summed to obtain a lip aperture variability (LAVAR) index. A low LAVAR index means that the repeated movement trajectories are more consistent and less variable (Figure 4), and a high LAVAR index indicates higher variability of successive repetitions of the same word, nonword, or tongue twister (Figure 5).

Mean movement durations, and variability (SD) of movement durations for the production of each stimulus was also obtained. Duration measures were included to determine the possible effect of condition on rate of speech production. Mean duration and duration variability were automatically computed for the trimmed segments of each word, nonword, and tongue twister by the custom MATLAB® analysis program.

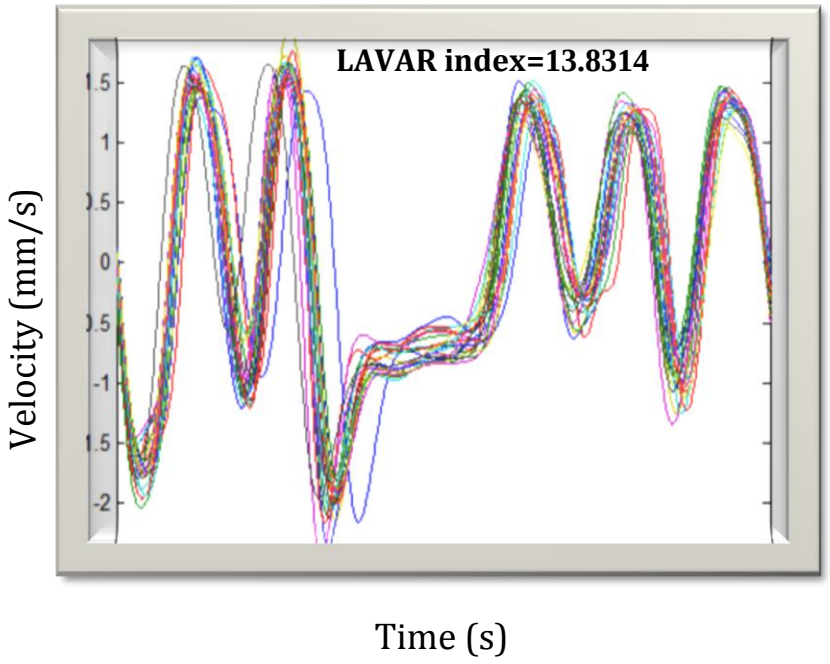

Figure 4. Multiple productions of one tongue twister with a relatively low LAVAR index value, indicating a higher level of speech movement coordinative consistency.

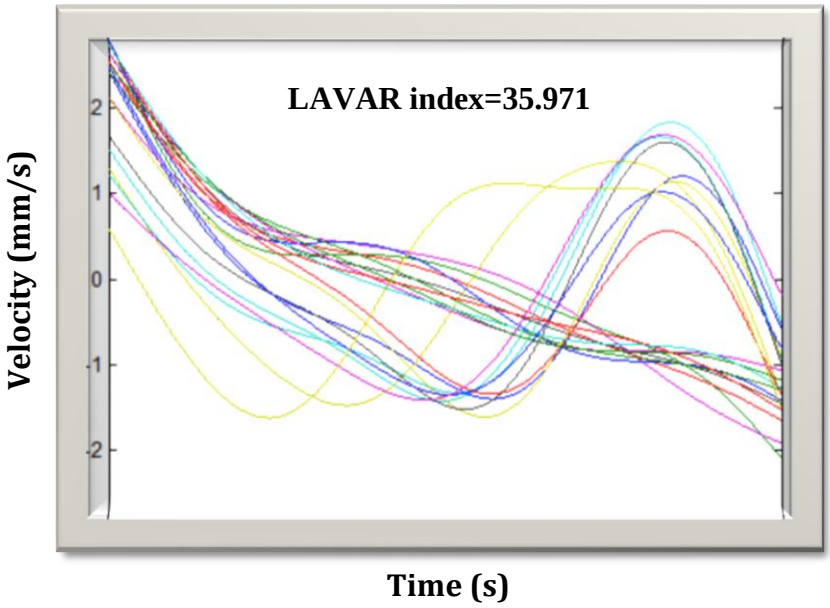

Figure 5. Multiple productions of one real word with a relatively high LAVAR index value, indicating a lower level of speech movement coordinative consistency.

2.5. Statistical analysis

For each dependent variable (% phonemes correct, LAVAR index values, mean duration, and duration variability), within-subject repeated measures of analyses of variance (ANOVAs) were used to determine whether there were significant influences of ORDER (between subjects factor; order of occurrence of conditions), and within-subject factors of STIMULUS (4 levels for nonwords, 4 levels for real words, and 2 levels for tongue twisters), and CONDITION (attentional focus). Each set of stimuli (nonwords, real words, tongue twisters) was analyzed separately for each dependent variable. Alpha was set to 0.05.

The percent of phonemes correct was transformed using a rationalized arcsine transform program in MATLAB (The MathWorks®, Natick, MA, 2001), written by Studebaker (1985), before statistical analysis. The rationalized arcsine transform allows for translation of percentages into values on a linear and additive scale, and results in values that better reflect the relationship of percentages within a sample than other arcsine transforms (Studebaker, 1985).

Chapter 3. Results

There was no effect of ORDER ($p > 0.05$) on any of the dependent measures analyzed for each set of stimuli (nonwords, real words and tongue twisters). Therefore, a completely within subjects repeated measures ANOVA with CONDITION (internal vs. external focus) and STIMULUS was completed.

3.1. Behavioral Analysis (% phonemes correct)

There was no effect of CONDITION on behavioral accuracy for the productions of nonwords [$F(1, 19) = 1.86$, $p = 0.19$], real words (no variance, 100% accuracy for all real words across internal and external focus conditions), and tongue twisters [$F(1, 19) = 0$, $p = 1$], (Figure 6).

The repeated measures ANOVA for phoneme accuracy of nonwords showed a main effect of STIMULUS, $F(3, 57) = 11.45$, $p < 0.0001$, such that participants demonstrated significantly poorer accuracy scores for N2 (poothfaum) compared to the other nonwords (Tukey-Kramer multiple comparisons, $p < 0.05$). There was no significant CONDITION x STIMULUS interaction [$F(3, 57) = 0.19$, $p = 1$], (Figure 6).

The repeated measures ANOVA for phoneme accuracy of tongue twisters showed no effects of STIMULUS on behavioral accuracy, $F(1,19) = 0.11$, $p = 0.75$, and no CONDITION x STIMULUS interaction [$F(1, 19) = 0$, $p = 1$], (Figure 6).

3.2. Kinematic Analysis

Due to a significant amount of missing data for N2 (‘poothfaum’) and N4 (‘boofmoivope’) (insufficient accurate productions; N2=53.2% data missing; N4=30% data

missing), statistical analysis of kinematic data for nonwords was completed only for N1 (‘meepvoob’) and N3 (‘peemvootham’) for 16 participants who produced sufficient accurate productions of both nonwords. Statistical analysis on kinematic data from real words was completed on 19 participants (data from one participant could not be analyzed due to technical errors). Kinematic data were obtained from all 20 participants for tongue twisters.

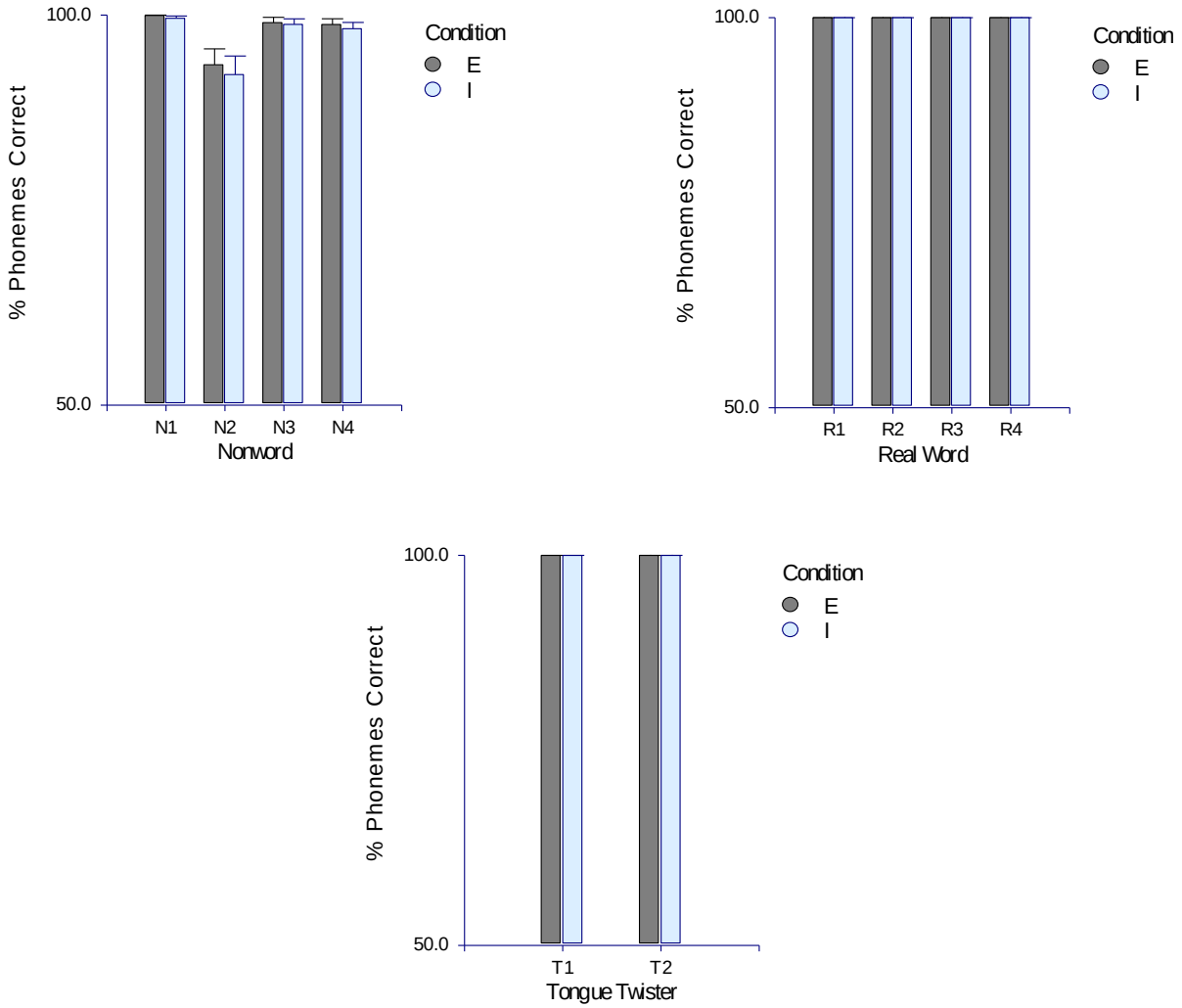

Figure 6. Behavioral accuracy (% phonemes correct) by stimulus (nonwords, real words, and tongue twisters), for both internal and external focus of attention conditions. Error bars indicate the standard error of the mean.

Lip aperture variability

Nonwords

Repeated measures ANOVAs for lip aperture variability (LAVAR index) revealed no main effects of CONDITION, $F(1,15)=3.42$, $p = 0.08$; or STIMULUS, $F(1,15)=1.28$, $p = 0.27$, for N1 and N3, and no significant interaction between CONDITION and STIMULUS, $F(1, 15) = 0$, $p = 0.99$. Lip aperture variability was comparable for N1 and N3, and across the internal and external focus conditions (see Figure 7).

Real Words

Significant main effects of CONDITION, $F(1,18)=4.82$, $p<0.05$; and STIMULUS, $F(3,54)=27.51$, $p<0.0001$, on lip aperture variability were noted for the production of real words. The CONDITION x STIMULUS interaction was not significant, $F(3, 54) = 1.53$, $p = 0.22$. Overall, lip aperture variability was significantly lower in the external condition, when compared to the internal condition (Tukey-Kramer multiple comparison, $p < 0.05$). The LAVAR index was significantly lower for the production of R2 compared to all other real words, and lip aperture variability was highest for R1 and R3, which were not different from each other (Tukey – Kramer multiple comparisons, $p < 0.05$). In other words, speech movement coordinative consistency was greatest for the production of R2 and lowest for the production of R1 and R3 (see Figure 7).

Tongue Twisters

There were no main effects of CONDITION, $F(1,19)=0.89$, $p = 0.36$; or STIMULUS, $F(1,19)=0.15$, $p = 0.70$, associated with tongue twister lip aperture variability, indicating that an increase in complexity did not result in a corresponding decrease in speech movement

coordinative consistency (see Figure 7. There was no CONDITION x STIMULUS interaction, $F(1, 19) = 1.54$, $p = 0.23$.

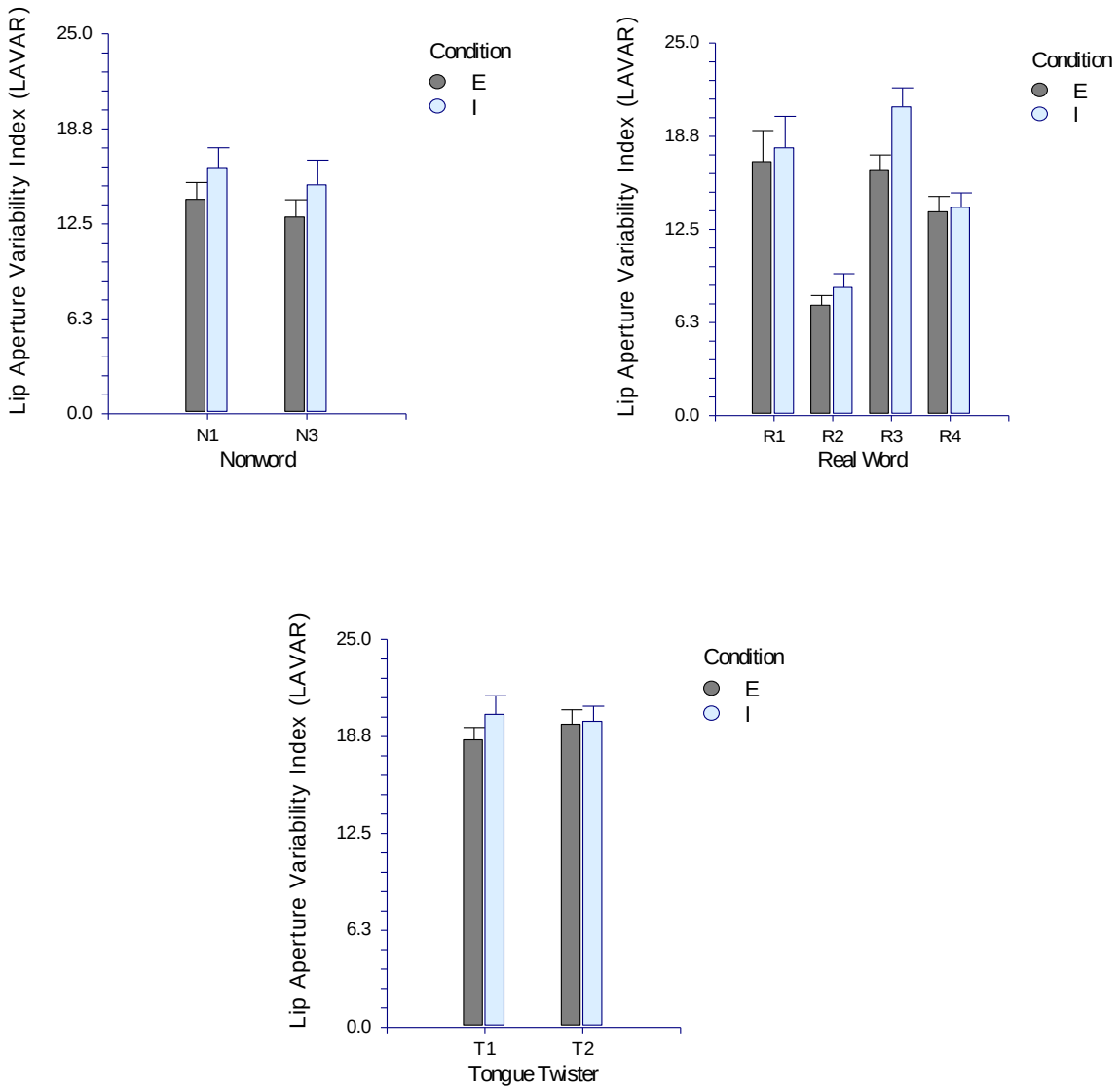

Figure 7. Lip aperture variability (LAVAR) index values for each stimulus type (nonwords, real words, and tongue twisters), in both internal (I) and external (E) focus of attention conditions. Error bars indicate the standard error of the mean.

Mean duration

Nonwords

Repeated measures ANOVAs for mean duration of N1 and N3 revealed main effects of CONDITION, $F(1,15)=10.19$, $p<0.01$; and STIMULUS, $F(1,15)=205.79$, $p<0.0001$; but no significant CONDITION x STIMULUS interaction, $F(1,15)=0.55$, $p = 0.47$. Post-hoc analysis using Tukey-Kramer multiple comparisons suggested that mean durations of N1 and N3 were greater in the internal condition compared to the external condition ($p < 0.05$), indicating that participants produced these nonwords more slowly in the internal focus of attention condition (Figure 8). As expected, the mean duration for N3 was greater than the mean duration of N1.

Real Words

Main effects of CONDITION, $F(1,18)=7.69$, $p = 0.01$; and STIMULUS, $F(3,54)=232.24$, $p<0.0001$ were observed for real words. In addition, the CONDITION x STIMULUS interaction was significant, $F (3, 54) = 3.95$, $p = 0.0$. Post-hoc analyses revealed that participant productions of only R2 (bathtub) and R4 (paperclip) were significantly faster in the external vs. internal focus of attention condition (Tukey-Kramer multiple comparison, $p < 0.05$), (Figure 8).

Tongue Twisters

Main effects of CONDITION, $F(1,19)=24.55$, $p<0.0001$; and STIMULUS, $F(1,19)=16.48$, $p<0.001$, were also present for tongue twisters. The CONDITION x STIMULUS interaction was not significant, $F(1, 19) = 1.54$, $p = 0.23$. Participants were significantly slower in the internal focus of attention condition for the production of both tongue twisters. Overall, TT1 (bake big batches of bitter brown bread) was produced with longer durations than TT2 (four furious friends fought for the phone), (Tukey-Kramer multiple comparisons, $p < 0.05$), (Figure 8).

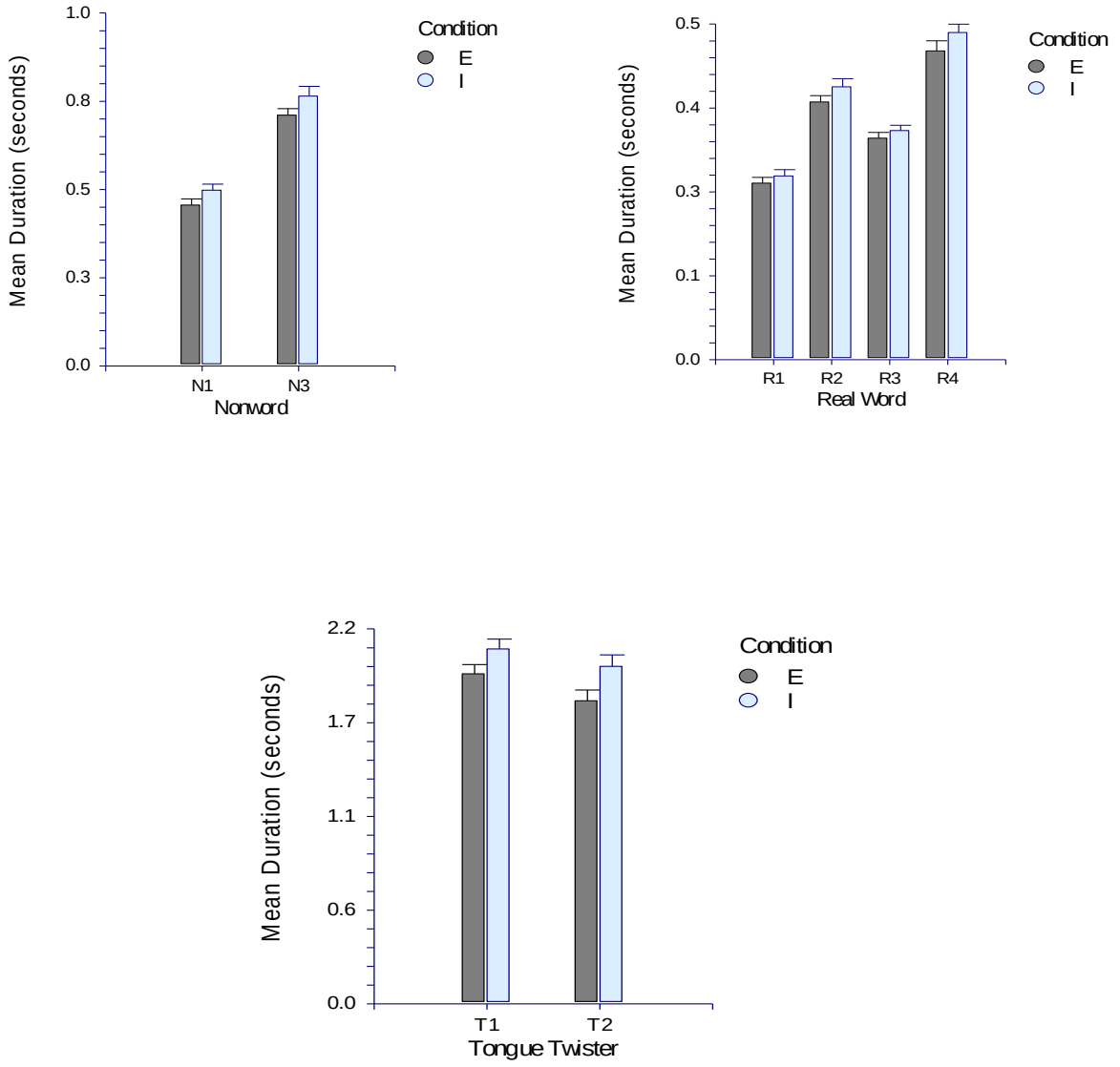

Figure 8. Mean duration for each stimulus type (nonwords, real words, and tongue twisters), in both internal (I) and external (E) focus of attention conditions. Error bars indicate the standard error of the mean.

Duration variability

Nonwords

Repeated measures ANOVAs of duration variability revealed a marginal effect of CONDITION on duration variability for the production of N1 and N3, $F(1,15)=4.14$, $p= 0.059$, but no main effects of STIMULUS, $F(1,15)=2.35$, $p = 0.14$; and no significant CONDITION x STIMULUS interaction, $F(1,15)=0.29$, $p = 0.59$. There was a trend toward increased duration variability for the production of N1 (meepvoob) and N3 (peemvootham) in the internal focus of attention condition (Figure 9), however, this trend produced a marginal effect only.

Real Words

Repeated measures ANOVAs of duration variability did not reveal any main effects on duration variability for the production of real words of CONDITION, $F(1,18)=0$, $p= 0.95$; or STIMULUS, $F(3,54)=2.36$, $p= 0.08$, and no significant CONDITION x STIMULUS interaction, $F (3, 54) = 0.45$, $p = 0.72$, indicating that although mean durations of R2 (bathtub) and R4 (paperclip), were shorter in the external focus of attention condition, duration variability was not similarly affected (Figure 9).

Tongue Twisters

Repeated measures ANOVAs of duration variability for tongue twisters showed a main effect of STIMULUS, $F(1,19)=4.77$, $p<0.05$, but no main effect of CONDITION, $F(1,19)=0.05$, $p= 0.83$, and no CONDITION x STIMULUS effect, $F (1, 19) = 0$, $p = 0.95$. Post-hoc analysis revealed that TT1 (bake big batches of bitter brown bread) was produced with greater variability in duration compared to TT2 (four furious friends fought for the phone), (Tukey-Kramer, $p < 0.05$), (Figure 9).

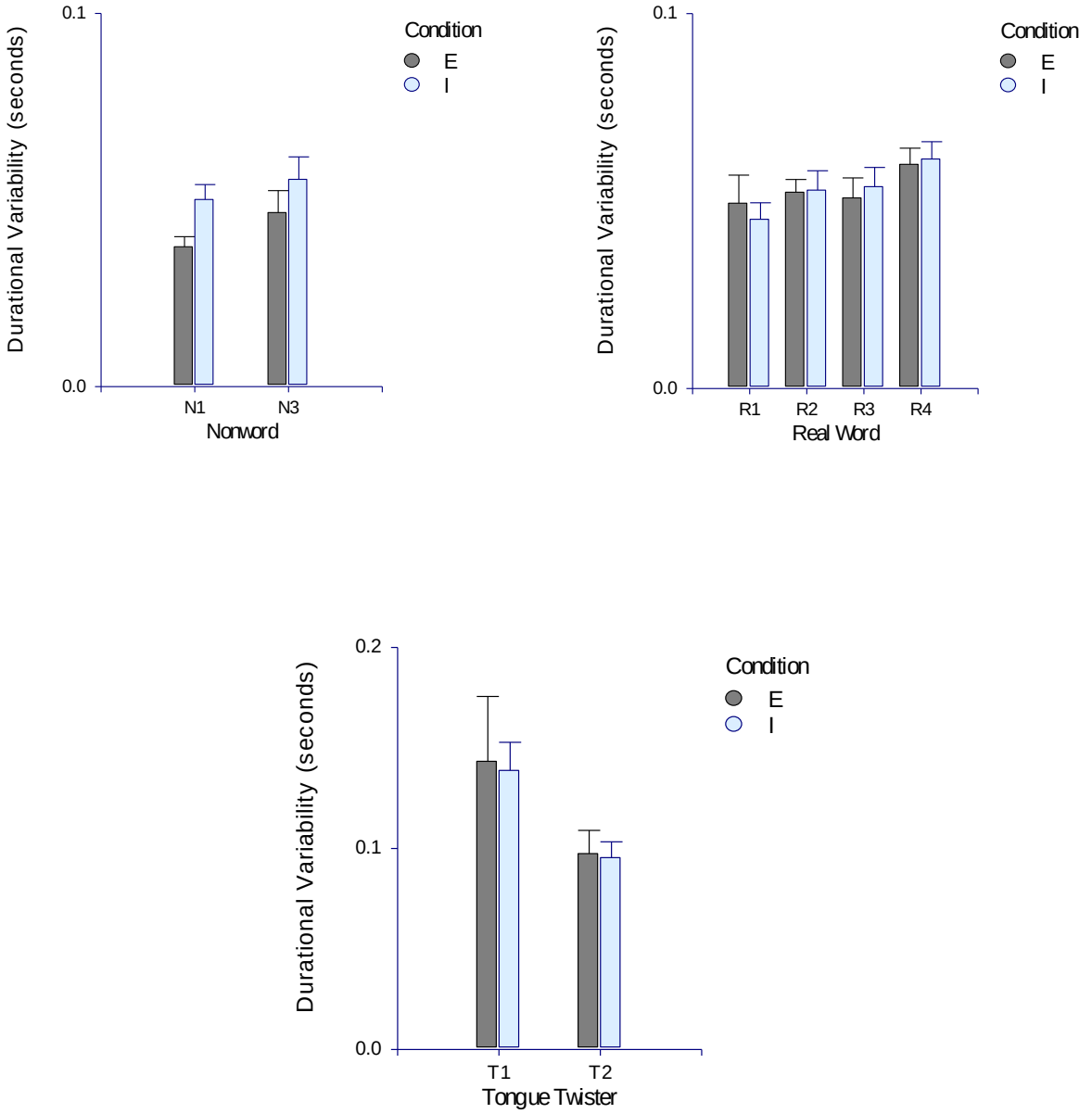

Figure 9. Duration variability for each stimulus type (nonwords, real words, and tongue twisters), in both internal and external focus of attention conditions. Error bars indicate the standard error of the mean.

Chapter 4. Discussion

4.1. Behavioral Analysis (phonemic accuracy)

Focus of Attention Effects on Behavioral Accuracy

Although it was predicted that attentional focus would affect behavioral accuracy, this did not prove to be the case. There are several factors that may have contributed to this result. For nonwords, the overall percentage of errored productions (totaled for both external and internal conditions) was high (40.7% of all productions). This may suggest that the challenge of accurately producing the nonword stimuli selected for this experiment might have led participants to focus on the final instructions given in both conditions of "as quickly and accurately as you can", rather than the more condition-specific instructions, resulting in performance that may not have reflected focus of attention. In the case of real words, the effects of attentional focus condition may not have negatively impacted behavioral accuracy due to the established motor program associated with these stimuli. The finding that certain real words were produced more slowly in the internal condition compared to the external condition support the possibility that because established speech motor programs are associated with more consistent speech motor coordinative consistency (Smith et al., 2004), attentional focus instructions produce alterations in other variables of speech motor control (e.g., speech rate) rather than production accuracy. Similar observations may be made about the tongue twister stimuli included in this experiment. Although their construction presents inherent challenges, (Mowrey & MacKay, 1990; Keller et al., 2002), both tongue twisters consisted of familiar words, for which an established motor program was expected.

Stimulus Effects on Behavioral Accuracy

The only effect of stimulus (complexity) observed for phonemic accuracy was noted for the production of nonsense words. "Poothfaum" (N2) proved to be a difficult word for a 45% of participants. It is unclear why "poothfaum" was significantly poorer in accuracy than "meepvoob" (N1), since these two nonsense words are both 2-syllable, CVCCVC combinations with comparable biphone frequencies. One may argue that syllable structure and biphone frequencies alone do not sufficiently characterize complexity or production challenge, however, for this study these measures were used to establish similar complexity, based on research findings indicating that measures of phonotactic probability are better predictors of spoken nonword repetition than neighborhood density or duration alone (Vitevitch & Luce, 2004). It is possible that the transition from an interdental fricative (/θ/) to a labiodental fricative (/f/) caused this particular nonword production to be more complex. The majority of errors produced for N2 consisted of either elimination of the labiodental fricative (/f/), ("poothfaum" produced as "poothaum", 20% of errors), or reversal of the interdental and labiodental fricatives ("poothfaum" produced as "poofthaum", 52 % of errors).

Complexity effects on behavioral accuracy were not noted for real words and tongue twisters. Both categories of stimuli include familiar combinations of phonemes, and familiar words. It can be argued that for young adults, with years of experience producing speech, familiar words and combinations of phonemes place lesser demands on cognitive-linguistic processes, compared to unfamiliar nonword stimuli (Maner et al., 2000; Kleinow et al., 2000). Another possibility is that the computation of the behavioral accuracy measures in this study did not account for phoneme addition or self-correction. In the present study, if a participant produced "bake big bra…batches of bitter brown bread", for example, the production was

considered 100 % accurate in terms of % phonemes correct (per methods for scoring used by Dollaghan & Campbell, 1998), although it was excluded from kinematic analysis due to disfluency and self-correction. An alternate scoring system, that accounted for disfluencies and self-corrections in the accuracy score may have been more sensitive to differences between stimuli and across the focus conditions.

4.2 Kinematic Analysis: LAVAR index (lip aperture variability)

Condition Effects

Effects of condition on lip aperture variability were noted only for the real words. Overall, lip aperture variability was higher in the internal condition for all real words. Interpretation of these results suggests that during the production of words for which a fully developed speech motor program already exists, focusing on articulatory placement during the internal condition resulted in interruptions in lip aperture. This finding provides support for the idea that an internal focus of attention (e.g. articulatory placement and coordination) disrupts 'skilled' performance of previously acquired motor patterns. According to the *constrained action hypothesis*, posited by McNevin and Wulf, (2001), previously mastered motor processes are inherently automated, and an external focus of attention allows the motor system to maximize performance. Conversely, a focus of attention on the movements themselves (internal), results in a reduction in performance resulting from interruption of these automated processes. In the introduction, it was hypothesized that similar effects might be noted for speech motor performance, and that, for speech, a focus on acoustics would equate the external focus of attention condition, while an internal focus would be on articulatory placement and coordination (Maas et al., 2008). Additionally, because the words were familiar, it is possible participants did

not have to expend resources on achieving production accuracy, and could instead focus more completely on other elements of the instructions (such as awareness of articulatory placement and coordination).

It is interesting that a main effect of condition on lip aperture variability was observed for real words, but not for nonwords or tongue twisters. There are several factors that may have affected participant performance during the nonword production tasks. Although exclusion of N2 (‘poothfaum’) and N4 (‘boofmoivope’) from kinematic analysis reduced the percent of missing data considerably, fourteen percent (14%) of total productions of N1 (‘meepvoob’) and N3 (‘peemvootham’) were not used for kinematic analysis because of inaccurate production or technical error. This may indicate that the nonwords generated for this experiment were difficult to produce accurately. Perhaps the inclusion of only one- and two-syllable nonwords would have resulted in higher phonemic accuracy scores, providing more useable data for kinematic analysis. It is also possible that inclusion of a greater percentage of data might have revealed patterns and associations that were not apparent with the smaller sample of nonwords available for this analysis.

Another consideration that applies to the current experiment is that of the instructions given. Although participants were clearly instructed to center their awareness on the motor and sensory aspects of individual phoneme production, they were also instructed to produce each stimulus “as quickly and accurately” as they could, in order to ensure that only true condition effects, rather than a difference in instructions, would be apparent in the results. It is possible that accuracy, and possibly speed, superceded other details of the instructions, particularly if the nonwords were challenging. Participants were asked to rate how well they had followed the instructions after each group of five pseudorandomized blocks of the four nonwords, but it is

possible that when providing this rating, participants were referring to their attempted accuracy rather than the focus of attention instructions. Many participants provided high self-rating scores for adherence to instructions, but no discernable difference was apparent in their productions between the two conditions.

The challenge of producing a tongue twister accurately is high (Mowrey & MacKay, 1990; Keller et al., 2002). A longer utterance, such as the tongue twisters used in the current experiment, places more demands on both motor planning and cognitive resources (Maner et al., 2000). For the current experiment, participants were asked to repeat the tongue twisters from memory, tasking cognitive processes such as working memory, required to coordinate cognitive, linguistic, and motor elements (Dromey & Benson, 2003). In addition, the construction of tongue twisters in general, involving repeated reiteration and the use of similar phonemes, likely places additional challenges on the motor speech system than spontaneous speech. It is possible that using more simple stimuli would result in noticeable differences between conditions. As mentioned previously, it is also possible that inclusion of "quickly and accurately" in the instructions resulted in participants focusing on production accuracy rather than articulatory placement and movement.

It is important to reiterate that while Maas et al. (2008) suggest using complex stimuli (e.g. tongue twisters) to study of focus of attention effects on speech motor performance, the current findings seem to suggest that using simpler stimuli may facilitate higher adherence to focus of attention instructions and therefore, may increase the possibility of finding differences between external and internal focus of attention on performance.

Another important consideration that applies to lip aperture variability measures for nonwords, real words, and tongue twisters is that lip aperture is theorized to be a higher order

goal of the motor speech system, reflecting the overall target of speech production, while individual articulatory patterns are viewed as lower order synergies (Smith & Zelaznik, 2004). In other words, the higher order goal of lip aperture is likely produced with relatively higher consistency than individual articulatory movements (e.g., lower lip movement). It is possible that even in the internal condition of the current experiment, possible effects on articulatory patterns and muscle coordination were not apparent because stability of the higher order goal (LAVAR) may have been maintained similarly in the internal and external focus conditions, but differences may have been present at the level of individual articulator performance (e.g. lower lip movement).

Finally, the measurement technique must be considered in discussing findings. It is plausible that other measures not included in the present study (e.g., electromyography) are more sensitive to differences in focus of attention on speech production. In a study conducted by Zachry et al., (2005), participants were not only more accurate in the external condition, but also employed more efficient muscle performance, as measured using electromyography. Mowrey et al., (1990), used hooked-wire electrode electromyography to observe and quantify speech motor activity during production of phonological errors, demonstrating an alternate measurement technique that provides detailed data about specific muscle activation and efficiency during the performance of a speech task. Future studies should include alternate means of measurement that might reflect changes in the efficiency of production under the two conditions (internal and external).

Complexity Effects on Speech Movement Coordination

Lip aperture variability was found to be lower for R2 (‘bathtub’), and higher for R1 and R3 (‘pushup’ and ‘buttercup’, respectively). It should be considered that although R3

(‘buttercup’) consisted of more syllables and a different CVC structure than R1 (‘pushup’) and R2 (‘bathtub’), similar results were not found for R4 (‘paperclip’), although comparable in length and structure to R3. It is not clear why R1 would have higher lip aperture variability values than R2. It is possible that as a group, participants had more experience producing ‘bathtub’ than any of the other real words. However, this is only a speculation, and this question may bear further investigation.

4.3. Kinematic Analysis: Duration and duration variability

Condition Effects of Kinematic Measures of Timing

In the present study, differences in attentional focus seemed to produced the greatest effect on measures of timing, especially on mean duration of utterance production. Both nonwords included in the analysis (N1;‘meepvoob’ and N3; ‘peemvootham’) had significantly longer mean duration values and demonstrated a trend towards increased duration variability in the internal versus the external condition (see Figures 8 and 9).

These findings can be interpreted as suggesting that maintaining an internal focus during speech production tasks resulted in reduced efficiency of the speech motor system, and therefore higher mean duration values. Research has shown that the limb motor system has a natural tendency to adopt an external focus of attention, resulting in fluid integration of reflexive and voluntary control mechanisms, and more successful and efficient movements (e.g. Wulf, 2001; Zachry, 2005; Peh, 2010). Findings from the current study indicate that this may be the case for the speech motor system as well, and a disruption to automatic skilled movement production results in slowing of speech motor processes. On the other hand, it is possible that longer

production durations during the internal focus condition reflect a trade-off between speed and accuracy.

For real words, mean durations were found to be higher for R1 (‘insert word’) and R3 (‘) in the internal condition. It is interesting that R1 and R3 also showed the highest lip aperture variability values during the internal condition. As mentioned in Maner et al. (2000), performance stability in adults depends largely on speech rate. Slower rates of speech were found to produce greater speech movement variability for the same stimuli. Similar findings were also discussed by Kleinow et al. (2001). Measurements of speech motor stability for one utterance (“buy Bobby a puppy”) were compared for normal, slow, and fast rates of speech, with the result that speech motor stability was lowest during slow speech. Kleinow and colleagues posit that this finding may indicate more variable neural command signals to speech muscles and more variable biomechanical properties of the speech structures. It is possible that during the internal focus of attention condition, participants were more successful at maintaining an internal focus during production of R1 and R3, resulting in both higher mean durations and greater lip aperture variability for these stimuli (see Figures 8 and 7, respectively). It is unclear, however, why this should be the case for R1 and R3 only, and not for R2 and R4.

Mean durations (but not durational variability) were found to be longer for both tongue twisters in the internal focus of attention condition (Figure 8). This may reflect that for longer, more challenging stimuli (multiple words, repetitive phonological similarities), slower speech allowed for higher behavioral accuracy, particularly when focusing on articulator placement and coordination. This may also support the idea that efficient production of familiar words is interrupted by the conscious imposition of control (McNevin, 2001). During the external focus of attention condition, participants produced the tongue twisters more rapidly, without an

increase in errors. When asked to focus on articulator placement and coordination, tongue twisters were produced more slowly, although total errors and self-corrections were comparable between conditions. This may suggest that participants employed a slower rate of speech in order to maintain accuracy, indicating a reduction in overall production efficiency. An increase in duration in the internal condition was not associated with a corresponding increase in lip aperture variability for tongue twisters or nonwords, unlike that observed for real words. Once again, it is speculated that complex stimuli may not be as sensitive to condition effects on speech motor coordination because of an increased focus on accuracy, likely at the cost of rate.

Overall, these findings support the hypothesis that maintaining an external focus of attention during performance of motor speech tasks results in shorter production durations relative to the internal condition. This was expected, as a focus on articulatory placement and movement is likely to result in reduced speed of production, resulting in longer duration times.

Complexity Effects on Kinematic Measures of Timing

As expected, N3 (‘peemvootham’) had longer mean durations than N1 (‘pushup’) because it is a longer nonword, more complex nonword (Walsh et al., 2006; Sasisekaran et al., 2010). Although both tongue twisters consist of seven words and contain a similar pattern of repeated sounds, mean duration values and duration variability were higher for T1 (‘bake big batches of bitter brown bread)’ in both conditions relative to T2 (‘four furious friends fought for the phone’). Although there was no significant difference in accuracy between the tongue twisters, participants did produce more errors for T1 (22/800). It is possible that the increase in errors and higher overall mean duration relative to T2 indicate that T1 was more challenging to repeat accurately, and that participants may have reduced production speed to improve accuracy.

4.4. Conclusion

The current study was the first attempt to examine the role of attentional focus on speech production using an experimental protocol including multiple repetitions of words, nonsense words, and tongue twisters, with the expected alternate hypothesis that maintaining an external focus of attention during a speech performance task would result in (a) increased accuracy (% phonemes correct), (b) more highly coordinated lip aperture trajectories (lower LAVAR values), (c) shorter production durations, and (d) lower durational variability than the internal focus condition for both nonwords and real words.

Overall, the results of this study did not support the presence of increased accuracy, or more highly coordinated lip aperture trajectories, in the external relative to the internal condition for the more complex stimuli used in the current study. It is speculated that simpler stimuli (e.g., real words) are perhaps more sensitive to effects of condition on speech motor coordination due to reduced cognitive-linguistic processing demands. However, in general, shorter production durations in the external condition relative to the internal condition were observed, giving some support to the theory that operating in the external condition results in more efficient, automatic control of speech movements (Maas et al., 2008; Freedman et al., 2007).

4.5. Suggestions for Future Research

A secondary goal of this study was to provide pilot data for future studies investigating the role of attentional focus applied to oral-motor learning and performance in speech production. Although the alternate hypothesis was not completely supported, findings from this study do indicate speech motor performance differences, primarily in timing variables, between

the internal and external focus of attention conditions. The following suggestions are made for future research in this area.

The current study was designed as a first attempt to address the question of how focus of attention affected speech motor performance, based on extensive research in limb motor control, and a few studies on oral motor performance. The experimental design for this study was chosen to examine a variety of contexts of speech production (unfamiliar nonwords, familiar real words, and articulatorily complex tongue twisters). The stimuli for this experiment were selected for phonotactic similarity, based partly on research by Vitevitch and Luce (2004) indicating that for both words and nonwords, phonotactic similarity results in comparable processing times. The intention was to ensure that the nonwords and real words included in this experiment would be comparably challenging to eliminate the possibility that any observed effects of condition were in fact a result of discrepancy in the production challenge of individual stimuli. Two levels of length (two-syllable and three-syllable) were included for both words and nonwords, to examine the possible effects of increased complexity (length) on performance in the two focus conditions (internal and external). However, other measures of complexity, such as neighborhood density (Vitevitch, 2004), were not considered. A few nonwords chosen for the present experiment were unexpectedly challenging for participants to produce accurately. Future studies might consider including simpler, novel combinations to achieve a better balance between novelty and complexity of nonword stimuli, in order to elicit a greater number of accurate productions for analysis.

Additionally, stimuli for this experiment were designed to include a high percentage of bilabial, palatal, and alveolar stops and fricatives, so that participants in the internal focus condition could be easily directed to specifics of sound production. Since it has been

demonstrated that concurrent motor, cognitive, and linguistic tasks negatively impact speech motor performance (Dromey et al., 2003), stimuli were presented and repeated without a carrier phrase in this experiment, in order to reduce overall cognitive load. This resulted in smaller segments of each stimuli available for kinematic analysis, based on the peak velocity for the opening movement of the initial bilabial and the last opening movement preceding the final bilabial consonant. In future experiments, it might be advantageous to use a carrier phrase, so that the entire production of the target word or nonword might be isolated for analysis, especially if complexity of stimuli were reduced overall. It is possible that inclusion of the entire production might reveal effects or patterns that were not apparent in this experiment.

It is also possible that the length of time participants spent producing speech during this experiment (approximately 1-1.5 hours), the experimental setting, and the overall time of the experiment (2-3 hours), resulted in participant fatigue. For the present study, twenty productions were elicited of each stimuli in both conditions (internal and external). This number was selected to ensure that at least 10 error-free productions of each stimulus were available for kinematic analysis (Maner et al., 2000, Smith et al., 2004, Sadagopan et al., 2008). However, it could be argued that a minimum number of productions (10 per Maner et al., 2000) of less challenging stimuli would likely result in an equal number of useable productions for kinematic analysis, while reducing the possibility of participant fatigue. Fewer trials per stimuli would also reduce the possibility of practice effects obscuring temporary changes produced by different attentional focus conditions.

For the purposes of this experiment, an internal focus of attention was considered to be on articulatory placement and coordination, while an external focus of attention was on acoustic output (Maas et al., 2008). However, it could also be argued that the external focus of attention

condition for speech includes communicative intent with a partner (roughly equivalent to the 'goal' mentioned in limb motor studies, [e.g. Shea et al., 1999; Wulf et al., 2001; Peh et al, 2010]). In future studies, alternate definitions of an 'external focus of attention' for speech should be explored.

The instructions given for this experiment were based on those used in limb motor studies investigating the effects of an internal versus external focus of attention (Zachary et al., 2005; Shea et al., 1999). Instructions for both conditions concluded with "as quickly and accurately as you can", in order to ensure that any effects on accuracy or duration could not be attributed solely to a difference in instructions. It is possible that during this experiment, attempted accuracy precluded participants from adhering to the rest of the instructions, particularly during the internal focus condition. In future studies, instructions that emphasize aspects of internal focus with no mention of accuracy may provide more informative results.

Finally, it should be noted that all of the limb motor and oral motor studies considered in the design of this experiment included a form of feedback. In the limb motor studies (in general), participants were able to gauge the accuracy and success of their performance by observing whether the action applied to an object (golf ball, basketball, etc.) achieved the desired goal (e.g. went through the basketball hoop)[Wulf et al., 2001; Zachary et al, 2005]. In the oral motor study conducted by Freedman et al., (2007) visual feedback was provided after each trial showing the participant's performance relative to the target. In the current study, no feedback was provided, beyond the inherently available acoustic and kinesthetic feedback of verbal production. Although attempts were made to reinforce adherence to focus of attention using deception (i.e. informing participants that only acoustic or kinematic data was being recorded for the external vs. internal conditions), the fact that both acoustic and kinesthetic feedback was

available to participants during both conditions cannot be discounted. Future studies should incorporate the inclusion of additional feedback, or the removal of acoustic feedback (through masking, for example) to investigate focus of attention effects on speech motor performance.

References

Doyon, J., Benali, H. (2005) Reorganization and plasticity in the adult brain during learning of motor skills. *Current Opinion in Neurobiology, 15*, 161-167.

Dromey, C., Benson, A. (2003) Effects of concurrent motor, linguistic, or cognitive tasks on speech motor performance. *Journal of Speech, Language, and Hearing Research, 46,* 1234-1246.

Freedman, S., Maas, E., Caligiuri, M., Wulf, G., Robin, D. (2007) Internal versus external: Oral-motor performance as a function of attentional focus. *Journal of Speech, Language, and Hearing Research, 50,* 131-136.

Hatakenaka, M., Miyai, I., Mihara, M., Sakoda, S., Kubota, K. (2007) Frontal regions involved in learning of motor skill-A functional NIRS study. *Neuroimage, 34(1),* 109-116.

Keller, T., Carpenter, P., Just, M. (2003) Brain imaging of tongue-twister sentence comprehension: Twisting the tongue and the brain. *Brain and Language, 84,* 189-203.

Kleinow, J., Smith, A. (2000) Influences of length and syntactic complexity on the speech motor stability of the fluent speech of adults who stutter. *Journal of Speech, Language, and Hearing Research, 43,* 548-559.

Kleinow, J., Smith, A. (2001) Speech motor stability in IPD: Effects of rate and loudness manipulations. *Journal of Speech, Language, and Hearing Research, 44,* 1041-1051.

Maas., E., Robin, D., Austermann-Hula, S., Freedman, S., Wulf, G., Ballard, K., Schmidt, R. (2008) Principles of motor learning in treatment of motor speech disorders, *American Journal of Speech-Language Pathology, 17,* 277-298.

Maner, K., Smith, A., Grayson, L. (2000) Influences of utterance length and complexity on speech motor performance in children and adults, *Journal of Speech, Language, and Hearing Research, 43,* 560-573.

Mowrey, R., MacKay, I. (1990) Phonological primitives: Electromyographic speech error evidence, *Journal of the Acoustical Society of America, 88(3),* 1299-1312.

Peh, S., Chow, J., Davids, K. (2010) Focus of attention and its impact on movement behavior, *Journal of Science and Medicine in Sport, 529,* 1-9.

Ramig, L., Sapir, S., Countryman, S., Pawlas, A., O'Brien, C., Hoehn, M., Thompson, L. (2001) Intensive voice treatment (LSVT) for patients with Parkinson's disease: a 2 year follow up, *Journal of Neurology, Neurosurgery, and Psychiatry, 71,* 493-498.

Sadagopan, N., Smith, A. (2008) Developmental changes in the effects of utterance length and complexity on speech movement variability, *Journal of Speech, Language, and Hearing Research, 51,* 1138-1151.

Sapir, S., Spielman, J., Ramig, L., Story, B., Fox, C. (2007) Effects of intensive voice treatment (The Lee Silverman Voice Treatment [LSVT]) on vowel articulation in dysarthric individuals with idiopathic Parkinson disease: Acoustic and perceptual findings. *Journal of Speech, Language, and Hearing Research, 50,* 899-912.

Sasisekaran, J., Smith, A., Sadagopan, N., Weber-Fox, C. (2010) Nonword repetition in children and adults: Effects on movement coordination. *Developmental Science, 13:3,* 521-532.

Schmidt, R. (2003) Motor Schema Theory after 27 years: Reflections and implications for a new theory. *Research Quarterly for Exercise and Sport, 74(4),* 366-375.

Schulz, G., Stein, L., Micallef, R. (2001) Speech motor learning: Preliminary data. *Clinical Linguistics and Phonetics, 15(1,2),* 157-161.

Shea, C., Wulf, G. (1999) Enhancing motor learning through external-focus instructions and feedback. *Human Movement Science, 18,* 553-571.

Smith, A., Zelaznik, H. (2004) Development of functional synergies for speech motor coordination in childhood and adolescence. *Developmental Psychobiology, 45,* 22-33.

Studebaker, G. (1985) A "rationalized" arcsine transform. *Journal of Speech and Hearing Research, 28,* 455-462.

Vitevitch, M., Luce, P. (2004) Increases in phonotactic probability facilitate spoken nonword repetition. *Journal of Memory and Language, 52,* 193-204.

Wulf, G., Lauterbach, B., Toole, T. (1999) The learning advantages of an external focus of attention in golf. *Research Quarterly for Exercise and Sport, 70(2),* 120-126.

Wulf, G., McNevin, N., Shea, C. (2001) The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology, 54(4),* 1143-1154.

Wulf, G., Prinz, W. (2001) Directing attention to movement effects enhances learning: A review. *Psychonomic Bulletin and Review, 8(4),* 648-660.

Zachary, T., Wulf, G., Mercer, J., Bezodis, N. (2005) Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention. *Brain Research Bulletin, 67,* 304-30