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THE RELATIONSHIP OF SOMATOSENSORY PERCEPTION AND FINE-
FORCE CONTROL IN THE ADULT HUMAN OROFACIAL SYSTEM

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for degree of Doctor of Philosophy
in the College of Health Sciences at the University of Kentucky

By

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Lexington, Kentucky

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Lexington, Kentucky

2014

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ABSTRACT OF DISSERTATION

THE RELATIONSHIP OF SOMATOSENSORY PERCEPTION AND FINE-FORCE CONTROL IN ADULT HUMAN OROFACIAL SYSTEM

The orofacial area stands apart from other body systems in that it possesses a unique performance anatomy whereby oral musculature inserts directly into the underlying cutaneous skin, allowing for the generation of complex three-dimensional deformations of the orofacial system. This anatomical substrate provides for the tight temporal synchrony between self-generated cutaneous somatosensation and oromotor control during functional behaviors in this region and provides the necessary feedback needed to learn and maintain skilled orofacial behaviors.

The Directions into Velocity of Articulators (DIVA) model highlights the importance of the bidirectional relationship between sensation and production in the orofacial region in children learning speech. This relationship has not been as well-established in the adult orofacial system. The purpose of this observational study was to begin assessing the perception-action relationship in healthy adults and to describe how this relationship may be altered as a function of healthy aging. This study was designed to determine the correspondence between orofacial cutaneous perception using vibrotactile detection thresholds (VDT) and low-level static and dynamic force control tasks in three representative age cohorts. Correlational relationships among measures of somatosensory capacity and low-level skilled orofacial force control were determined for 60 adults (19-84 years).

Significant correlational relationships were identified using non-parametric Spearman's correlations with an alpha at 0.1 between the 5 Hz test probe and several 0.5 N low-level force control assessments in the static and slow ramp-and-hold condition. These findings indicate that as vibrotactile detection thresholds increase (labial sensation decreases), ability to maintain a low-level force endpoint decreases. Group data was analyzed using non-parametric Kruskal-Wallis tests and identified significant differences between the 5 Hz test frequency probe and various 0.5 N skilled force assessments for group variables

such as age, pure tone hearing assessments, sex, speech usage and smoking history. Future studies will begin the processing of modeling this complex multivariate relationship in healthy individuals before moving to a disordered population.

Key Words: Orofacial, Sensation, Force, Healthy Aging, Speech

Nicole Michele Etter

April 9, 2014

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Chapter One

Introduction

Every year 750,000 Americans are estimated to suffer a new or recurrent stroke¹ joining the approximately 7 million individuals currently living with stroke.² Another 1.7 million Americans are estimated to sustain a traumatic brain injury annually.³ Medical costs for individuals surviving stroke (CVA) have been estimated to range from \$28 billion¹ up to \$51 billion⁴ and approximately \$60 billion for those incurring a traumatic brain injury (TBI) in the year 2000.³ As people live longer and enjoy more active lifestyles, the risk of stroke and traumatic brain injury is estimated to continue increasing. In fact, projections for the year 2030 indicate an additional 4 million individuals will have a stroke, an increase of almost 25%.² With decreased lengths of stay in acute rehabilitation and decreased approved outpatient services, a rising incidence rate, and medical costs estimated to grow each year, medical professionals are faced with the demanding challenge of identifying and treating the behavioral sequelae of neurologic injuries in an efficient, yet effective manner.^{2,5,6}

Dysarthria, a multidimensional disruption in speech production, is one possible sequelae occurring after neurologic injury. Speech dysarthria can be caused by either peripheral nervous system injuries or central lesions related to both pyramidal and extra-pyramidal damage.⁷ Dysarthria has been described as including weakness, paralysis, dyscoordination, primary and secondary sensory deprivation, and/or alteration in the tone of the speech musculature.⁸ Dysarthrias represent a collection of neurologically-based speech production disorders

resulting in both perceptually observable decreases in intelligibility and physiologic abnormalities in the strength, range, steadiness, and muscle tone or performance accuracy of speech movements.⁹⁻¹¹ Speech dysarthrias have been shown to negatively effect quality of life by increasing feelings of social isolation due to decreased communicative abilities in social situations.¹² Estimates for the incidence of speech dysarthria in the United States after non-progressive neurological injury, (such as CVA or TBI), are not clear given that most current literature on this topic is twenty plus years old at this time.¹³ Recent estimates for incidence hold that 42% of all individuals with a CVA¹⁴ and 33-50% of all individuals with traumatic brain injury¹⁵ have some degree of speech dysarthria.

Much of the current research regarding assessment and treatment of speech dysarthria focuses on the motor movements and the clinician's perception of speech intelligibility. In a review by Duffy,⁷ the motor aspects associated with disordered speech production are concretely defined; however, little quantitative research exists concerning the somatosensory aspects of the orofacial system and even fewer reports formally examine the relationship between somatosensation and speech production. Speech therapy is conducted by providing patients with acoustic, visual and tactile feedback. Thus, the role of the clinician is to modify and adapt the sensory experiences of clients to achieve a desired speech action. As such, treatment approaches designed to increase intelligibility in adults with non-progressive dysarthria secondary to neurologic injury would benefit from high quality research into not only the kinetics and kinematics of speech, but the somatosensory elements that underlie speech

production and the relationship between somatosensation and fine force control parameters.

A central theoretical model that will be used in this dissertation to frame the relation between somatosensory and fine force control is known as the Directions into Velocity of Articulators (DIVA) model¹⁶⁻²⁰ developed by Frank Guenther and colleagues. At its core, this model postulates that the way an individual produces speech will effect how he/she perceives speech, and vice versa. This idea is consistent with earlier and foundational theoretical positions such as the Motor Theory of Speech Perception^{21,22} developed by Alvin Liberman at Haskins Laboratories during the early 1960's. The DIVA model, described in detail in the next chapter, is a computer network model describing the feedforward and auditory and somatosensory feedback systems involved in the learning and maintenance of skilled speech production in children.

In the context of the DIVA model's premise of bidirectional and reciprocal influences of perceptual-action during speech, deficits in auditory and/or somatosensory perceptual processing might negatively impact an older individuals' ability to adapt to novel sensorimotor experiences and/or maintain learned skills. Application of this model with healthy adults using perturbation has shown that participants will use auditory and/or somatosensory feedback to adjust their speech strategies to achieve the desired speech goal. Therefore, the quality of incoming sensory feedback and an individual's ability to process and use that information becomes paramount for correct speech production. If one couples the increase in prevalence of stroke and other neurologic events in aging

adults^{2,23} with known age-related changes and declines in somatosensory processing, it is possible that the ability for aging patients to take full advantage of rehabilitative experiences crafted by the therapist may be compromised. Before better assessments and treatments can be designed for individuals with speech dysarthria, more research is thus required to characterize alterations in sensory and force capabilities in healthy young and older adults.

The purpose of this dissertation work is to begin the process of describing the relationship between orofacial perception-action in healthy, English-speaking adults. This exploratory foundational research will identify the relationship between labial sensation and production using a vibrotactile threshold detection method and low-level force control assessments. Finally, a description of how aging influences the reciprocal relationship between sensation and force control will be provided.

In the following chapter I will provide: 1) an introduction into current theoretical models used to guide assessment and treatment approaches in speech dysarthria; 2) a review of sensorimotor literature in the orofacial region of healthy young, aging, and disordered populations; 3) a discussion of the content gaps in our current appreciation of sensorimotor integration in healthy and disordered populations, and finally, 4) hypotheses for future directions for the field of sensorimotor speech disorders.

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Chapter Two

Review of Literature

This chapter will provide a critical review of the literature regarding the sensorimotor characteristics of healthy young, older, and disordered speakers. The purpose of this review is to critique the current literature on orofacial systems involved in speech perception and production. A selection of theories used to frame experimental studies and clinical assessment and treatment will be presented with a focus on how these theories provide a framework for future studies. Basic science literature regarding kinetic, kinematic, and somatosensory assessment with healthy and impaired participants will be provided to frame our current appreciation of orofacial sensorimotor elements with particular attention given to the lips. Finally, I will present selected empirical gaps in our fund of knowledge regarding how auditory and somatosensory feedback may apply to the assessment and treatment of speech deficits after neurologic injury.

Current Theoretical Models for Speech Production and Perception

The use of theoretical models can be beneficial to researchers and clinicians to understand complicated processes of speech perception and action. Generally, speech researchers use theoretical models to guide hypotheses and questions and/or place their findings in the context of the larger field of sensorimotor communication disorders. Clinicians may find it easier to treat patients when they are able to understand the complexity of speech production. Often though there can be a disconnect in communication between the

researcher (bench) and the clinician (bedside), and a good theoretical model may help to effectively bridge this gap. The field of motor speech disorders may benefit from the guiding principles of a theoretical model to help in the transitioning of bench research to clinical practice.

Various theoretical models have been used to guide the assessment and treatment of speech dysarthria from the laboratory to the clinic setting. The most pervasive model is the Darley, Aronson and Brown (DAB) classification system, also referred to as the Mayo Clinic model.^{24,25} Work by DAB set the foundation for early definitions and classifications of speech dysarthria based on neurologic and perceptual assessment. Their classification system, and resulting model, has been used unfailingly in current laboratory research and clinical treatment settings. Other theoretical models are well known in research settings, but have yet to make their way into clinical practice. Theoretical positions like the Motor Theory (MT) of Speech Perception^{21,22} and Dynamic Systems Theory (DST)^{26,27} and models such as DIVA^{19,28-31} have focused on the learning and maintenance of speech in healthy populations. In comparison to DAB, these selected theories of speech production place a high importance on the quality of auditory and somatosensory feedback for correct speech production. Through numerous studies the application of these theories in healthy individuals highlights how alterations in feedback or mechanical perturbation can disrupt speech production and its compensation. Application of these theories to an impaired population may provide critical insights into mechanisms related to the re-learning of speech after neurologic injury.

Darley, Aronson, and Brown (DAB)

In the original work by Darley, Aronson, and Brown, speech dysarthrias were described as a “disturbance in muscular control” caused by a neurologic disorder or injury leading to “paralysis, weakness, or incoordination of the speech musculature.”^{24(p246)} In fact DAB were some of the first researchers to recognize and stress that speech dysarthria was caused by neurologic injury or impairment, where as previous researchers thought of dysarthria as strictly a peripheral disorder.⁷ In their seminal work, DAB created a means of identifying speech disorders by categorizing numerous subjectively assessed features regarding the sound and creation of speech and correlating these factors to a given neurologic disorder. Their classification scheme was based upon perceptual features and subjective ratings of speech production variables including pitch, loudness, vocal quality, respiration, prosody, articulation and what they described as the overall intelligibility of the speech sample, including variables such as “bizarreness” of speech. DAB used perceptual consensus from three speech-language pathologists (SLPs) who listened to 30-second speech samples to establish the five original dysarthria categories: *spastic*, *ataxic*, *hypokinetic*, *hyperkinetic*, and *flaccid* dysarthria. DAB later added a sixth category of *mixed dysarthria*, which represented a combination of characteristics of flaccid and spastic dysarthria associated with amyotrophic lateral sclerosis (ALS). These six classifications, along with the addition of *apraxia of speech* (AOS), have been classically described in the speech pathology literature as motor speech disorders.^{9,24}

Although DAB did not specifically intend to create a model for understanding dysarthria, their work continues to be used in clinical and research settings to diagnose, label, and provide a gross description of a patient's dysarthria for behavioral interventions. In an edited work by Weismer,³² Duffy writes that the Mayo approach "continues its dominance in research and clinical practice today."^(p.17) The persistent use of this classification system as a guiding model to the exclusion of others may not be optimally beneficial for moving the study of assessment and treatment of speech disorders forward, as the DAB approach is not without numerous flaws. First, their original report on the behavioral and assumed physiological features of speech disorders relied extensively on the perceptual judgment of a handful of SLPs listening to short speech samples without the benefit of conversational context. They did neither physical nor objective examinations of speech kinematics, kinetics, or sensation. Secondly, the classification categories developed by DAB were not well defined or lacked enough specificity and distinctiveness to be of real diagnostic value. For example, motor features ranging from flaccid to spastic defined the category of "mixed dysarthria". (Not surprisingly the most common diagnosis of dysarthria clinically is mixed,⁷ with the next most common being flaccid dysarthria at only 9%.) The heavy use of a non-specific, catchall category such as *mixed dysarthria* suggests that these classifications are not an effective means for clearly differentiating subclasses of dysarthria because of the wide range of muscle characteristics that can fit into this broad category. Lastly, the DAB classification system is dogmatically utilized in research as well as in the assessment and

treatment of individuals with stroke and traumatic brain injury. While the original work by DAB did include individuals with upper motor neuron disorders, it was not specified if any of their subjects had had a stroke or brain injury. Attempts to use this classification system with individuals with stroke have shown a lack of homogeneity in diagnosing speech dysarthria. In fact, Weismer notes that individuals with stroke or traumatic brain injury have been labeled under each of the seven classifications.³² Therefore, if the intended purpose of DAB was to connect neurogenic disorders or lesion sites with a specific motor speech diagnosis, it is likely not ideal to use this scheme for individuals with strokes or TBI. Individuals with stroke and TBI were not part of the original study and don't appear to follow the classifications devised due to the high degree of variability of dysarthria in these populations.^{32,33} The fact that numerous treatment approaches for dysarthria for individuals with stroke or traumatic brain injury have been directly informed by the DAB classification is thus problematic at best.

In reference to the DAB classification, Netsell has stated that studies in speech disorders have highlighted that the perceptual-physiologic relationship for skilled speech movements are much more complex than to those alluded to by the original DAB hypothesis.³⁴ For example, in the DAB classification scheme, rate was a key variable assessed by the researchers in their speech samples. In fact, rate is viewed as a distinguishing characteristic between certain dysarthrias, and as such has become a primary treatment manipulative. However, as noted by Kent and Rosen, the causes for decreases in rate could stem from any of a number of factors, including weakness, fatigue or inefficient temporal processing.

In some cases, using a slower rate may actually be a compensation strategy employed by the individual with dysarthria in an attempt to achieve the tactile and proprioceptive feedback needed to inform evolving skilled speech output.²⁶

Weakness is another term often used to describe numerous dysarthrias simply based on the acoustical perception of “imprecise consonants” or other qualitative descriptors of speech (eg. slurred or mushy). In treatment, weakness has been used as the principle rationale behind non-speech oral motor exercises (NSOMEs). Given the ubiquitous use of the term “weakness” it is interesting to note that when using objective instrumental kinetic and kinematic assessments, little progress has been made to confirm the assumption of weakness or explain the role of “strength” and “force” changes in skilled speech production.²⁶ In fact, it has been found that under normal conditions, lip forces during skilled speech require approximately 2 Newtons or less, an estimate of 10-20% of the maximum force the musculature of the lips are capable of achieving.³⁵⁻³⁷ Therefore, muscle weakness cannot be the sole agent responsible for explaining decreased speech accuracy in consonant production.

Given this brief overview of the DAB model, it is suggested that the use of this model may be less than adequate to act as the central guidepost for the field of sensorimotor speech disorders, particularly when applied to individuals with non-progressive speech dysarthria following neurologic impairment, such as stroke or TBI. While DAB’s work did help to establish the importance of recognizing the neurologic basis of acquired speech disorders, the continued and dogmatic use of this classification system for all neurologic populations is

unfounded. What is needed instead is a theoretical model that can take into account factors such as the precise location and severity of injury, pre-morbid speech abilities, somatosensory and auditory feedback mechanisms and other neuroanatomical features to characterize a patient's speech deficit. In the following section, a selection of theoretical constructs and a possible candidate model for speech perception-action will be presented.

Theories of Perception-Action in Speech

The Motor Theory (MT) of Speech Perception^{20,21,36} postulates three main principles: 1) that speech processing is a special event; 2) there are invariant motor commands for the articulators to produce a specific configuration that is then perceived by a listener; and 3) there is a direct linkage between speech production and speech perception.^{21,38} Although the Motor Theory of Speech Perception has received criticism within the field of speech perception, it is nonetheless a useful tool for providing insight into how a listener may perceive an intended phonetic gesture of a speaker. While speech is complex, the idea that speech is special and requires separate and unique biological underpinnings appears to be unfounded.²² The remaining two principles though have more evidence to support their claims.^{22,39} There are numerous studies in speech science literature to demonstrate the importance of incoming sensory afference, both auditory and somatosensory, to inform speech perception and motor output.³⁹⁻⁴³ Imaging studies using functional MRI⁴⁴ and transcranial magnet stimulation (TMS)⁴⁵ have demonstrated that cortical excitation occurs in motor areas when speech is auditorily perceived. During speech development and

throughout speech use, the auditory signal is typically assigned primacy to identify accuracy and provide feedback to correct production errors.^{39,46} It is specifically this tenant of MT, the reciprocal relationship of sensation and production, that may be useful to expand upon.

Dynamic Systems Theory (DST) is another motor control theory that has possible applications to speech motor control.²⁶ This research will use a Bernstein view of DST,^{47,48} and its close theoretical cousin sensorimotor neural selectionism,⁴⁹⁻⁵¹ to illustrate how neurobehavioral networks form developmentally and how complex dynamic performance emerges from the interaction of neurobiological networks and environmental affordances.^{27,52-54} In DST, researchers use conceptual heuristics such as attractor states or attractor “wells” to characterize stable behaviors, while in selectionist network theories, these similar states would be referred to as prototype exemplars of a perceptual category.^{49,51} Speech remains flexible in achieving spatiotemporal targets within the context of a stable attractor state because performance features of speech are continuously updated through real world sensory feedback.²⁷ When individuals perform an action they are not accessing a stored motor plan in a ‘homunculus’ that has previously been learned and then saved in the brain. Humans (and other organisms) are capable of numerous behavioral variations to accomplish a functional goal based in part on the defined structures of the body and how the body interacts with environmental constraints. In fact, these models can be used to understand how our nervous system acts to calculate and specify the necessary sensorimotor transforms to achieve a desired outcome/movement

goal.²⁷ The famed Russian-born motor control theorist Nikolai Bernstein has contributed greatly to our understanding of movement and motor control by hypothesizing that movement is the result of interactions of the central nervous system (CNS), the physical properties of the musculoskeletal system, and environmental forces.⁴⁷ Bernstein was one of the first researchers to explicitly define movement in terms of cooperative and multifaceted synergistic interactions among the body, environment and intent.⁴⁸

Bernstein's notions of synergies in movement are generally applicable to the orofacial and vocal tract systems. For example, in the context of the sound source and filtering systems of the human vocal tract, we know that there are near limitless 3D geometric deformations of vocal tract space that can result in the sounds of a language. As individuals learn a new language, there may be increased perceived effort to coordinate the tongue, teeth, and lips to form the correct sounds at the individual level. At this stage, speakers are most rigid in their production of sounds to ensure correct speech execution. As skill develops, speakers become more flexible in their means of accomplishing the production goal; they have more freedom in not only how the lips, jaw, and tongue can move and interact, but they are also less affected by changes in task demands and environmental perturbations. For example, tongue placement may not have to be as exact to still produce sounds within an envelope of perceived correctness. Therefore, using a concept adapted from Bernstein (1967), healthy, skilled speakers have more invariant results even when using variant means of production. As skilled speakers, individuals can use several degrees of freedom

in varying means and degrees to produce a common and functionally appropriate acoustic goal.

According to Bernstein the fundamental problem for understanding movement systems is “*the process of mastering the redundant degrees of freedom*” or more succinctly, how the motor control apparatus is organized to use its inherent adaptive capacity to achieve a function goal.⁴⁷ Research has shown that individuals will attempt to use the most efficient motor plan that stays within the acceptable envelope of completing the task or goal. Davids et al. write, “This task-specific view may provide a better framework for understanding the role of inter- and intra-individual variability in the provision of diagnoses and treatment interventions in human movement by sports medicine.”⁵⁵ The variety in body parts and processes to choose from when executing a motor goal has been termed as “degrees of freedom.” Degrees of freedom are the individual variables that we are capable of manipulating by either freezing them (holding them constant) or freeing (allowing flexibility) to accomplish a goal.^{27,56} This concept provides a framework for understanding features of coarticulation, a necessary skill for running speech that comes from the complex interplay of the anatomy arranged in such a way as to allow for a range of acceptable articulatory gestures to produce the given acoustic signal.²⁶ In this case, variation is not just “noise” but a hallmark of a skilled speaker. In fact, it is possible that in disorders of speech, patients no longer have the flexibility of the production system to achieve the desired speech goal. It is often implied that individuals with dysarthria have a problem with coordination of their movements. Coordination can be defined as a

pattern in spatiotemporal movements to reach a target goal that is repeatable.^{26,57} This definition emphasizes that speech is a goal-directed behavior or action; however it also implies that reaching the intended movements relies on being able to successfully repeat a pattern.

Continuing this line of thinking, it is reasonable to hypothesize that individuals with dysarthria may exist within a state defined by excessive degrees of performance variation. As such, more clarity is needed to define what precisely constitutes performance “variation”. For example, at some time points, variation is a positive attribute of a highly skilled speaker, providing the person with the ability to achieve a speech goal from a large array of combinatorial solutions. At other times though, variation becomes a drawback to the system, resulting in an inability to achieve the intended movement goal. Based on data from perturbation studies, skilled speakers when faced with mechanical,^{58,59} displacement,^{53,54} and auditory^{60,61} perturbations, will compensate for unintended target errors by rapidly reorganizing their production system. Therefore, it is possible that individuals with dysarthria are constrained in their ability to make specific target sounds, with changes in neuromuscular control and sensory feedback post-neurologic injury functioning as a perturbation in and of itself. Therefore, retraining and a recalibration of acceptable speech output must be of sufficient intensity to alter the behavioral stability of disordered speech and return the patient to more functional and adaptive speech production. A model that may describe how recalibration of a dysarthric speaker’s perception-action loop may occur is the DIVA model.

Directions into Velocities of Articulators (DIVA) Model

The Directions into Velocities of Articulators (DIVA) model can be used to provide insights into speech dysarthria. The DIVA model of speech perception is a recent theoretical model that attempts to relate the neuromotor and biomechanical properties of the speech system to the sensory processes deemed necessary for speech production (See Figure 1).^{19,26,28,29,62,63}

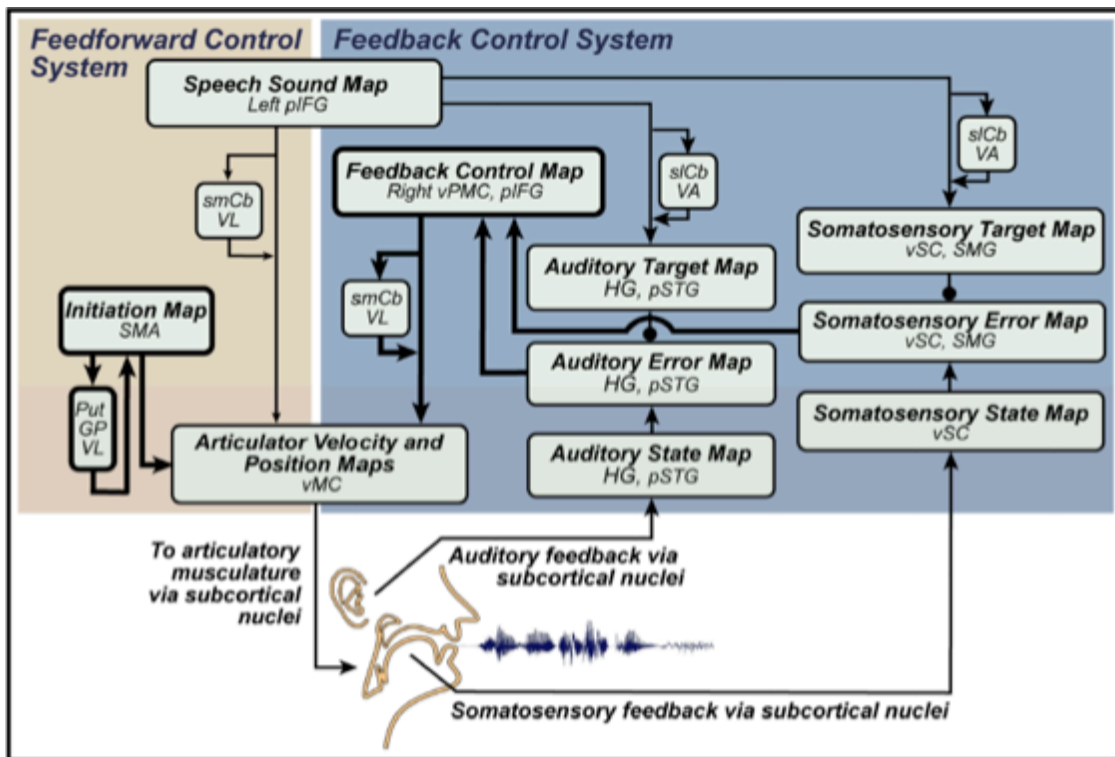


Figure 1: DIVA Model Schematic¹⁸

Schematic of DIVA model from Tourville and Guenther, 2009. See text for details.

This innovative computer model was created to highlight the importance of perception in the production of speech while tying speech production to biologically known anatomical substrates and functions from the growing literature in the area of functional brain imaging.^{18,64} The Directions into Velocities of Articulators model, DIVA, was primarily intended as a computer simulation-

based neural network for understanding speech development in healthy children.¹⁹ One critical feature of DIVA is that it formally highlights known brain regions involved in speech production, including bilateral medial and lateral frontal cortex, parietal cortex, superior temporal cortex, the thalamus, basal ganglia and cerebellum and how these structures communicate for learning a skilled behavior.^{18,64} These areas of the brain are used for the planning, execution, and if necessary, the correction and adaptation of skilled speech activities.

Over the past decade and a half since its conception, the DIVA model has been repeatedly tested and continually refined. The current instantiation of the model seeks to provide a coherent framework for explaining speech perception-action phenomena including: the use of motor equivalence, feedback and feedforward processes, the effect of speaking rate and, how speech skill is developed and refined throughout developmental learning.¹⁸ In the schematic of the model above in Figure 1, each box represents a specific set of neurons with arrows corresponding to axonal projections thus depicting information transforms through a series of synapses with another area of the neural mapping. Starting in the upper left hand corner of the model, the *speech sound map* corresponds with neural networks that maintain the learned syllabary for the speech sound production; this area correlates to Broca's area in the inferior frontal gyrus. By activating the speech sound map, the subsequent motor command enters the motor cortex via feedback and feedforward control subsystems interspersed within the perisylvian language zone along the lateral convexity of the cortical

mantle.⁶⁵ Feedback control subsystems pertains to both audition and somatosensation.

In a mature speaker, the system has completed a lengthy training process that matches the intended speech goal to an acoustic and tactile/proprioception target. This training process simulates the developmental time course and neurobehavioral events in the acquisition of human speech by a child. In healthy, typically developing children, this process occurs during babbling and early speech behavior to tune and organize feedback error maps with the motor commands and to develop sensory maps via tactile, proprioceptive and auditory feedback signals. One key element of this model is that the training of phonemes creates target regions and not tightly bound endpoints. This structure presumably allows for a wide variety of allowance for speech sound production and perception, an important factor for coarticulation in running speech, contextual variations, and rate effects.^{62,65} In work with children, Kuhl and colleagues have found that during speech development, children cultivate an inhibitory response to ignore variations in speech that are irrelevant to deciphering their native language.⁶⁶ The process of training the error maps and sensorimotor transforms ensures that the speech sound map cells are activated both when producing and perceiving sounds, a phenomenon that is hypothesized to involve mirror neuron system. Briefly, mirror neurons are a class of cells discovered by Rizzolatti and colleagues in the mid- 1990's that are activated when a primate performs a specific action and when it observes that specific action being performed by a conspecific. This neurophysiological mechanism may play a fundamental role in

imitative motor learning, including speech.^{45,67,68} However Lotto, Hickok, and Holt have argued that due to the linguistic complexity of speech perception and production of coarticulation, mirror neurons should not be viewed as the primary solution of speech perception.⁶⁹ Their application to the emergence of human behavior remains a hotly contested area of research.

Although the DIVA model posits an explanation for how speech is learned by the developing infant and child, it may also offer critical insights into how the speech system can generally be re-trained after neurologic injury. For example, one of the basic mechanisms of the model is a continuous updating of auditory and somatosensory error maps based upon real-time performance-related afference. This feature clearly highlights the importance of auditory and somatosensory feedback and feedforward control systems.⁶⁵ Recent work by Ostry and colleagues⁷⁰ supports this contention by demonstrating that the sensorimotor system can adapt and alter target endpoints following a period of speech motor learning, thus demonstrating that adaptations not only happen in speech motor systems, but in the auditory representation of the phonemic goals as well. Further research by Ostry and colleagues,^{40-43,71-74} highlights the adaptability of the speech system to performance perturbations, highlighting the flexibility of the system in spite of imposed mechanical, auditory, or somatosensory interference. Future therapies for speech dysarthria may benefit from specifically exploiting mechanistic features of feedback and feedforward control systems to target speech goals. For example, by providing specific alterations in somatosensory or auditory feedback, patients may attempt to

compensate for performance discrepancies in a manner that increases speech intelligibility. For individuals with dysarthria, it may be important for the therapist to provide adequate feedback in the accuracy of the target, and an ongoing readout of performance accuracy to help the client maintain effective learning of necessary sensorimotor transformations.²⁶

Although DIVA began as a model of speech acquisition and phoneme refinement during development, it may provide insights to the relearning and refinement of speech production/perception post-injury. In fact, there is already precedent for using DIVA to model phonological disorders in children,²⁰ adult stuttering,⁷⁵ and apraxia of speech.¹⁸ In light of this brief discussion, it is reasonable to conclude that the DIVA model may offer clinicians and researchers alike a framework for guiding the design of assessments and treatments for individuals with dysarthria. This model combines not only the auditory perceptual measures of the listener, but also the auditory and somatosensory characteristics of the speaker while grounding all of this in a neurobiological substrate. In short, DIVA could be the key model needed to move the field of speech motor disorders forward.

Anatomy and Physiology for Speech Production and Perception

The orofacial system is responsible for producing numerous functional behaviors including feeding, facial gestures of expression, and speech.⁷⁶⁻⁷⁹

Speech is a highly-skilled fine motor task produced rapidly with great accuracy while maintaining flexibility in achieving articulatory targets and can be improved

with practice.^{76,80} Speech movements require the rapid and highly coordinated interplay of numerous orofacial area muscle groups working synergistically towards an intended action.

Labial Muscles

The muscles of the lower face responsible for speech production possess unique anatomical characteristics that are morphologically different from skeletal muscles. The muscles of the lower face do not possess fascia, have no well-defined insertion loci, lack tendonous attachments to the skull, have variant fiber orientations, interdigitate with other surrounding muscle groups and embed themselves directly into the overlying skin.^{35,81,82} Externally, the muscles of the lips are covered with skin and are internally covered by mucous membrane.⁸³ The lip musculature is comprised of no fewer than ten intrinsic and extrinsic muscle groups that extend from the maxilla and mandible and insert directly into the labial skin.^{35,83-85} The major mass of the upper and lower lips are made up of the orbicularis oris (OO) muscle with fibers that originate from one corner of the mouth and travel to the other corner in an imbricated pattern. The OO muscle functions to close and round the anterior oral region⁸³ in a sphincter-like and compressing manner.⁸⁶ See Figure 2 for an image of the complex interdigitation and potential movement angles for the muscles of the lips.⁸⁵

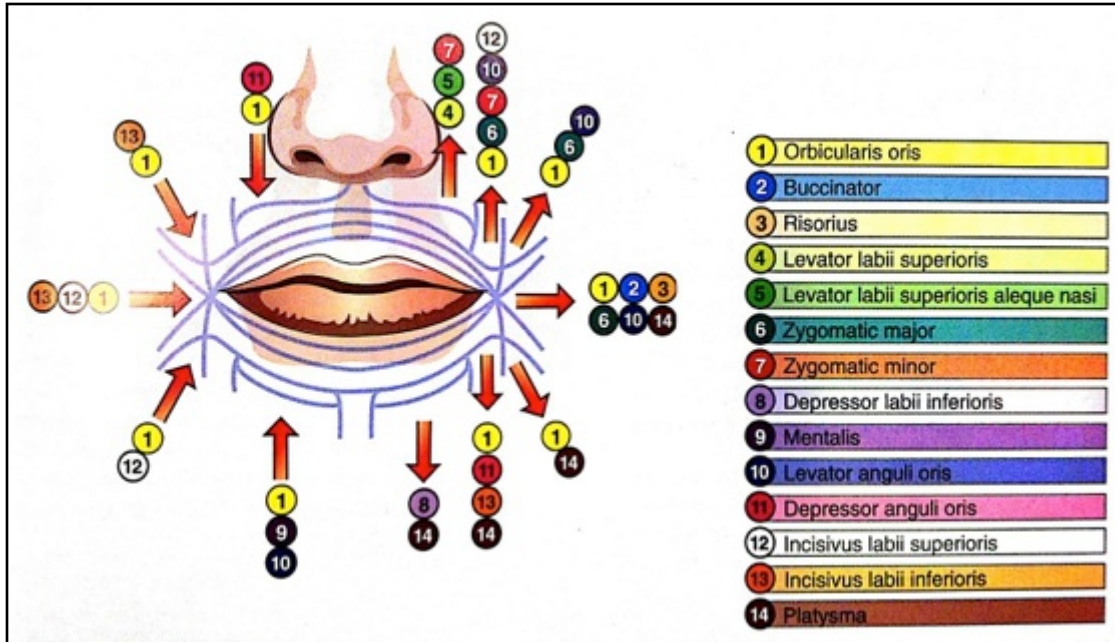


Figure 2: Interdigitation of Labial Muscles⁸⁵

Image of various muscles that make up the lips to illustrate the high level of interdigitation and the complex movement patterns that are achieved through different muscle groups working together, unlike isometric movement of the limbs.

Interdigitation of labial muscles and the fact that these muscles insert directly into the overlying skin allows for complex co-contraction of these muscles to create innumerable labial positions for gestures and speech production purposes.³⁵ In fact, the labial system shares characteristics with the biomechanical properties of a muscular hydrostat, a muscular organ that maintains its own supportive shape and is able to generate three-dimensional conformational tissue changes.⁸⁶

Mechanoreceptors in Lower Face

Muscles. Because vision is limited as a feedback mechanism for speech motor control, humans rely heavily on auditory, proprioceptive and mechanoreceptive information.³⁵ The vocal tract possesses unique combinations

of somatosensory receptors including pseudo-muscle spindles, select joint receptors, chemo- and baroreceptors and various cutaneous mechanoreceptor classes that are able to detect low-threshold sensory events such as stretch, strain, air pressure/flow and vibration.^{35,79} The labial system possess a unique array of sensory endings compared to other vocal tract structures. For example, the morphological equivalent of joint capsules or intrafusal fibers have not been identified in the lips, suggesting an alternative strategy for obtained proprioception information through cutaneous channels.^{84,87,88}

Cutaneous. Glabrous, or non-hairy, skin contains four mechanoreceptors: Merkel cells, Meissner, Ruffini, and Pacinian corpuscles (PC).⁸⁹ The skin overlying the lips only contain three of these receptors; Pacinian corpuscles have not been identified in the lips.^{90,91} All mechanoreceptors in the lips are innervated by large diameter type II A β fibers that originate from the second (V₂) and third (V₃) divisions of the trigeminal nerve.⁹² These receptors can be differentiated from each other by their physiologic response to ramp and hold activity and vibration. Similar to other cutaneous mechanoreceptive classes, these endings possess both slow (SA type I or II) or rapid (RA I) adaptation properties.

Numerous studies have been completed characterizing somatosensory processing in the perioral skin to various low-level mechanical inputs.^{35,76,93-100} Classically, a four channel theory of sensitivity to vibration has been suggested to code vibrotactile responses in glabrous skin within an operating range of 0.4 to over 500 Hz.¹⁰¹ Researchers have confirmed the presence and distribution of various mechanoreceptors in the glabrous skin of the lips and palm versus non-

glabrous or hairy skin. Using the classification of Bolanowski and colleagues,¹⁰¹ the P channel is associated with Pacinian corpuscles and responds well to vibratory inputs from 250-300 Hz, however has an operating range up to 800 Hz. The lack of PCs in the face has been confirmed by psychophysical studies demonstrating a drop off in perceptual response at 250 Hz.⁷⁶ Three non-Pacinian channels have been identified in the lower face. The non-Pacinian I (NP-I) channel is associated with the rapidly adapting type I receptor or Meissner corpuscle. The Meissner corpuscle is sensitive to vibratory inputs between 3 and 100Hz.¹⁰¹ The Meissner corpuscles respond to lower frequency vibration often characterized as flutter. Generally, rapidly adapting endings encode stimulus information at the onset and offset and are better for encoding dynamic content of a stimulus.⁸⁹

The non-Pacinian II (NP-II) channel is associated with the slowly adapting type II receptor, or Ruffini end organ. The involvement of Ruffini endings for mechanoreception is somewhat controversial. It is hypothesized they Ruffini's may be involved in detecting stretch or used for proprioception directly. Ruffini's respond to a frequency range from at 15-400 Hz.¹⁰¹ The last channel is characterized as a third form of non-Pacinian (NP-III) channel and is associated with the slowly adapting type I ending or Merkel disc. Merkel discs contribute to the detection of pressure and form and respond to vibratory inputs from 0.4 Hz to just over 100 Hz.¹⁰¹ Finally, free nerve endings are also present in the facial skin, but their role in orofacial proprioception is currently unknown. The lips have a higher number of slowly adapting endings that respond throughout the duration

of stimulation in the receptive field.⁸⁹ These receptors are also responsive to contraction, stretch, deformation of the labial muscles, and direct contact providing important and necessary feedback underlying skilled orofacial gestures and behaviors.^{35,88}

The various types of mechanoreceptors available in the lower face, both glabrous and non-glabrous skin, contribute to the overall ability of the face to detect small variations in stretch.³⁵ In fact, the lower face is highly sensitive to small levels of contraction, stretch, velocity adjustments and load dynamics,^{76,77,84,102-104} all of which correlate well with inputs necessary for maintaining the skills needed for complex orofacial behaviors, like speech.¹⁰¹ This high sensitivity likely plays an important role in maintaining performance skill through the feedback from self-generated orofacial behaviors.¹⁰⁵ Cutaneous and proprioceptive information gathered from mechanoreceptors in the lips reach the cerebrum for perceptual processing via select cranial nerves and the thalamus.

Afferent Information and Perception

All mechanoreceptive, nociceptive, and thermoreceptive sensory information from the skin of the face is transmitted centrally via the trigeminal nerve (CN V).⁸⁹ The trigeminal nerve is made up of three branches serving distinct anatomical areas of the face: ophthalmic, maxillary and mandibular. The ophthalmic branch innervates the anatomical area from the nose tip superiorly to the scalp, including the eyelid, cornea, and mucous membrane of the nasal cavity. The maxillary branch supplies the areas of the lower eyelid, mucous membrane of the upper mouth and nose, as well as the upper part of the pharynx

and sinuses. Finally, the mandibular branch supplies the lower teeth and gingiva, lower face, and the skin of the ear.⁸³ Peripheral branches of the trigeminal ganglion enter the trigeminal nerve at the mid-pons level. Large diameter afferents, responsive to vibration and indentation and serving the ipsilateral side of the face, innervate second-order neurons centrally.⁸⁹ The principal sensory nucleus (V_p) of the Trigeminal in the pons is mapped somatotopically and is the primary target for all sensory inputs from low threshold cutaneous mechanoreceptors. Afferent neurons from V_p project axons across midline at the level of the pons to join the fibers of the medial lemniscus. The trigeminal fibers continue rostrally via the trigemino-thalamic tract and terminate upon third-order neurons in the ventral posteromedial (VPM) nucleus of the thalamus.¹⁰⁶ The VPM is the primary thalamic nucleus for all facial cutaneous inputs in humans and primates.¹⁰⁶

Cortical Maps and Representations

Axons from the thalamus project to the primary sensory cortex (S1). S1, located anatomically on the postcentral gyrus, contains functionally and architecturally distinct areas and is organized to form a complete somatotopic map of the body. The primary sensory cortex can be divided into four subareas based on the form of somatosensory information it receives from subcortical regions: Areas 3a, 3b, 1, and 2 (from rostral to caudal).^{35,89} Information from rapidly adapting endings, such as Meissner cells, synapse on to Area 1. Area 2 is primarily activated by joint information. Muscle spindle afferents that encode position and velocity synapse on to Area 3a. The slowly adapting

mechanoreceptors of the skin, including the Merkel and Ruffini endings, synapse on to Area 3b.^{35,89,92}

Adult speakers have fully developed central sensory (tactile, proprioception and auditory) maps that are heavily integrated with surrounding cortical areas. The distribution of receptors is not even throughout the body and thus the corresponding mappings on S1 reflect this state with a larger representations for the orofacial region comparatively. For example, there is a disproportionately large representation of the skin of the lower face, lips, and tongue on the lateral postcentral gyrus highlighting the increased sensory acuity of the lips due to experience, and use.³⁵ These mappings are not fixed; instead the varying sizes of cortical maps reflect life-long use, behavioral experience, and skill competency.^{89,107-110}

Motor System

The primary motor cortex (M1), anatomically located on the precentral gyrus, receives somatosensory inputs directly from the thalamus and S1 via Area 5 and 7 of the parietal lobe.^{89,92} At a gross level, M1 appears to have distinct areas for major body regions organized in an inverted somatotopy similar to S1. However, intra-areal organization does not appear to possess the somatotopically organizational layout found in S1. Supramaximal electrical stimulation of a circumscribed area of M1 can activate numerous related muscle groups. As such, it has been suggested that M1 is organized to promote coordination among functionally related muscle groups (synergies) rather than organized at the level of single muscles.¹¹¹ Overlapping efferent representations

for jaw, lips, and tongue musculature have been noted in lateral regions of M1.¹¹² This fractionated and overlapping organization suggests that M1 is not a direct map of the body's musculature (a homunculus), but rather a map of behavioral function (movements, actions, and behaviors) and muscular synergies. Such a mapping suggests a complex interplay among multiple performance-related areas through reciprocal connections with premotor cortex, the supplemental motor area, somatosensory cortices (SI and SII), and the thalamus.¹¹³

A disproportionately large area of the neocortex is dedicated to executing the functional orofacial gestures needed for speech production. Prior to an action, activity patterns in M1 are highly correlated with the production of precision force generation necessary for preparation of speech production.¹¹⁴⁻¹¹⁶ During the preparatory phase, corticomotoneuronal firing patterns change in relation to the early phases of fine force control and rate of force change.^{114,117,118} In fact, M1 appears to contain populations of neurons that are tuned to differentially respond to static or dynamic activities,¹¹⁴ a feature that may be beneficial during the production of complex force dynamics needed for speech.

Projections from M1 descend to the brainstem where motor inputs via high-density monosynaptic projections are made directly to the facial motor nucleus in the pons.¹¹⁹ The facial nerve's motor fibers supply innervation for facial movements for gestures and behaviors.⁸⁸ The facial nerve travels through the internal auditory canal and mastoid bone to the stylomastoid foramen and separates into five peripheral branches (temporal, zygomatic, buccal, mandibular and cervical) innervating all facial muscles.¹²⁰

Muscles of the lower face are characterized as having smaller motor units allowing for finely graded and highly fractionated movements.^{35,121} The high density of monosynaptic projections and the low innervation ratio of motor units of the lower face allows for a highly coordinated system capable of making the finely graded adjustments in force and position necessary for skilled speech production.^{122,123}

Assessment of Speech Production and Perception in Healthy Populations

Assessment of lip function

Increased knowledge regarding the performance anatomy of the lower face will be beneficial toward understanding speech sensorimotor control in healthy, aging, and disorder populations.^{35,124} Physiologic assessments of orofacial function have been completed in passive, static, and dynamic states. This section will provide a brief overview of our current appreciation of physiological assessments in the lips of healthy adults.

Healthy Young Adults

The perioral region is one of the most sensitive areas on the human body.^{76,125-129} As described above, the perioral region does not contain muscle spindles, golgi tendon organs, nor joint receptors;^{76,130} therefore, work in proprioception is often studied using mechanical stretch, strain and vibration applied to the skin. Using cutaneous mechanical and vibrotactile detection methods on glabrous and non-glabrous skin has been a popular model for sensory assessment in the lower face.^{76,93-95,98-100} Work by Barlow⁷⁶ confirmed

that the face has different types and distributions of mechanoreceptors compared to other body areas, such as the hand. He also found that of the orofacial skin sites assessed, glabrous skin had significantly lower vibrotactile detection thresholds than non-glabrous (hairy) skin, indicating better tactile sensitivity in glabrous skin. There is some evidence to indicate sex differences in perioral sensation,¹²⁵ although more research is needed to confirm these results.

Because of the complex interdigitation of the labial muscles, mechanical stimulation to the skin of either the upper or lower lip will evoke a reflex response in inferior and superior divisions of the orbicularis oris (OOm).¹³¹ However, similar mechanical stimulation to more remote musculature like the chin will not evoke the same specified response.¹²³ There is partitioning within the orbicularis oris as well. In a study using electromyography (EMG),¹³² researchers found a functional compartmentalization of the OOm suggesting that the lip is not activated as a single muscle entity during varying speech sounds. This finding is consistent with early kinematic data demonstrating variations in upper and lower lip movements for speech sounds.^{133,134} For example, the lips demonstrate velocities of 5 up to 25 cm per second during speech.³⁵ The upper and lower lips are not equal in their contribution to speech sounds with the lower lip moving up to twice the distance of the upper lip for certain sounds¹³⁵ as well as being the faster of the two structures.⁸³ Interestingly, most of the lower facial muscles insert into the lips giving the lips a large potential repertoire of fractionated movements for speech sounds.³⁵

Perturbation studies have been used to assess the responsiveness of the orofacial system to external loads.^{58,59,136-139} These studies have demonstrated that the lower face is able to functionally adapt to unexpected changes in movement trajectories in a predictive and rapid manner.³⁵ In a study by Folkins and Abbs,¹⁴⁰ force perturbations were applied to the jaw to prevent closing movements necessary for bilabial stops. The researchers found that despite the mechanical load, participants were able to make rapid compensatory adjustments to achieve the target sound, demonstrating an online reorganization of jaw and lip movements during speech tasks. In further work, Gracco and Abbs⁵⁹ applied smaller, unanticipated loads to the lower lip during bilabial productions of the phoneme /b/ and found again that subjects were able to compensate to complete the target phoneme. Continuing their collaboration, Gracco and Abbs⁵⁹ hypothesized that speech movements are organized at the goal or action level. This work relates well to the motor control theories discussed previously as it demonstrates that labial actions may be planned at a higher cortical level and that the overall movement plan is more important than individual articulator control.^{27,141} In a recent perturbation study using fMRI to determine central cortical effects, researchers found that mature speakers were able to compensate for perturbations by adjusting other functionally-related articulators (e.g. lips, tongue, jaw).¹⁴² Additionally, while not the focus of this review, numerous studies utilizing perturbations to the jaw have also confirmed online compensatory responses of articulators to maintain speech output in the face of altered production.^{41-43,72}

Various studies have been completed to distinguish the maximum level of force the tongue and lips can attain and what amount of force is necessary for speech production.^{37,86,143} Kent and colleagues¹⁴³ reviewed results from various studies indicating maximum reported lip¹⁴⁴ forces during bilabial lip closures of up to 4 Newtons, upper lip forces around 4 Newtons and lower lip (in males) forces up to approximately 15 Newtons.¹⁴⁴ Work by Muller and colleagues calculated forces necessary for speech production to be less than 2 Newtons.⁸⁶ Differences in force control for the upper and lower lips have been confirmed by Barlow and Netsell¹²³ through the demonstration that lower lip force control is less variable during static lip control tasks. While males and females demonstrated differences in maximum force compression in these studies, they compare similarly in skilled ramp and hold force assessments using end-point targets similar to those found during speech (0.25 to 2 Newtons).³⁶ Labial studies of healthy, young individuals reveal a complex and highly sensitive system capable of rapid movements and finely skilled adjustments needed for speech production.

In a healthy adult, speech has reached such a high level of mastery that it continues to be produced with high rates of speed and accuracy with little to no cognitive thought as to *how* it is produced.²⁶ Minimal errors are made and corrections are completed in a predictive and rapid manner. Speech is so over learned and highly skilled that adult speakers are able to produce speech in the face of numerous perturbation states. It is not until after injury, whether central or peripheral, that individuals must concentrate on how speech is produced and consciously attend to speech movements, work to identify errors, and plan

corrections. As stated by Netsell, it should be noted that speech patterns are not fixed motor movement routines; “the speaker’s internal referent is what it ‘feels’ and sounds like to produce certain speech movements and acoustics.”⁸⁰(pg.10)

Because correct production of a target phoneme is heavily based upon acoustical feedback, there is an acceptable level of variance in the system. Motor equivalence allows for motor system elements (in this case the various positions of the vocal tract) to have considerable variation and yet maintain successful speech end-products.^{77,145} However, behavioral and physiological changes associated with healthy aging may impact the ability of older adults to correctly perceive and produce speech.

Healthy Aging

Alterations in tactile detection capacities are known to occur throughout the skin as a function of healthy aging. These aging-related somatosensory perceptual changes are characterized in part by increases in tactile detection thresholds, independent of the form of the stimulus, suggesting a progressive diminution of cutaneous somatosensory sensitivity. Several studies demonstrating alterations in tactile sensation with aging have been completed using different body locations such as the hand and fingertips,¹⁴⁶⁻¹⁵³ foot sole,¹⁵⁴ or a combination of locations including hand, foot, shoulder and cheek.¹⁵⁵⁻¹⁵⁷ In spite of what is known about structural changes in skin with aging and sun exposure,^{158,159} as well as the diminution of aging-related perceptual sensitivity to tactile stimuli in the fingers, hands and feet, relatively little is known pertaining to

vibrotactile perceptual changes in the lips of the aging, regardless of health status.

Our current appreciation of aging-related orofacial and perioral tactile sensitivities is based upon limited and low-resolution assessment methods of tactile perceptual skills.¹⁶⁰⁻¹⁶² For example, in a study by Stuart and colleagues,¹⁵⁷ a group of healthy older adults had increased vibrotactile detection thresholds (decreased sensation) on the non-glabrous skin, or hairy skin, of the face (cheek). Applications of this study to labial sensation may be restricted due to the testing location (non-glabrous skin of the cheek versus the glabrous skin of the lips), and the small set of test frequencies (30 and 200 Hz) used to assess mechanoreceptor responsivity. In fact, these vibrotactile test stimuli were not optimally suited to probe the orofacial sensorium with any great resolution given that although the known range of sensitivities of orofacial cutaneous mechanoreceptors is from DC to 300 Hz,^{76,77} the bandwidth of tissue kinematics created by functional orofacial behaviors, such as speech, is from DC to < 20 Hz.⁸⁶

Heft and Robinson used a variety of somatosensory tests, including temperature and two-point discrimination, to demonstrate an increase in detection thresholds in glabrous orofacial skin illustrating generally decreased sensitivity in a cohort of older participants.¹⁶³ Results from this study identified some general changes in somatosensation in older adults; however, the relatively broad and uncontrolled nature of the test stimuli provided less than optimal estimations of the fine-grained sensory capacities necessary to support

skilled orofacial behavior. Finally, Wong and colleagues assessed tactile spatial acuity on the fingers and the lips of blind individuals proficient in Braille as compared to age-matched controls.¹⁶⁴ Although not their primary area of interest, these investigators found a main effect of age for decreased sensory acuity. The behavioral consequences of alterations in somatosensation have not been well documented. It is possible that the effects of decreased sensation with age are not perceived until the system has been sufficiently perturbed by sequelae from neurologic injury.

Speech Perception and Production in Clinical Populations

Assessment of Dysarthria

Speech dysarthria can be studied and assessed by clinicians in two general ways. The first and more common assessment method is through a mostly perceptual (subjective or observational) evaluation that at best may include objective acoustic parametrics and the appreciation of neurological confirmatory signs. In general, perceptual characterizations of dysarthria are generally based on acoustic and overt production features of prosody, loudness, rate, and articulatory precision. While some of these acoustic and observable production measures can be assessed objectively, they do not provide a direct measure of the underlying physiological function. Indirect physiological assumptions can be made from perceptual assessment measures; however, the validity and reliability of those assumptions are tenuous at best.

Clinically, the accepted guidelines for examination of motor speech disorders are comprised of four components: 1) a detailed case history, 2) an examination of speech structures during static movements of non-speech tasks, 3) assessment of perceptual speech characteristics, and 4) subjective assessments of intelligibility, speech naturalness, comprehensibility, and efficiency of production by the SLP.⁹ In some clinical settings, the SLP's experience is the primary (and only) resource available and is heavily relied upon to diagnosis and treat speech production deficits. This may be of concern given that SLPs may have varying internal references for what constitutes as acceptable "intelligibility" based on their years of experience and background in listening to speech from individuals with neurologic impairments.

A second approach to assessment of dysarthrias in the clinical setting is through a direct physiologic approach.⁵⁷ Many clinicians consider the oral mechanism exam to operate as a reliable and valid physiological approach. Unfortunately, oral mechanism exams are not always an accurate or reliable measure of the underlying speech physiology, but rather should be considered as generally subjective in nature. Oral mechanism exams rely on a clinician's characterization of articulatory subsystems that are not calibrated to a known and unbiased metric and can be easily influenced by a clinician's level of experience. In addition, the typical oral mechanism exam employs non-specific measures of oromotor competency through various static or non-speech measures that are not well suited to provide sensible indicators of real-time speech production.

Thus, it is possible that oral mechanism examinations are not sensitive enough to specify distinguishing factors of dysarthria.

Physiologic Laboratory Assessment Measures

In the laboratory setting there are other means of assessing dysarthria available, including electromagnetic articulography (EMA), electropalatography (EPG), and custom-made tongue and lip force transducers that have been used in populations with traumatic brain injury and stroke.

Traumatic Brain Injury. Several instrumental assessment methods have been used to study dysarthria after TBI, providing researchers with unique and critical insights to the kinematic properties and force production capacities of articulatory sub-systems in this population. The instrumental approach with the greatest representation in the literature concerning traumatic brain injury is by far electromagnetic articulography (EMA).^{15,165,166} In an early study using EMA, Jaeger et al., identified significant differences in syllable durations, peak velocity, and amplitude ratios between control and severe TBI speakers.¹⁶⁵ In more recent studies, significant differences in the speech patterns of individuals with TBI have been more difficult to identify when compared to feature-matched controls.^{15,166} Kuruvilla and colleagues noted that the rate of production of /t/ and /k/ were comparable between control, mild TBI and severe TBI groups. In fact, no significant differences were found between any of the groups for syllable or sentence productions conditions, with the single exception of the release of /t/ in sentences when comparing the severe group to healthy controls.¹⁶⁶ In a different investigation of subjects with TBI, no statistically significant difference in tongue-

jaw coordination during dynamic speech tasks was noted.¹⁵ It is of interest that perceptual differences were clearly observed; however between-group kinematic differences were not found. It is possible that the apparent disconnect between physiological factors and acoustic output may be indicative of differences in the selected experimental tasks or conditions. This disconnect suggests the need for better-defined task conditions and/or the use of methods with sufficient resolution to detect fine-grain changes in speech physiology that affect the acoustic stream.

Kinematic study of speech dysarthria in people with TBI have also benefitted from the use of electropalatographic (EPG) assessments.¹⁶⁷ EPG has been used to identify changes in articulatory temporal patterns of tongue-to-palate contact. In TBI groups specifically, prolonged durations in various phases of consonant production (increased tongue-to-palate articulation) were noted during the production of probe syllables. These observations mirror data by Bartle and colleagues¹⁵ who compared spatio-temporal aspects of jaw and tongue motion. In general, EPG studies have been successful in identifying three tongue-to-palate contact patterns in the speech of TBI subjects related to speech imprecision noted during perceptual assessment. The three identified patterns were: articulatory undershoot, articulatory overshoot, and placement of the tongue further posteriorly than normally expected.¹⁶⁸

Custom-made pressure transducers have been used to assess tongue strength, endurance, fine pressure control, and rate in TBI subjects.¹⁶⁹ In a study by Goozee et al., comparisons between groups of TBI subjects and healthy controls were conducted using repetitive movements within a non-speech

context. No statistically significant differences were found between groups in tongue strength and fine pressure control. Further statistical analysis revealed only weak correlations between non-speech tongue parameters and the altered perceptual characteristics observed in the traumatic brain injured group. These results seem to give more weight to the Gracco and Abbs hypothesis introduced earlier in that speech is a goal-directed behavior in which the entire intended speech goal is important. Simply put, speech production is more than the sum of its parts. Speech disturbances may benefit from analyzing not only the individual articulators, but how they interact at the behavioral level.

In a study by Barlow and Burton,³⁶ a custom-made load-sensitive cantilever was used to sample compression forces from the lips at midline in a small cohort of TBI patients. Varying results were identified during the performance of a ramp and hold force control task for the TBI cohort. Three of the 4 individuals demonstrated a significant force overshoot during the ramp-and-hold production. The authors suggested that the inability of TBI subjects to adequately gauge compression forces might reflect impairment in motor unit recruitment and regulation. It was further hypothesized that sensory feedback for appropriately grading the effort level of the oromotor system may also be related to the observed force control deficits.

While speech dysarthria in TBI populations is the most studied physiologically and objectively, the general consensus of these reports is somewhat scattered and still not well defined. There is only cursory evidence that non-speech assessments can be related to perceptual intelligibility features.¹⁶⁹ In

fact, few studies have been able to identify consistent and significant differences in task performance between dysarthric TBI populations and their normal controls, and even fewer have been able to correlate performance findings to perceptual characteristics directly. Again these data, on the whole, suggest the need for better-defined task conditions and the development of methods with enough resolution to detect small changes in speech physiology. Clearly, instrumental/physiological approaches must possess the necessary degree of resolution to be of increased value and as such, useful to the practicing clinician.

Cerebral Vascular Accident (CVA). Apraxia of Speech (AOS), while not generally considered a classic form of dysarthria, is nonetheless a specific subtype of neurogenic speech disorders that typically results after a stroke. AOS is associated with a deficit in speech motor planning, versus a clinically apparent deficit in speech execution. Because of the inability to correctly plan speech movements, kinematic studies in AOS may be well suited to objectively assess production differences in these individuals.

In a series of single-subject studies, Barry¹⁷⁰⁻¹⁷² found similar EPG patterns of tongue-palate production as those previously reported for TBI populations (see discussion above). Articulatory overshoot, altered tongue-to-palate contact, reduced duration of the closure phase for fricatives, and increased duration time on approach for plosives and stops were all features shared by the AOS speaker and TBI subjects. Although classical categorizations of speech dysarthria type have attempted to separate dysarthrias based on injury type and location, these studies have identified similar disordered speech

characteristics for apraxia of speech and traumatic brain injury. Future classification systems may chose to incorporate elements of timing and articulatory placement to distinguish dysarthria types.

In a different study comparing the oral function of 16 participants with stroke to matched controls, measures of lip strength, endurance, and rate of movement were found to be reduced in AOS clients.¹⁷³ Although physiologic differences were identified in this report, the researchers were unable to observe a direct relationship between the collected kinematic data to their perceptual observations. Finally, several studies have been completed using EPG to compare healthy controls to individuals with dysarthria and aphasia.^{170,174-177} In these reports, various timing and duration differences were noted between the two groups, particularly in the coordination of tongue-to-palate movements, described as misdirected articulatory gestures.^{175,178} In these studies, researchers found that although individuals with apraxia of speech had spatially normal gestures in EPG patterns, their movements were not at the correct place in the target utterance. This is of great importance as participants perceptually produced the target utterance, but demonstrated abnormal production patterns.^{175,178}

In a review by van Lieshout,¹⁷⁹ studies using EMA were identified that described motor disruptions to individual articulators in speech dysarthria. General movement patterns for an individual with AOS and Boca's aphasia were found to be similar to healthy controls with specific task-related differences in upper lip movement and overall lip coordination.¹⁷⁹ Bartle-Meyer et al.¹⁸⁰

examined tongue kinematics in relation to words of increasing length for individuals with AOS as compared to feature-matched controls. Increased movement durations and larger tongue movements for some specific consonant tasks were observed. Inconsistent results were found in a second study by Bartle-Meyer et al.¹⁸¹ when comparing articulatory coupling in tongue-tip and tongue-back multisyllabic stimuli.

Although group data did not show strong trends, overall, individuals with AOS demonstrated a decreased ability for independent functional movements, particularly in relation to the tongue and jaw. AOS secondary to cerebral vascular accidents is an area that clearly calls for more investigation using objective instrumental approaches. Existing studies, although limited by small sample sizes and inconsistent results, have at least begun to illuminate the unique behavioral characteristics of AOS. Even though AOS has traditionally been characterized as a purely motor planning disorder, unique kinematic production features are seemingly identifiable and thus available for future studies.

While physiologic assessments are providing a means of objective assessments of dysarthria in the laboratory, currently, clinicians rely on perceptual assessment of dysarthria. It is important to note that as early as the 1970s, researchers have suggested that disorders of speech may be associated with oral tactile perception deficits,¹⁸² yet standardized sensory assessments are not utilized or unavailable to clinically assess and diagnosis speech dysarthria at this time.

Treatment of Non-Progressive Speech Dysarthria

With such a complex and multifaceted disorder, clinicians should expect an evidence base for treatment approaches to be as multifaceted as the disorder itself. Unfortunately for Speech-Language Pathology, the opposite has been found to be true. In a previously published systematic review by Sellars et al.,¹⁸³ the authors confined their search to include randomized controlled trials. When no randomized controlled trials were found, the authors concluded that “there is no evidence of quality” to support the effectiveness of one type of speech-language therapy over another type for a population of adults with non-progressive brain injuries that resulted in speech dysarthria.^{145(pg.2)} Sellars et al. called for more research on the topic and repeated their review of RCT’s on this topic again in 2002 and 2005 with the same results.^{184,185}

Although no randomized controlled clinical trials have been identified, there have been several clinical intervention case studies and single-subject designed studies that can aid clinicians in identifying appropriate clinical treatment techniques for their clients. In a review by Palmer and Ederby,¹⁸⁶ the authors organized several single-subject, cohort designs, and suggested treatment programs by the intervention approach for any stable dysarthria. Palmer and Ederby searched literature from the 1970s to 2006 pertaining to all types of speech dysarthria; they were able to identify 23 studies that fit their inclusion criteria, and only 8 that were published after 1996. The authors regard this lack of publication as evidence that treatment of speech dysarthria is an under-studied area of research.¹⁸⁶

Several authors have stated that the principle goal of behavioral treatment for motor speech disorders is to attempt to maximize the effectiveness, efficiency, and naturalness of communication to achieve improvement in overall speech intelligibility.^{7,187,188} While this definition is an agreed upon ideal for therapy, what intervention clinicians choose to be most effective, or efficient, or geared toward increasing intelligibility is still under debate, partly because the field of motor speech disorders lacks clarity on an agreed upon definition of what “intelligibility” is and what factors can affect intelligibility. Duffy offers one definition as, “the degree to which a listener understands the acoustic signal produce by the speaker.”^{7(p.96)} Unfortunately, this definition does not clarify what goes into the acoustic signal, and most importantly isn’t focused on the listener understanding the intended message of the speaker. Several factors could alter speech intelligibility including context and gestures, as well as rate, prosody, articulation, and respiration.^{7,8,189}

Many treatment approaches to dysarthria are a direct reflection of more motor-based ideals, and possibly reflect the name of the field itself, “*motor* speech disorders”. This next section contains a brief introduction to various types of treatments employed in this population with more discussion on the validity of the treatments given later in the review. Oral motor exercises for “strength”; pacing boards, metronomes, and alphabet boards for rate control; singing exercises for fluency; and articulation therapy for a direct symptomatic approach have all been used to treat dysarthria.

Singing Exercises. Melodic intonation and singing therapy have gained some popularity for the treatment of non-progressive speech dysarthria; however, little empirical evidence exists to support its use. Current studies are case studies, present preliminary data, or have been done in a Parkinsonian dysarthria group.¹⁹⁰⁻¹⁹² In a pilot study by Tamplin,¹⁹² individuals demonstrated a perceptual improvement post-treatment of speech naturalness using various intonation and singing exercises. Although with a small sample size (n=4) and non-significant objective tests, more research would need to be done on the use of singing to improve intelligibility or speech naturalness before warranting clinical use.

Prosody. There are several distinct prosodic characteristics that influence and shape the acoustic signal sent to the listener. Prosodic characteristics of speech can include pitch, loudness, silence, and segment durations.⁸ One therapy that has been successful in treating prosodic features of speech, specifically loudness, for individuals with dysarthria as the result of Parkinson's Disease (PD) is the Lee Silverman Voice Treatment® program.¹⁹³⁻¹⁹⁶ In a study completed by Wenke et al., researchers used the LSVT® program for individuals with non-progressive speech dysarthria and were able to demonstrate increased intelligibility through changes in many perceptual characteristics, such as loudness, articulatory precision, sustained phonation, and fundamental frequency ranges after treatment.

Rate Control Methods. Speech rate has been considered one of the more easily modifiable aspects of speech and altering speech rate has been shown to

increase speech intelligibility.¹⁹⁷ Therefore, it is not surprising that attempting to slow the speech rate of individuals with dysarthria has been a popular clinical approach in various types of dysarthria using rate drills, alphabet boards, and rate training using a metronome.¹⁹⁸⁻²⁰³ Although many of these studies illustrated positive effects of increasing intelligibility through rate control methods, they may not be appropriate for this population, given that some of the studies were completed with individuals with Parkinson's disease.²⁰²⁻²⁰⁴ It is plausible to hypothesize that slowing speaking rates could improve articulation in the non-progressive speech dysarthria population as well because it provides more time for tactile feedback to be utilized and incorporated into the speech gesture, however this notion has not been empirically determined.

Phonation Therapy. Individuals with speech dysarthria can exhibit difficulties with phonatory characteristics such as problems with breathiness, short phrases, monoloudness and monopitch.^{7,8} For several of these deficits, surgical interventions and prosthetic devices are available, demonstrating the connection between phonatory characteristics such as pitch alterations and improved speech intelligibility.²⁰⁵⁻²⁰⁹ For behavioral treatment approaches, Lee and McCann²¹⁰ attempted to increase speech intelligibility of bilingual Mandarin-English speakers by focusing treatment on respiration and improving participant phonation. Although improvement was seen in English, results from this study demonstrated that phonation therapy significantly improved intelligibility in Mandarin, a language reliant on pitch/tone changes, more than English.

Non-Speech Oral Motor Exercises. Non-speech oral motor exercises (NSOMEs) are a popular and commonly used exercise program for children and adults with motor speech disorders.^{186,201,211} With little empirical evidence to support their use, it was startlingly to find that 85% of respondents to a national poll reported using NSOMEs to treat dysarthria.²¹¹ Proponents of NSOMEs claim the non-speech exercises are used to improve the strength, endurance, tension or force of the orofacial muscles.¹⁸⁶ In fact, in a review paper by Weismer, he comments that the “frequent appeal to oromotor, nonverbal tasks is misguided.”^{212(p.315)} NSOMEs employ the use of exercises to target a deficiency in one area of speech production based off of assessment following the Mayo Clinic view created by DAB (discussed below). Unfortunately, this technique of dividing the parts of the speech system ignores the basic tenet that speech is an integrative task using motor control, tactile and auditory feedback, and cognitive processing. Speech is greater than the sum of its part and non-skilled oral motor exercises disregard this fact. After a review of literature concerning non-speech oral motor exercises, Weismer concludes “there is neither theoretical nor empirical support for a continued focus on oromotor, nonverbal tasks in our field.”^{212(p.342)}

There is an important distinction to acknowledge between non-speech exercises and unskilled oromotor exercises. In recent work using BOLD fMRI and nonsense vocal tract gestures as compared to speech sounds, researchers found common neural substrates in overlapping activation of speech and skilled, yet non-speech movements.²¹³ This study suggests that the use of nonsense words can activate speech structures because they still require skilled,

coordinated orofacial movements. It may be hypothesized that a series of skilled oromotor exercises (SKOMEs) may have more empirical support for the treatment of non-progressive speech dysarthria, but that is a topic that is still very much up for debate in the field.

Articulation Therapy. Using more of a direct, symptomatic approach, some articulation therapy is often incorporated into treatment plans for dysarthria. During therapy, patients are given specific articulatory targets and feedback regarding their accuracy.^{186,201,214} In a more recent study, Robertson completed a combination of orofacial exercises, diadochokinetic rates (DDKs), sound sequences and articulation exercises with simple C-V-C and complex sound combinations and found that participants demonstrated increased intelligibility after a 10 week intervention program.²⁰¹ It is possible that articulation therapy approaches, with their interplay of skilled speech movements, auditory feedback, and clarity of response judgments from the clinicians, could provide the necessary combination of skilled motor and sensory exercises for improved speech.

The American Speech-Language and Hearing Association (ASHA) has made a call for the use of Evidence-Based Practice (EBP) therapy measures²¹⁵ encouraging clinicians to use the best research available, his/her clinical expertise, and the client's values. If the goal of speech therapy is to improve overall speech intelligibility, there are several available options for clinicians to choose from when determining how to treat speech dysarthria in adults with non-progressive secondary to neurologic events. Determining if these interventions

are best practice is another matter. The wide variety of treatment types available may be an artifact of the individual-nature of dysarthric speech. As each individual's dysarthria is somewhat unique based on location of injury, severity of dysarthria, pre-morbid speech abilities and characteristics of the individual's speech, it is possible to hypothesize that no one treatment technique may work for everyone. However, because so few well-controlled clinical studies have been done, it is difficult for the field to reach consensus on what constitutes the best approach. Clinicians are left to rely on their sense of clinical judgment and interpret the needs of their client on a case-by-case basis. Although, this should arguably be done with every client, the literature available on the topic does not aid the clinician in determining a best-practice approach. Clinically, it is most likely appropriate to combine multiple treatment approaches based on the client's needs and goals for therapy, although the literature available for review does not address this assumption.

Empirical Needs in Understanding Speech Production and Perception in Clinical Populations

The Patient-Clinician-Laboratory (PCL) model,²¹⁶ found in the athletic training literature, encourages the bench-to-bedside model of using patient goals, clinical research, and laboratory science to produce higher-quality and more translational research to meet the functional needs of the patient. Unfortunately, particularly in the assessment and treatment of speech dysarthria, there appears to be gap between the theoretical models, the laboratory/bench research and

application in the clinical setting. Given the previous review, there appears to be four major deficiencies in our current appreciation of motor speech disorders that could better help our understanding of speech dysarthria. These deficiencies include: 1) the lack highly-skilled assessment and treatment tasks that sufficiently challenge the speech system; 2) the appreciation of the sensory mechanisms involved in speech disorders and how this information can be used for better assessments and treatments of dysarthria using finely-tuned, skilled tasks; 3) the need for more translational research that can best connect the laboratory researcher to the clinician; and finally 4) an understanding of how aging can alter the previous three areas of concern.

Skilled Assessment and Treatment Measures

“Although it is not reflected in the classical literature, there appears to be a substantial physiological and neurophysiological basis for expecting differential impairment of speech motor subsystems across classes of dysarthric speakers.”^{37(p.616)} This quote from Barlow and Abbs, made in 1983, illustrates the importance of needing skilled clinical assessments that can help SLPs (and other health professionals) classify speech dysarthrias with a greater degree of accuracy and consistency. In laboratory and clinical assessments and with interventions for individuals with non-progressive speech dysarthria, the use of isolated movements or repetition of a single phoneme is a popular means to assess and treat dysarthria. However, gross non-speech and/or isolated syllable tasks, (not controlled for speech-like forces) may not provide a sufficient diagnostic challenge to reveal disrupted function of primary articulators within

various classes of motor speech disorders or provide adequate therapeutic interventions to rehabilitate the vocal tract system. Upon closer inspection of many of the above reviewed studies, statistically significant results were typically not found until the sensorimotor system was adequately challenged through the performance of more dynamic tasks.^{15,36,166,167} Based upon these considerations, it is suggested that not only should greater importance be placed upon objective instrumental approaches for evaluation and therapeutic practices, but more importantly, that increasingly complex tasks should be incorporated to sufficiently challenge the disordered speech system. Challenging the speech production system may operate to reveal the performance boundaries and limitations faced by the system that directly impact the real-time dynamics of speech production.

As described by Dworkin,^{217(p.187)} “A good percentage of clinical time is spent treating the articulation subsystem in patients with motor speech disorders. Speech clinicians realize, however, that disturbances of the articulation subsystem rarely occur in isolation. Coexisting respiratory, resonance, phonatory and/or prosodic subsystem breakdowns are not uncommon.” Here, Dworkin is pointing out that disruptions can occur within any part of the vocal tract system, and often occurs at the point of interaction of the entire system. This is why placing the isolated sounds and syllables into the context of running speech is vital to testing and re-training the vocal tract system...simply put, context matters.^{54,218} Clients seeking treatment for motor speech disorders would most likely benefit from the use of relevant speech tasks in context, highlighting again

that speech production is the culmination of multiple subsystems working together.

Assessment and Treatment Using Sensory Channels

Given the ubiquitous nature of the DAB/Mayo Clinic model and the heavy emphasis on motor aspects in the assessment and treatment of dysarthria, there is one glaringly large gap in our understanding of dysarthria: sensation. Sensory inputs (somatosensory and auditory afference) are important for not only accurate speech perception, but speech production as well, and maybe take on even greater relevance after neurologic injury. In an edited work by Maassen,²⁶ Kent and Rosen suggest that, “A long term goal of research on motor speech disorders has been to document rather than simply infer, the sensorimotor impairments. This remains an important and largely unrealized, goal.”^(p.286) Primarily, the field of Motor Speech Disorders (as the name implies) follows a predominantly “motor” point of view.

SLPs have traditionally been trained to focus on the motor aspects of speech disorders with little concrete consideration of sensory factors that may be contributing to the features of a given disorder. This oversight suggests that, on the whole, we are inadvertently missing half of the equation in our assessment and treatment of speech dysarthrias. For example, in the studies reviewed earlier, imprecise tongue movement is consistently identified as a factor in the perceptual characteristics of dysarthria. For correct tongue placement and manipulation, tactile and proprioception are critical feedback signals to correct and maintain performance accuracy.¹¹ The ability to perceive the precise

placement of the tongue and to adjust position to match an acoustic target requires a peripheral sensorium with a high response fidelity to movement-related feedback. ***Considering that therapeutic intervention primarily consists of manipulating a patient's sensory environment to drive changes in motor output,⁷⁷ understanding the sensorimotor physiologic characteristics of speech dysarthria may provide the clinician with useful insights for tailoring and maximizing therapeutic goals.***

Kent and Rosen's position has two important implications for clinical practice. First, clinicians have the responsibility to document impairments as objectively as possible using direct physiologic assessment in context, as discussed above. Second, greater appreciation and better understanding of the relationship between sensory (both tactile and auditory) and motor function in speech production disorders may potentially lead to improvements in our clinical understanding of speech dysarthrias, and inform the development of more focused and efficient clinical interventions.

Many of the features of speech production disorders that clinicians note perceptually are, in fact, sensorimotor deficits that may have unique kinematic and/or force correlates that may distinguish one deficit sub-type from another. For example, the most frequently measured sensorimotor features in an individual with speech dysarthria are rate, paralysis, paresis, and coordination.⁵⁷ Although these features are key characteristics of various speech dysarthrias, SLPs are generally trained to rely on subjective clinical judgment to determine the degree to which these factors are impaired or different from normal speakers

or other etiologies. The incorporation of objective instrumental measurements from evaluation through treatment would benefit practicing clinicians, allowing them to better determine the relationship between behavioral performance changes and perceptual features. Such an understanding can only operate to improve the clinical experience for the patient.

Need for (more) Translational Research

As mentioned above, there is a dramatic inconsistency between research in the laboratory setting and its translation to clinic practice. First, there is a need for translational work in diagnostics. Traditionally, differential diagnosis and the development of treatment plans have been based on perceptual (subjective) characteristics alone without employing objective instrumental assessment strategies to characterize the physiological properties of participating articulatory subsystems. Yet, considering that neurological damage will result in various degrees of aberrant speech physiology that, in turn, may lead to significant abnormalities in perceptual speech characteristics,³⁴ the need for physiologic assessment appears highly warranted. Various physiologic assessments are done in the laboratory setting, but have not yet been translated in to clinical settings; most likely due to time needed to train clinicians and perform the assessment, cost of equipment, and the fact that current clinic models of assessment do not advocate its need.

Second, translational work from laboratories must be incorporated into treatment programs and assessment development. The World Health Organization's International Classification of Functioning, Disability, and Health

(ICF) can be a useful framework for planning speech interventions in dysarthria,³³ particularly if clinicians are aware of personal and environmental factors that may alter the normal baseline of speech intelligibility, as well as what the patient's functional goals are for participation level in their activities of daily living (ADL's) or social environment. A better understanding of principles of neuroplasticity and motor control theories and how they can and cannot be applied to speech production, may result in better therapy outcomes. Unfortunately, the extent of high quality evidence for the treatment of non-progressive speech dysarthria is nominal at best.¹⁸⁶

Effects of Aging on the Coupling of Perception-Action in Speech

The fourth identified gap in the current appreciation of the motor speech disorders pertains to alterations in the sensory and motor production aspects of aging adults. As incidence and prevalence rates for stroke and traumatic brain injury continue to increase for individuals over 65 years of age,² it will be important for clinicians to accurately identify differences in normal aging processes versus deficits from neurologic injury or disease. Additionally, assessment protocols and treatment paradigms may need to be altered to accurately diagnose and treat disorders in this special population.

Current general motor control theories, including those for speech motor control, posit that the planning and production of skilled behaviors are highly dependent on the quality and integrity of both sensory and motor elements.^{19,42,141,142,219} As such, the lack of a fine-grain appreciation of aging-related changes in orofacial perceptual sensitivity may not be trivial. Altered

levels of somatosensory transduction and transmission along medial lemniscal - thalamocortical pathways may likely impact the activity-dependent maintenance and integrity of skilled orofacial movements, given the tight perception-action coupling that exists during functional orofacial behaviors.⁹⁷ The distinctive musculo-cutaneous substrate of the lower face underling the generation of complex three-dimensional deformations during orofacial behaviors⁸⁶ is hypothesized to be responsible for the production of salient movement-related afference necessary to maintain skill in the orofacial area.^{76,77,79,137,138,220-222}

Unfortunately, little is currently known about the effect of decreased vibrotactile detection for behaviorally-related processes underlying the performance of normal orofacial activities in the aging population. Some indications may be obtained from studies that have demonstrated that alterations in vibrotactile sensitivity in human foot sole may be a contributing factor to changes in gait patterns.¹⁵⁴ Alterations observed in this study may have a similar effect as it pertains to behaviors such as speech production; although at the auditory-perceptual level, participants may continue to maintain functional speech abilities. As sensory experiences in the orofacial region are primarily the result of self-generated action, ongoing learning and updating of central orofacial sensorimotor representations are influenced by those self-generated sensory experiences.¹⁰⁵ Significant alterations in ones capacity to detect low-level threshold activity may have the greatest implications on informing orofacial behavior after neurologic injury as therapists are working to restore functional

behaviors within the context of a system that may have significant pre-morbid deficits in the ability to detect sensory events consequent to the therapeutic task.

Mechanical and proprioceptive sensory feedback during speech may become even more important for maintaining skilled speech due to the decrease in auditory feedback in aging adults secondary to hearing loss. A recent study reported hearing losses in approximately 33% of individuals between 61-70 years and more than 80% of individuals 85 years and older.²²³ In fact, Anderson and colleagues discussed the decrease in neural processing rates and neural inhibition leading to decreased auditory processing for acoustic information which may present older adults with temporal synchrony discrepancies for rapid speech perception.²²⁴ This delay in speech perception may have greater implications for training and therapy after a neurologic event.

Rationale and Research Questions

The application of the DIVA model in various studies highlights not only the importance, but also the absolute necessity of quality sensory feedback for speech-related actions. The lower face contains specialized mechanoreceptors at spatial positions ideal for transducing stretch and strain of the facial skin. These mechanoreceptors provide afferent feedback centrally, allowing the lower face to behave as a highly coordinated system, while still maintaining adaptability to incoming stimuli to complete skilled, functional oromotor behaviors, such as speech or swallowing.⁷⁶⁻⁷⁹ In fact, consistent with hypotheses yielded from the DIVA model and portions of the Motor Theory of Speech Perception, researchers have hypothesized that much of the sensorimotor feedback from the lower face is

likely achieved through self-generated movement-related afference allowing an individual to continuously update and maintain their own skill level.¹⁰⁵ The distinctive muscle-to-skin relationship in the lower face allows for the generation of complex 3-dimensional deformations of the facial skin, providing an anatomical substrate for the tight temporal synchrony of cutaneous somatosensation and performance features of skilled speech behaviors.^{35,79,103,130,225} The sensory events that are correlated with active orofacial skin deformations of stretch and strain provide a rich array of afferent discharges presumed vital for speech production and other orofacial behaviors.^{76,77,137,138,222}

Overall, it is possible that patients, especially older adults, would benefit from speech rehabilitation therapy strategies tailored to their needs and that take advantage of somatosensory and auditory feedback, making these routes into the CNS more salient during interventions. Before treatments can be identified and implemented though, further assessment of changes in somatosensory and skilled low-level force targets in healthy aging adults is needed. The current dissertation was designed to begin characterizing changes in labial vibrotactile detection thresholds, accuracy in achieving low-level force endpoints, the relationship between these sensory and motor assessments, and finally how the labial sensorimotor relationship may change as a function of aging. In the next chapter, I will discuss the specific questions and methodologies used in this study.

Given the literature review above, this dissertation will address the following central questions: ***Is there a correlational relationship between***

labial vibrotactile detection thresholds and non-speech skilled low-level force control measures in healthy adults? Are the features of this relationship sensitive to changes as a function of healthy aging?

Sub-questions will include:

- Do 5 and 10 Hz vibrotactile detection thresholds change with aging?
- Does accuracy in a skilled, non-speech dynamic force task change with aging?
 - For the static force condition, how does reaction time, slope, and mean force hold for time phase 1 and 2 change in aging?
 - For the slow and fast ramp-and-hold force conditions, how does reaction time, slope, and mean force hold for time phase 1 and 2 change in aging?
- What role do variables such as speech usage, smoking history, and pure tone hearing thresholds play in this sensorimotor relationship?

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Chapter Three

Methods

The primary aim of this observational dissertation was to identify and describe the relation between labial cutaneous sensitivity to vibrotactile inputs and precision force control tasks in three different age bracketed cohorts of adults, with particular attention to how the labial system's perception-action relationship changes as a function of increasing age.

Participants

An a priori Mann Whitney test with 80% power and a 2-sided alpha of 0.1 was used to determine that 20 participants were needed in each of three experimental groups for adequate power to detect a significant difference between groups. Alpha was set at 0.1 given the preliminary observational nature of this study. As such, a total of 60 community-dwelling adults (40 females; 20 males) who self-reported as healthy were recruited from the greater Lexington, KY area. All participants were naïve to the testing protocol. Participants were divided into three age groups: Young (18-39 years; mean 26.2 years), Middle (40-64 years; mean 52.3 years), and Older (65 + years, mean 72.8 years). Participants were screened to ensure they were alert, able to give consent, and met all study inclusion criteria listed below. This study was approved by the University of Kentucky Office of Research Integrity and Institutional Review Board (Protocol #: 13-0263-P2H). All screening information was gathered through self-report and completed prior to any assessment procedures. All participants:

- Reported that they were free of any craniofacial anomalies, injuries, or active lesions to the lower face, neurological injuries (such as stroke or traumatic brain injuries), or other progressive neurologic disorders such as dementia or Parkinson's disease
- Indicated feeling in "good" general health or better on the day of testing
- Denied being on, to the best of their knowledge, any medications that could cause excessive drowsiness
- Denied having had a recent dental visit in the last month that involved oral surgery or any form of a local anesthetic

A total of sixty-two individuals were screened. Two were excluded from the study; one participant had multiple orofacial surgeries in the last three years and the second had a history of cerebral hemorrhage.

Subjects were audio-recorded reading The Grandfather Passage, a common procedure in clinical testing procedures, to ensure perceptually normal speech intelligibility.⁷ All participants were judged to be 100% intelligible at the paragraph level as confirmed by two outside speech-language pathologists. Pure tone hearing threshold assessments were completed at 500, 1000, 2000, 4000 and 8000 Hz. Participants were asked to identify their current level of speech use on a 5-point scale with larger numbers indicating increased average speech use. (See Appendix A for a breakdown of each speech use category). Participant group data for age, sex, smoking history and puretone hearing threshold average are reported in Table 1.

Table 1: Participant Demographics

Demographic data for each group including: age range, average, and standard deviation, male to female ratio, smoking history frequency counts for current smokers “yes”, people who have never smoked “no” and people who have smoked and quit “former”, and pure tone threshold averages for the right and left ear in Hz.

	Age (SD yrs)	Male: Female	Smoking History (Response: N)	Pure Tone Avg (dB)
Young	19-35 Avg 26.2 (4.85)	6m:14f	Yes: 1 No: 18 Former: 1	Right: 10.38 Left: 9.44
Middle	42-64 Avg 52.3 (6.54)	5m:15f	Yes: 1 No: 12 Former: 7	Right: 14.56 Left: 14.19
Older	65-84 Avg 72.8 (5.73)	9m:11f	Yes: 3 No: 9 Former: 8	Right: 28.69 Left: 27.56

Central Hypothesis

Is there a correlational relationship between labial vibrotactile detection thresholds and select parameters of skilled orofacial force control in healthy adults? If so, what is this relationship and how does it change as a function of aging? The null hypothesis for this experiment is that there are no correlational relationships between labial vibrotactile sensation capacity and parameters of skilled, low-level force control. The alternative hypothesis states that there will be a correlation between vibrotactile sensation capacity and parameters of skilled force control and that this relationship changes as function of healthy aging. We hypothesize a negative correlational relationship in that as vibrotactile detection thresholds increase (demonstrating less sensitivity) parameters of skilled force control will decrease and/or demonstrate increased variability. The following force control measures were included in this study: reaction time, rise time, peak force, and mean force during two hold phases. See Table 2 for definitions of

each force variable and Figure 3 for a stylized schematic of a participant's response.

Table 2: Force Variables and Operational Definitions

Variable	Operational Definition
Reaction Time	Time interval from the moment the light-emitting diode (LED) was turned on until labial force had reached 10% of peak force.
Rise Time	10% to 90% percent intercepts during force recruitment task phase
Peak Force	Maximum amplitude of force during the force ramp phase
Mean Hold Force	Mean force output during each of two consecutive 1.5 second epochs (Time 1 and Time 2)

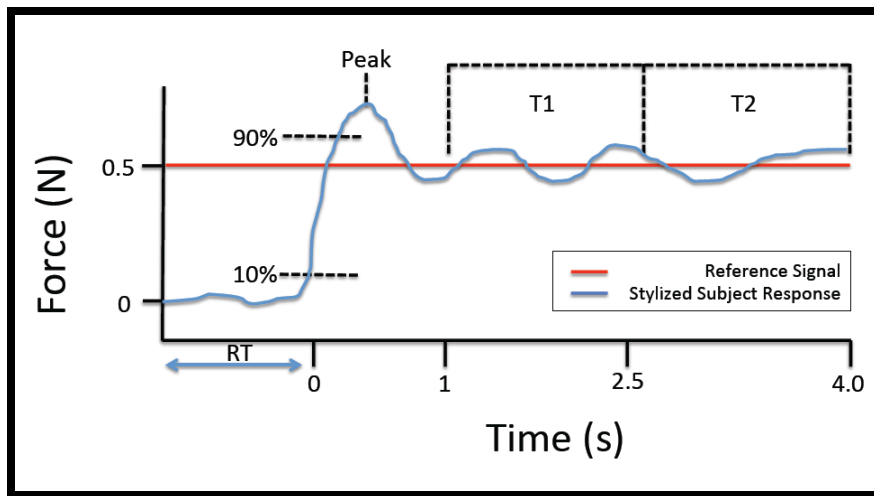


Figure 3: Stylized Schematic of Force Control Measures

Stylized schematic of a participant's response during the static force condition programmed to 0.50 N to illustrate the variables collected. (Adapted from Barlow & Burton, 1990)³⁶

Labial Vibrotactile Detection Threshold Procedures and Analysis

Cutaneous Stimulation Delivery System. Sinusoidal vibrotactile inputs

were delivered to the vermilion of the left lower lip (LL) at a point halfway

between the mid-sagittal plane and the oral angle via a custom-made mechanical

stimulus generator system mounted onto an articulated microscope arm. The stimulus delivery system consisted of a Bruel & Kjaer (Model 4810) Minishaker, a flat-surfaced nylon stimulus probe (surface area = 0.5 cm²), and a rigid surround (17 millimeter [mm] outside diameter with a probe-surround gap = ~1 mm). A Schaevitz micro-miniature linear variable differential transformer (LVDT) was serially coupled to the outboard end of the Minishaker to provide displacement information (1 micron resolution) of the probe (Figure 4). The output of an arbitrary digital waveform generator (Wavetek Model-29) was conditioned by a power amplifier (Bruel & Kjaer, Model 2706) and provided the input signal to the Minishaker. Synthesized waveforms were 1 second in duration with a 150 millisecond linear rise-fall decay to eliminate the possibility of on/off mechanical transients. Probe displacement signals from the LVDT were digitized at 5 kHz (ADInstruments – 16 bit A/D).



Figure 4: Vibrotactile Mechanical Stimulus Delivery System Setup and Subject Orientation.

Inset image shows close-up view of probe placement on the left lower lip.

Vibrotactile Detection Threshold Testing Procedure. Participants were seated in an adjustable chair with a neck pillow to minimize head movement during sensory assessment (Figure 4). Each participant was fitted with a bite block made from dental impression putty (Kerr Extrude®) to isolate motion of the mandible during testing and control for labial aperture size. Participants were oriented to the test stimuli (described as resembling the sensation of being lightly "tapped" or a "mild buzzing") and instructed to the details of the psychophysical assessment procedure. The rigid surround about the contactor probe was then placed on the LL with a 1000 micron (μm) contactor pre-load indentation. Following setup, vibrotactile stimulation was delivered to the LL at 5 and 10 Hz test frequencies. These test frequencies were selected because they were

shown to be sensitive to change in an aging population through pilot testing.²²⁶

Testing order for the two test frequencies was randomized across all participants.

Participants were told to respond to their perceptual detection of a stimulus event by rapidly depressing a handheld trigger switch. As 5 and 10 Hz test frequencies are outside the range of normal hearing, no auditory masking was needed for these test frequencies during vibrotactile assessment. The signal generated by the response switch (TTL – 5 volt square-wave) was digitized in synchrony with the vibratory test burst. Signal attenuation was accomplished manually with respect to the subject's perceptual response using a programmable logarithmic attenuator (PA4 Programmable Attenuator - Tucker-Davis, Alachua, FL, USA).

Preliminary threshold values were established using the method of limits.²²⁷ For this segment of the sensory assessment procedure, the vibration stimuli were delivered at a supramaximal level. Participants were instructed to “push the trigger button the moment you can no longer feel the vibration.” The researcher decreased the stimuli in 1 dB steps until the participant pushed the trigger button and the dB level was recorded. The participant was then asked to “push the trigger button the moment you just start to feel the vibration again.” The researcher began the stimuli at a low-level intensity and slowly increased the stimuli until the subject pressed their trigger button and again recorded the dB level. This procedure was repeated two additional times for a total of six trials. The resulting dB value from each trial was averaged to provide a starting index value for the next step in the detection protocol. The method of limits was used

primarily to narrow the response field and make identification of the exact threshold level in the next phase easier and quicker to perform.

Immediately following the method of limits, participants were given instructions for the second phase of the psychophysical assessment procedure: a 2-alternative forced choice (2-AFC) method. Two-AFC methods are a more accurate means of determining exact threshold levels as they are considered unbiased and criterion free. Participants heard the researcher say “trial 1,” “trial 2,” and “respond.” It was explained that they would feel a vibration in one of those two trials. Participants were told, “When I say ‘respond’ press the trigger button to indicate in which trial the vibration was located. If you are not sure, take your best guess.” (See Figure 5 for the visual aids provided to the subjects).

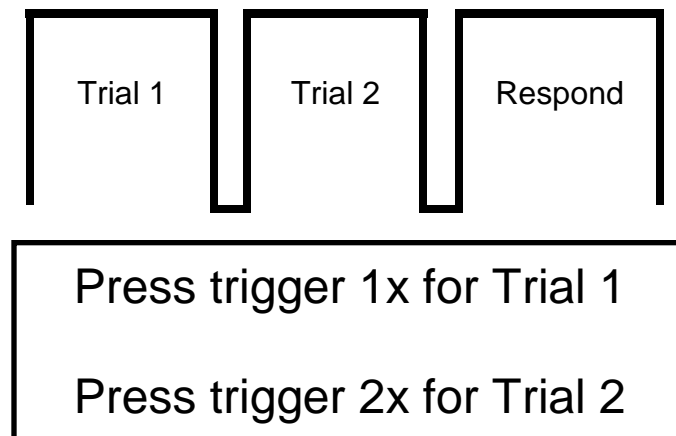


Figure 5: Visual Aids to Remind Participants of VDT 2-AFC Testing Procedures

Visual aids were placed in front of the participants to remind them of the 2-AFC procedures. The top panel shows the researcher’s wording during testing to remind them to wait until hearing the words “respond. The lower panel reminds participants how to respond when they felt the vibration.

Stimulus intensity began at each participant’s averaged dB value established earlier by the method of limits. The participant’s response for each train of stimuli was recorded using LabChart (ver. 7) and by hand. (See Appendix

B for stimuli randomization and recording method). For each three correct responses, the intensity was decreased. Intensity was increased after each incorrect response. All intensity changes were made in 1 dB steps. The threshold value was determined as the average value of five threshold crossings/reversals. No feedback regarding response accuracy was given during the time of testing.

Each participants data was collected and digitally stored in LabChart. Using LabChart's DataPad function, each participant's threshold (average of the five crossing described above) and standard deviation during that period were calculated and imported into Excel. A Kruskal-Wallis one-way analysis of variance was used to determine if there was a difference between groups at either the 5 or 10 Hz test frequency ($p = 0.1$). Post-hoc analyses using Mann Whitney tests, corrected for multiple comparisons using a Bonferoni correction were completed to identify differences between age sub-groups.

Vibrotactile Detection Threshold Assessment and Sub-questions. Sub-questions include:

- Do labial vibrotactile detection thresholds at the 5 Hz and 10 Hz test frequencies increase as a function of age, indicating less sensitivity?
- Do variables such as speech usage, smoking history, and pure tone hearing thresholds change in relation to labial vibrotactile detection thresholds?

The null hypothesis was that no significant difference would exist in vibrotactile detection thresholds between the three groups of healthy adults at either test frequency. The alternative hypothesis was that there are significant increases in

vibrotactile detection thresholds between the three groups at one or both test frequencies. We hypothesized that labial vibrotactile detection thresholds will increase at the 5 and 10 Hz test frequency with advanced aging. Additionally, we hypothesized that those individuals with self-reported increased speech usage, no significant smoking history, and better hearing thresholds would have decreased vibrotactile detection thresholds. This hypothesis is supported by data gathered in a pilot study comparing a cohort of individuals over 65 to a small reference group of younger participants. In this study, we identified significant differences at the 5 and 10 Hz test frequencies using a modified von Bekesy approach.²²⁶ No significant differences were identified between age groups for a 50 or 150 Hz test frequency. To better focus this current protocol, only the previously identified significant test frequencies of 5 and 10 Hz were chosen for inclusion.

Low-level Skilled Force Assessments Procedures and Analysis

Low-level force control assessments were conducted in three ways using: 1) visually-guided dynamic force tracking, 2) targeted static force control, and 3) slow vs. fast ramp-and-hold assessments. Each of the three force conditions are explained in greater detail below.

Visually-Guided Dynamic Force Tracking. Participants were seated in a comfortable chair. A custom-built stainless steel cantilever instrumented with strain gages and conditioned by a bridge amplifier (LP, -3 dB @ 20 Hz) was placed in their mouth so that it rested comfortably at the angles of oral opening. (See Figure 6).



Figure 6: Setup for Dynamic Force Condition

Participant set up during the visually-guided dynamic force task. Participants were seated with the force cantilever positioned between the oral angles. Participants were instructed to trace the sinewave pattern shown on the computer screen using the visual feedback provided by the transducer during a lip rounding gesture. The inset shows a close-up view of the force-transducer orientation to participant's lips.

Participants were told to track the cursor, a 2 Hz sinusoidally moving pattern with a 2 N peak-to-peak amplitude (previously described by Andreatta & colleagues^{97,228}) as “accurately and consistently as possible.” Participants were given speech-like phonemes (saying “oo-ee, oo-ee, oo-ee” like the word “movie or gooey”) to help organize their labial movements and increase the intentionality of the task. All participants were provided with a 5-minute practice period to gain familiarity with the dynamic tracking task. Immediately following the practice period, participants were given two minutes to rest and then were asked to begin

tracking the visual cursor. Three 10-second trials were recorded of the participant continuously performing the dynamic tracking task for offline analysis.

The dynamic tracking signal and the analog strain gage response were recorded in LabChart. Using LabChart's Data Pad function, each of the three 10-second trials were analyzed using a root mean square algorithm. Since recording was performed during continuous participant motion, there were no start and stop periods in the digitized record, therefore the entire 10 second period was analyzed. The root mean square for each trial was calculated in Excel to show the participant's average accuracy in tracking the sinusoidal pattern their overall standard deviation, and their absolute difference from the tracking signal. Non-parametric Kruskal Wallis tests were completed to compare dynamic force values with group data of age, smoking history, pure tone hearing average, and speech use.

Static and Ramp-and-Hold Tasks. To complete the second low-level force control tasks, participants were moved to a different computer workstation. Participants were fitted with a load-sensitive cantilever to sample midline compression forces of the lower lip. The analog force signal was conditioned by a bridge amplifier and low-pass filtered (LP, -3 dB @ 50 Hz). The signal was then digitized online using the FORCEWIN RT system (Neuro Logic, Lawrence, KS). An 8-bit digital-to-analog converter on the microprocessor was programmed to generate calibrated feedback signals that were displayed both on an oscilloscope and a computer monitor (see Figure 7).

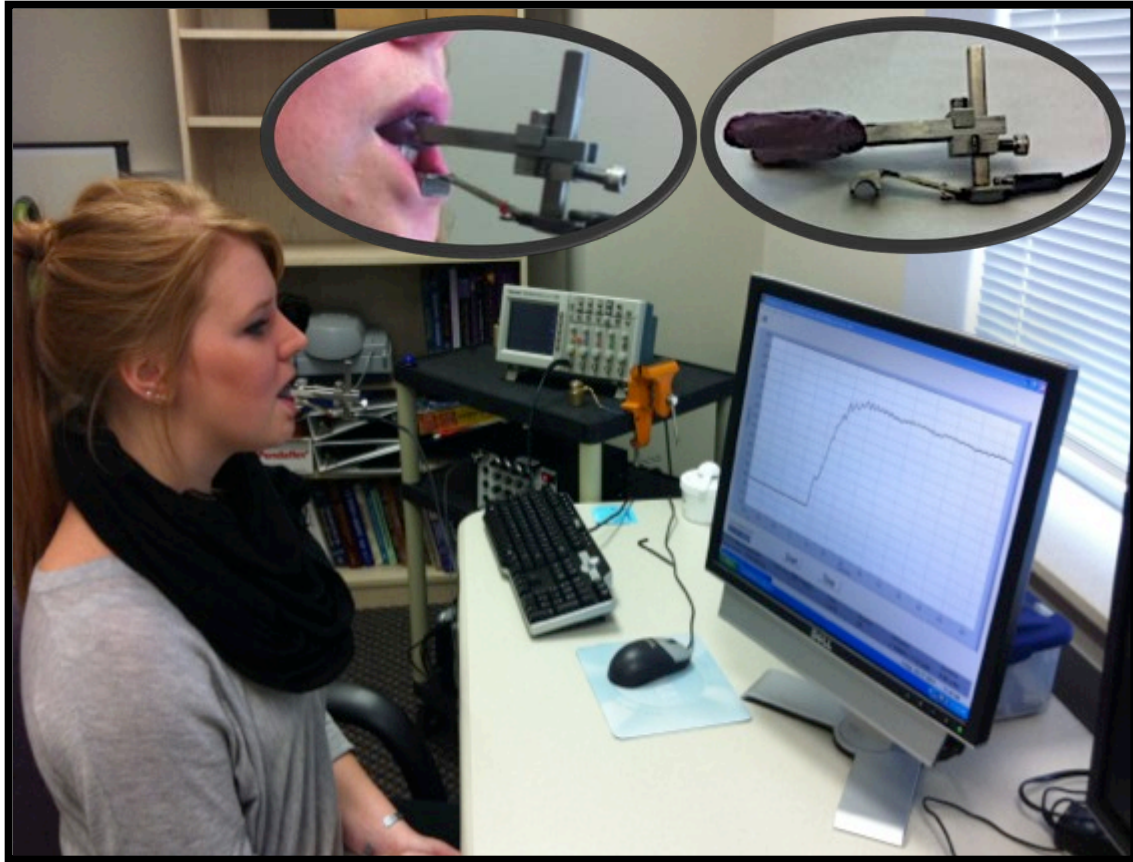


Figure 7: Setup for Static & Ramp-and-Hold Conditions

Participant setup for static and ramp-and-hold conditions during force assessments. Inset shows a close-up of the force cantilever placement in and outside of participant's mouth.

Target force endpoints of 0.25, 0.50, 1.00, and 2.00 Newtons for the static and two ramp-and-hold conditions were randomized and arranged into three complete, yet separate protocols. One of the three protocols was randomly assigned to each participant. Each of the three protocols began with a calibration and baseline measure. All protocols began with three trials of each of the four force endpoints in the static condition. Under the static condition, participants were asked to match the red target line they saw on the monitor as “rapidly and

accurately as possible”. (See Figure 8 for a screenshot sample of the static force condition).

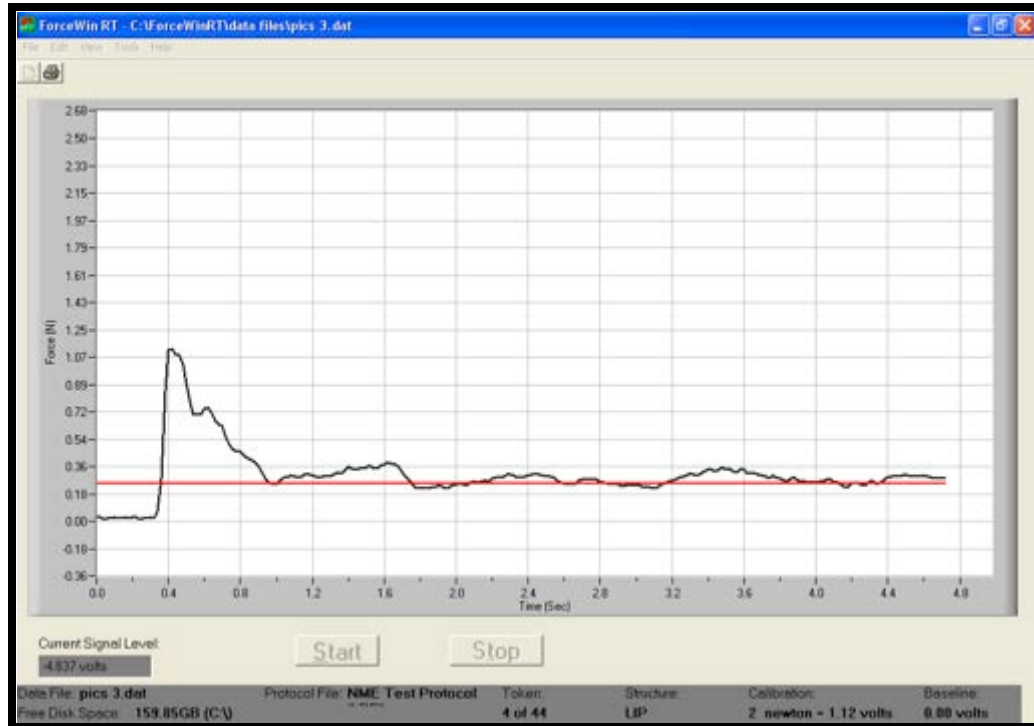


Figure 8: Screenshot of Participant Response during the Static Force Condition
Sample of participant response during static force condition. The red line is the computer-generated target force endpoint. The black line is a participant’s response when told to “match the red line as rapidly and as accurately as possible”.

After the static force condition was completed, participants were given another baseline to relax and for the principle investigator to remind them of the ramp-and-hold directions. During the ramp-and-hold conditions, participants were reminded to again match the line observed on the monitor as “accurately as possible”. Ramp periods were set using each of the four force endpoints over a fast 1 second ramp duration and a slower 2 second ramp duration. See Figures 9 and 10 for the fast and slow ramp conditions, respectively.

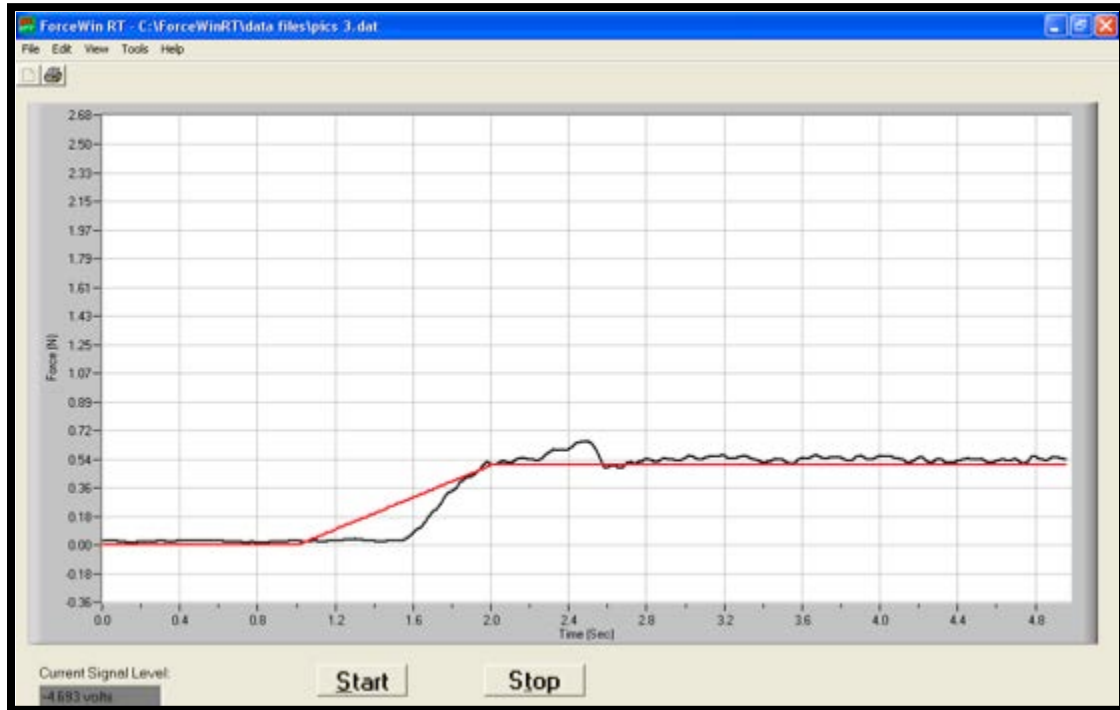


Figure 9: Screenshot of Participant Response in the Fast Ramp Condition
 Sample of participant response during the fast ramp (0.50 N/s) force condition. The red line is the computer-generated force target endpoint. The black line is a participant's response when told to "match the red line as rapidly and as accurately as possible".



Figure 10: Screenshot of Participant Response in the Slow Ramp Condition

Sample of participant response during the slow ramp (0.25 N/s) force condition. The red line is the computer-generated force target endpoint. The black line is a participant's response when told to "match the red line as rapidly and as accurately as possible".

Prior to testing, all participants completed the an abbreviated practice protocol to introduce them to the procedures and familiarize them with the force assessment device. (See Appendix C for a complete list of the practice and three assessment protocols, including the number of participants assigned to each protocol. Appendix D contains a sample of the entire force assessment protocol).

After signal acquisition, the automated FORCEWIN RT platform immediately quantifies various force measures from the digitized records for each of the subjects. Measures taken from each participant and task condition included: reaction time, rise time, peak force, and mean hold force and standard deviation during two hold phases (T1, T2). Reaction time was defined as the time interval from the time the trial started until the participant's force had reached

10% of the peak force. Peak force was identified as maximum amplitude of force during the force ramp phase. Rise time is the 10-90% intercept during dynamic force recruitment. The mean and standard deviation of the force output during T1 and T2 were taken from two consecutive 1.5 second periods during the hold phase (see Figure 3 referenced above). Analysis was completed using non-parametric Kruskal-Wallis tests comparing age, sex, smoking status, and speech use, versus each of the static and ramp-and-hold measures listed above.

Correlations between VDTs and Force Procedures and Analysis

Using the VDT and force assessment methods described above, the correlational relationship between labial vibrotactile detection thresholds and low-level skilled force assessments were analyzed after all testing procedures were finished. Non-parametric Spearman's correlations were completed to identify the relationship between the 5 and 10 Hz vibrotactile detection thresholds and the numerous force measures identified above.

Low-level Force Assessments and Sub-questions. Sub-questions include:

- Does accuracy in achieving a set force endpoint during a visually-guided dynamic task decrease as a function of aging?
- How do the variables of reaction time, rise time, peak force, and mean hold force for phase 1 and 2, change as a function of aging during the performance of a static, slow ramp and fast ramp-and hold force recruitment condition?

- How do variables such as speech usage, smoking history, and pure tone hearing thresholds influence findings in the dynamic, static, and ramp-and-hold forcing conditions?

The null hypothesis for these questions was that there would be no significant difference in accuracy to achieve a set force endpoint during a skilled force control task between the three groups. The alternative hypothesis was that there would be a significant decrease in ability and consistency to achieve a set force endpoint during a skilled low-level force control task between the three groups. Although there are no perceptual differences in the speech of older adults from younger adults, we hypothesized a decrease in accuracy of achieving a set force endpoint during the dynamic force task. For the static and ramp-and-hold variables, we hypothesized the aging participants would demonstrate increased reaction and rise time, decreased peak force, and greater instability during the mean hold force phases. These hypotheses are support by previous findings in the limb literature with regard to changes in fine motor control of aging adults.^{219,229}

Appendix A

The Levels of Speech Usage Categorical Rating Scale²³⁰

Undemanding:

Quiet for long periods of time almost every day.

Almost never

- talk for long periods
- raise your voice above a conversational level,
- participate in group discussions, give a speech or other presentation

Intermittent:

Quiet for long periods of time on many days.

Most talking is typical conversational speech.

Occasionally:

- talk for longer periods
- raise voice above conversational level
- participate in group discussions, give a speech or other presentation

Routine:

Frequent periods of talking on most days.

Most talking is typical conversational speech

Occasionally:

- talk for longer periods
- raise voice above conversational level
- participate in group discussions, give a speech or other presentation

Extensive:

Speech usage consistently goes beyond everyday conversational speech.

Regularly:

- talk for long periods
 - talk in a loud voice
 - participate in group discussions, give presentations or performances
- Although the demands of your speech are often high, you are able to continue with most work or social activities even if your speech is not perfect.*

Extraordinary:

Very high speech demands

Regularly:

- talk for long periods of time
 - talk with loud or expressive speech or
 - give presentations or performances.
- The success of your work or personal goals depends almost entirely on the quality of your speech and voice.*

Appendix B

Abbreviated Protocol for VDT Collection

Step 1: Method of Limits (5Hz)

Trial type	Starting dB	dB threshold indicated
Ascending	0	
Descending	3	
Ascending	2	
Descending	40	
Ascending	1	
Descending	38	

Indicated Operating Range for this Subject:

Step 2: 2-AFC Threshold 5Hz

Trial	dB	Train 1	Train 2	Correct?	Threshold Crossing #
1		X			
2		X			
3		X			
4			X		
5			X		
6		X			
7			X		
8			X		
9		X			
10		X			
11			X		
12			X		
13		X			
14			X		
15			X		
16		X			
17		X			
18			X		
19			X		
20			X		
21			X		
22		X			
23			X		
24			X		

Appendix C

Participant and Protocol Number

Young Group	Protocol #	Middle Group	Protocol #	Older Group	Protocol #
YA001	1	MA001	1	OA001	1
YA002	2	MA002	2	OA002	2
YA003	1	MA003	2	OA003	2
YA004	1	MA004	2	OA004	2
YA005	1	MA005	1	OA005	1
YA006	1	MA006	1	OA006	1
YA007	1	MA007	2	OA007	1
YA008	1	MA008	1	OA008	1
YA009	2	MA009	1	OA009	2
YA010	2	MA010	1	OA010	1
YA011	1	MA011	2	OA011	1
YA012	2	MA012	1	OA012	2
YA013	1	MA013	3	OA013	1
YA014	1	MA014	3	OA014	1
YA015	2	MA015	3	OA015	1
YA016	1	MA016	3	OA016	1
YA017	2	MA017	3	OA017	1
YA018	1	MA018	3	OA018	2
YA019	1	MA019	3	OA019	2
YA020	2	MA020	3	OA020	3

Appendix D

Sample protocol

Test Protocol #3		
Force Endpoint	# of Tokens	Condition
Baseline	3	
0.50	3	Static
1.00	3	Static
0.25	3	Static
2.00	3	Static
Baseline	2	
0.50	3	0.25 N/s ramp
2.00	3	2.00 N/s ramp
0.25	3	0.125 N/s ramp
1.00	3	1.00 N/s ramp
Baseline	2	
0.25	3	0.25 N/s ramp
1.00	3	0.50 N/s ramp
2.00	3	1.00 N/s ramp
0.50	3	0.50 N/s ramp

Chapter Four

Results

Sixty participants were included in this study (20 male and 40 female). Fifteen participants (25%) reported they were former smokers, 39 participants (65%) reported they had never been a smoker and 6 participants (10%) reported they were currently smoking on a daily basis, either cigarettes, cigars or a combination of both. Additionally, participants identified their amount of daily speech use on a 5-point scale. There were no participants that reported a 1 (or Undemanding speech needs) on the scale. Participants reported an amount of speech use using the remaining four levels: 2 (Intermittent) – 12 participants (20%), 3 (Routine) - 32 participants (53.3%), 4 (Extensive) – 8 participants (13.3%), 5 (Extraordinary) – 8 participants (13.3%).

Group Demographic Results

All data were analyzed using non-parametric tests, therefore raw data will be reported using medians and ranges rather than means and standard deviations. An average pure tone threshold level was determined using frequencies of 500, 1000, 2000 and 4000 Hz presented to the right and left ear. Participants with hearing aides were tested in both aided and unaided conditions. If applicable, the aided hearing thresholds were used for the participant's average. A non-parametric Kruskal Wallis test identified a statistically significant difference between the three groups for pure tone averages (p of <0.0001). Post-hoc testing using a Mann Whitney test identified a statistically significant difference between the young and older group at $p=<0.001$ and between the middle and older group

at $p=0.0010$ indicating significantly increased pure tone hearing thresholds, or decreased hearing acuity in older adults (see Figure 11).

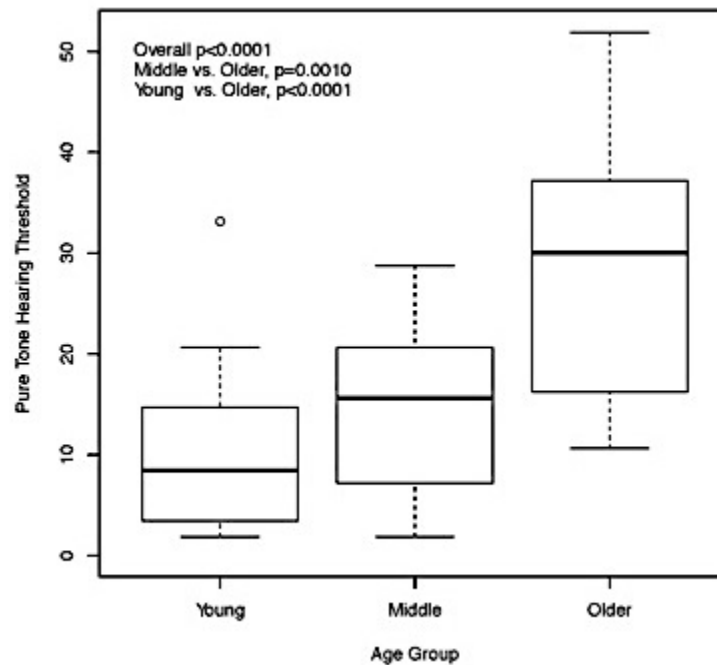


Figure 11. Pure Tone Hearing Averages by Age Group

Boxplot showing pure tone hearing threshold medians and ranges for the young, middle and older group. Higher thresholds indicate less sensitivity. Overall Kruskal Wallis and individual Mann Whitney p-values are listed.

Participants who self-identified as “current smokers” demonstrated significantly increased hearing thresholds, or worse hearing (Figure 12). A significant group differences was identified by smoking category: current, former, and non-smokers ($p=0.0016$). Post-hoc tests identified significant differences between the groups indicating a progression of worsening hearing based on smoking status. Participants that have never smoked were significantly different from current smokers ($p=0.0111$) and participants that were former smokers had significantly better hearing thresholds than current smokers ($p=0.0035$).

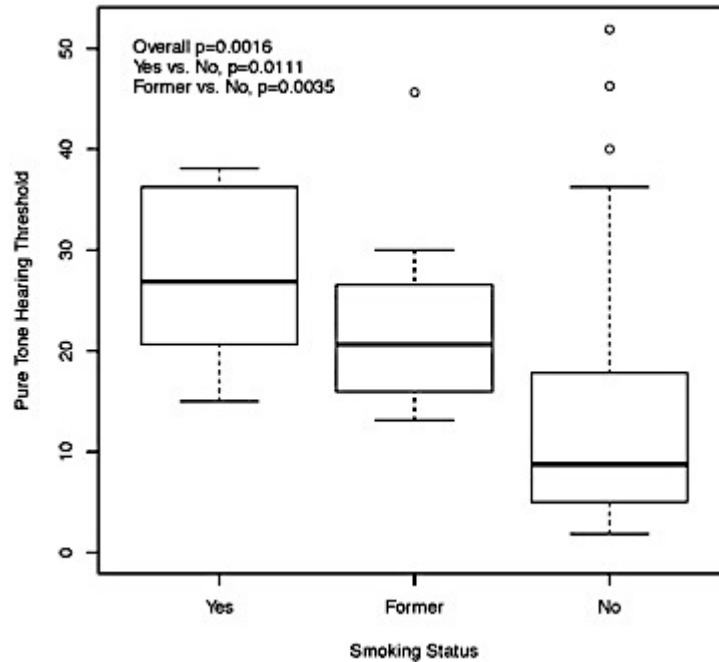


Figure 12: Pure Tone Hearing Averages by Smoking Status

Boxplot showing pure tone hearing threshold medians and ranges by current smoking status. Higher thresholds indicate less sensitivity. Overall Kruskal Wallis and individual Mann Whitney p-values are listed.

There was a significant difference between speech usage categories and pure tone hearing thresholds at $p=0.0526$ (Figure 13). Individuals with better hearing acuity (decreased pure tone average thresholds) reported increased speech use on a daily basis. There were no significant differences between sexes for pure tone average.

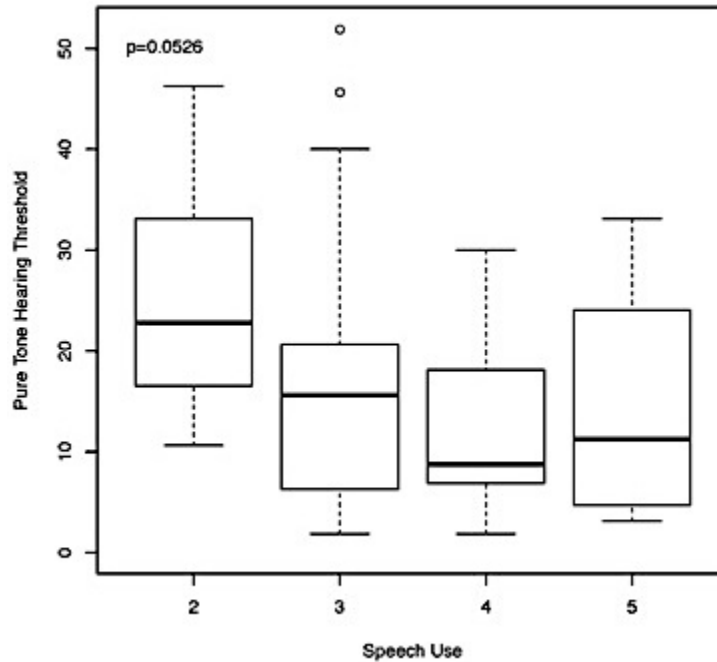


Figure 13: Pure Tone Hearing Averages by Speech Use

Boxplot showing pure tone hearing threshold medians and ranges by speech use. Higher thresholds indicate less sensitivity; higher number in speech use indicates increased speech usage. Overall Kruskal Wallis and individual Mann Whitney p-values are listed.

Results for Primary Question

Correlational Relationship between VDTs and Force. Nonparametric

Spearman's rank correlations were completed to compare the statistical dependence between multiple variables including age, pure tone hearing threshold, vibrotactile detection threshold, and various force measures during the dynamic, static, fast ramp, and slow ramp conditions. For the Spearman's rank correlation, age was treated as a continuous variable. In agreement with our power analysis, an a priori p-value of 0.1 was set to identify significant findings.

Age was found to be significantly positively correlated with pure tone average hearing thresholds ($r=0.605$; $p < 0.0001$) in that as age increased,

hearing thresholds increased, indicating decreased hearing acuity. The 5 Hz test frequency for vibrotactile detection thresholds was also found to be positively correlated with age ($r=0.302$; $p<0.019$) or as age increased vibrotactile detection thresholds increased, indicating decreased labial sensation. Pure tone hearing average was also positively correlated with the 5 Hz test frequency ($r=0.301$; and a $p=0.020$) demonstrating that as hearing acuity decreased, so did labial sensation for the 5 Hz test probe. The 10 Hz test frequency threshold was not significantly correlated with age or hearing average, but was correlated with the 5 Hz test frequency ($r=0.631$; $p<0.0001$).

Dynamic force values showed a significant positive correlation with pure tone hearing measures ($r=0.235$; $p=0.071$). A second way of analyzing the force data was to determine the absolute difference from the stimulus signal, labeled in the table as “absolute DF from normal”. When the difference from the dynamic force tracking signal was compared, a significant positive correlation with the 5 Hz test frequency was also identified ($r=0.253$ $p=0.050$) demonstrating that as vibrotactile detection thresholds at the 5 Hz test probe increased (decreased sensation), the participant’s overall distance from the reference signal also increased. See Table 3 for all correlation coefficients and p-values.

Table 3: Spearman's Correlation Coefficients and P-values for Dynamic Force Condition

Spearman's correlation coefficients and p-values for age, pure tone hearing thresholds, 5 and 10 Hz vibrotactile detection thresholds and standard deviations, and dynamic force data.

Spearman Correlations w/p-value listed below	AGE	PTA AVERAGE	VDT – 5Hz TR	VDT - 5 Hz - SD	VDT – 10Hz TR	VDT - 10 Hz - SD	DF-AVG	Absolute DF from normal
AGE	1.000	0.605 <.0001	0.302 0.019	0.26078 0.0442	0.159 0.225	0.22384 0.0856	0.139 0.290	0.117 0.372
PTA AVERAGE		1.000	0.301 0.020	0.26362 0.0418	0.097 0.461	0.17467 0.1819	0.235 0.071	0.165 0.209
VDT – 5Hz TR			1.000	0.97598 <.0001	0.631 <.0001	0.64094 <.0001	0.065 0.619	0.254 0.050
VDT - 5Hz - SD				1.000	0.67546 <.0001	0.68889 <.0001	-0.00725 0.9561	0.24891 0.0551
VDT – 10Hz TR					1.000	0.94487 <.0001	-0.018 0.891	0.178 0.173
VDT - 10Hz - SD						1.000	0.03704 0.7787	0.21888 0.0929
DF-AVG		Red - Significant at 0.05 Blue - Significant at 0.1					1.000	0.253 0.051
Absolute DF from normal								1.000

VDT Correlations with Static Force Condition. Age was found to be

correlated with mean force hold during time phase 1 ($r = -0.260$; $p = 0.045$) and rise time ($r = 0.376$; $p = 0.003$). The mean force during the hold phase for time 1 was not only correlated with age, but also with pure tone hearing thresholds ($r = -0.317$; $p = 0.014$), and the 5 Hz test frequency ($r = -0.284$; $p = 0.028$) and 5 Hz standard deviation ($r = -0.29763$; $p = 0.0209$). Mean force hold during time phase 1 was significantly correlated with the 10 Hz test frequency ($p = 0.074$) and standard deviation ($p = 0.0552$). The mean force hold for time phase 2 was also found to be significantly correlated with both the 5 and 10 Hz labial vibrotactile detection thresholds (p -values of 0.016 and 0.036 respectively) and standard deviations (p -values of 0.0104 and 0.0187 respectively). Mean force during the hold phase of time 1 and time 2 were significantly correlated with each other ($p < 0.001$). See Table 4 for a complete list of Spearman's correlation coefficients and p -values

for the static force condition. Note that age, pure tone hearing thresholds, and vibrotactile detection thresholds for the 5 and 10 Hz test frequency measures will remain consistent for each force data set. Significant correlations at $p < 0.05$ are highlighted in red, with significant correlations of $p = 0.1$ highlighted in blue.

Overall this data indicates that as a participant's threshold for the 5 Hz test frequency increases (decreased sensation), ability to maintain mean hold force during phase 1 and will decrease.

Table 4: Spearman's Correlation Coefficients and P-values for Static Condition
Spearman's correlation coefficients and p-values for age, pure tone hearing thresholds, 5 and 10 Hz vibrotactile detection thresholds and standard deviations, and static condition.

Spearman Correlations w/p-value listed below	AGE	PTA AVERAGE	VDT - 5Hz TR	VDT - 5 Hz - SD	VDT - 10Hz TR	VDT - 10 Hz - SD	Static - Mean Force Hold T1	Static - SD for T1	Static - Mean Force Hold T2	Static - SD for T2	Static - Peak Force	Static - Reaction Time	Static - Rise Time
AGE	1.000	0.605 <.0001	0.302 0.019	0.26078 0.0442	0.159 0.225	0.22384 0.0856	-0.260 0.045	0.103 0.432	-0.248 0.056	0.089 0.497	-0.061 0.642	-0.026 0.843	0.376 0.003
PTA AVERAGE		1.000	0.301 0.020	0.26362 0.0418	0.097 0.461	0.17467 0.1819	-0.317 0.014	-0.010 0.941	-0.244 0.060	-0.030 0.822	-0.174 0.184	0.142 0.279	0.478 0.0001
VDT - 5Hz TR			1.000	0.97598 <.0001	0.631 <.0001	0.64094 <.0001	-0.284 0.028	0.068 0.607	-0.309 0.016	0.052 0.695	-0.095 0.470	-0.106 0.420	0.224 0.086
VDT - 5Hz - SD				1.000	0.67546 <.0001	0.68889 <.0001	-0.29763 0.0209	0.04224 0.7486	-0.32853 0.0104	0.0292 0.8247	-0.12087 0.3576	-0.08435 0.5217	0.19304 0.1395
VDT - 10Hz TR					1.000	0.94487 <.0001	-0.232 0.074	0.139 0.291	-0.272 0.036	0.149 0.257	0.039 0.769	-0.066 0.619	0.154 0.239
VDT - 10Hz - SD						1.000	-0.24883 0.0552	0.09106 0.489	-0.30279 0.0187	0.10431 0.4277	-0.0152 0.9082	-0.03319 0.8012	0.20567 0.1149
Static - Mean Force Hold T1							1.000	0.037 0.778	0.857 <.0001	0.078 0.556	0.333 0.009	-0.169 0.198	-0.489 <.0001
Static - SD for T1								1.000	-0.046 0.730	0.987 <.0001	0.768 <.0001	0.112 0.393	-0.126 0.339
Static - Mean Force Hold T2									1.000	-0.064 0.626	0.220 0.092	-0.215 0.099	-0.335 0.009
Static - SD for T2										1.000	0.772 <.0001	0.104 0.429	-0.157 0.231
Static - Peak Force											1.000	0.173 0.186	-0.480 0.0001
Static - Reaction Time												1.000	0.043
Static - Rise Time													1.000

VDT Correlations with Fast Ramp-and-hold (0.5N/s) Condition. During the fast ramp-and-hold condition (0.5 N/s), age was significantly correlated with reaction time ($r = -0.271$; $p = 0.036$). Several of the fast ramp-and-hold measures were significantly correlated with each other, however none was significantly correlated with other sensation variables. See Table 5 for a complete list of

Spearman's correlation coefficients and p-values for the *ramp-and-hold over 1 second* condition.

Table 5: Spearman's Correlation Coefficients and P-values for Fast Ramp (0.5N/s) Condition

Spearman's correlation coefficients and p-values for age, pure tone hearing thresholds, 5 and 10 Hz vibrotactile detection thresholds and standard deviations, and fast ramping (0.5 N/s) data.

Spearman Correlations w/p-value listed below	AGE	PTA AVERAGE	VDT - 5Hz TR	VDT - 5 Hz - SD	VDT - 10Hz TR	VDT - 10 Hz - SD	Ramp (0.5N/s) - Mean Force Hold T1	Ramp (0.5N/s) - SD for T1	Ramp (0.5N/s) - Mean Force Hold T2	Ramp (0.5N/s) - SD for T2	Ramp (0.5N/s) - Peak Force	Ramp (0.5N/s) - Reaction Time	Ramp (0.5N/s) - Rise Time
AGE	1.000	0.605 <.0001	0.302 0.019	0.26078 0.0442	0.159 0.225	0.22384 0.0856	-0.063 0.630	0.230 0.077	-0.134 0.308	0.241 0.064	-0.076 0.563	-0.271 0.036	0.046 0.727
PTA AVERAGE		1.000	0.301 0.020	0.26362 0.0418	0.097 0.461	0.17467 0.1819	-0.007 0.956	0.149 0.256	-0.051 0.697	0.146 0.267	-0.002 0.987	-0.239 0.066	0.139 0.289
VDT - 5Hz TR			1.000	0.97598 <.0001	0.631 <.0001	0.64094 <.0001	-0.071 0.590	0.186 0.154	-0.109 0.409	0.144 0.272	0.100 0.448	-0.172 0.189	0.071 0.592
VDT - 5Hz - SD				1.000	0.67546 <.0001	0.68889 <.0001	-0.10278 0.4345	0.18039 0.1678	-0.11487 0.3821	0.12327 0.3481	0.12457 0.343	-0.13999 0.2861	0.04802 0.7156
VDT - 10Hz TR					1.000	0.94487 <.0001	-0.218 0.094	0.158 0.228	-0.072 0.583	0.132 0.314	0.167 0.201	-0.013 0.919	-0.007 0.959
VDT - 10 Hz - SD						1.000	-0.14493 0.2692	0.10095 0.4428	0.01017 0.9385	0.0631 0.6319	0.13449 0.3056	0.06596 0.6165	-0.02423 0.8542
Ramp (0.5N/s) - Mean Force Hold T1							1.000	-0.009 0.944	0.827 <.0001	0.031 0.816	-0.318 0.013	-0.134 0.309	-0.073 0.579
Ramp (0.5N/s) - SD for T1								1.000	0.065 0.624	0.968 <.0001	0.518 <.0001	-0.192 0.142	-0.423 0.001
Ramp (0.5N/s) - Mean Force Hold T2									1.000	0.051 0.701	-0.202 0.122	-0.132 0.315	-0.128 0.331
Ramp (0.5N/s) - SD for T2										1.000	0.457 0.0002	-0.205 0.117	-0.438 0.001
Ramp (0.5N/s) - Peak Force			Red - Significant at 0.05 Blue - Significant at 0.1								1.000	0.309 0.016	-0.451 0.0003
Ramp (0.5N/s) - Reaction Time												1.000	-0.450 0.0003
Ramp (0.5N/s) - Rise Time													1.000

VDT Correlations with Slow Ramp-and-hold (0.25N/s) Condition. In the 2 second ramp-and-hold condition, age was correlated with the standard deviations of the hold period for both the phase 1 and phase 2 timepoints, $p=0.020$, and 0.019 respectively. The 5 Hz test frequency was significantly correlated with multiple force variables including: mean force for hold phase 1 ($p=0.029$), standard deviation for hold phase 1 ($p=0.038$), mean force for hold phase 2 ($p=0.040$), and standard deviation for hold phase 2 ($p=0.047$). The 10 Hz test frequency was also significantly correlated with various force measures, including the standard deviations for mean force during the hold phase of time 1 ($p=0.001$)

and time 2 (p=0.001). This data indicates that as the 5 and 10 Hz test frequencies increased (less sensitivity), ability to maintain the mean hold force during times 1 and 2 also decreased. See table 6 for a complete list of Spearman's correlation coefficients and p-values for the *ramp-and-hold over 2 second* condition.

Table 6: Spearman's Correlation Coefficients and P-values for Slow Ramp (0.25N/s) Condition Spearman's correlation coefficients and p-values for age, pure tone hearing thresholds, 5 and 10 Hz vibrotactile detection thresholds and standard deviations, and slow ramping (0.25 N/s) data.

Spearman Correlations w/p-value listed below	AGE	PTA AVERAGE	VDT - 5Hz TR	VDT - 5 Hz - SD	VDT - 10Hz TR	VDT - 10 Hz - SD	Ramp (0.25N/s) - Mean Force Hold T1	Ramp (0.25N/s) - SD for T1	Ramp (0.25N/s) - Mean Force Hold T2	Ramp (0.25N/s) - SD for T2	Ramp (0.25N/s) - Peak Force	Ramp (0.25N/s) - Reaction Time	Ramp (0.25N/s) - Rise Time
AGE	1.000	0.605 <.0001	0.302 0.019	0.26078 0.0442	0.159 0.225	0.22384 0.0856	-0.213 0.102	0.281 0.030	-0.223 0.087	0.303 0.019	0.095 0.470	-0.133 0.313	0.003 0.982
PTA AVERAGE		1.000	0.301 0.020	0.26362 0.0418	0.097 0.461	0.17467 0.1819	-0.163 0.214	0.214 0.101	-0.212 0.104	0.183 0.162	-0.070 0.596	-0.086 0.512	0.126 0.337
VDT - 5Hz TR			1.000	0.97598 <.0001	0.631 <.0001	0.64094 <.0001	-0.282 0.029	0.268 0.038	-0.266 0.040	0.258 0.047	-0.027 0.836	-0.038 0.773	0.109 0.408
VDT - 5Hz SD				1.000	0.67546 <.0001	0.68889 <.0001	-0.28718 0.0261	0.28818 0.0256	-0.24189 0.0626	0.25711 0.0473	-0.02151 0.8704	0.00332 0.9799	0.09218 0.4836
VDT - 10Hz TR					1.000	0.94487 <.0001	-0.167 0.203	0.413 0.001	-0.213 0.102	0.404 0.001	0.037 0.778	0.065 0.623	-0.017 0.896
VDT - 10Hz - SD						1.000	-0.12573 0.3384	0.36055 0.0047	-0.18531 0.1563	0.3473 0.0066	0.03651 0.7818	0.07663 0.5606	-0.02304 0.8613
Ramp (0.25N/s) - Mean Force Hold T1							1.000	-0.225 0.084	0.865 <.0001	-0.200 0.126	-0.281 0.030	-0.105 0.423	0.003 0.984
Ramp (0.25N/s) - SD for T1								1.000	-0.217 0.096	0.961 <.0001	0.444 0.0004	-0.007 0.957	-0.366 0.004
Ramp (0.25N/s) - Mean Force Hold T2									1.000	-0.259 0.045	-0.151 0.250	-0.158 0.228	-0.074 0.576
Ramp (0.25N/s) - SD for T2										1.000	0.415 0.001	0.046 0.730	-0.340 0.008
Ramp (0.25N/s) - Peak Force											1.000	0.409 0.001	-0.783 <.0001
Ramp (0.25N/s) - Reaction Time												1.000	-0.535 <.0001
Ramp (0.25N/s) - Rise Time													1.000

Results for Sub-questions

Labial Vibrotactile Detection Thresholds. Non-parametric Kruskal Wallis tests with an alpha of 0.1 were used to compare the three age groups at the 5 and 10 Hz test frequency. Age was used as a discrete group variable in these analyses with three age groups: Young- 19-39 years; Middle- 40-64 years; Older- 65 years and older. There was a significant difference between age groups at the

5 Hz test frequency with a p-value of 0.0646 indicating increased vibrotactile detection thresholds in our individuals. Figure 14 illustrates the increased median threshold value for the older group versus the young and middle group. There were no significant differences between vibrotactile detection thresholds at 5 or 10 Hz for sex, speech usage or smoking history.

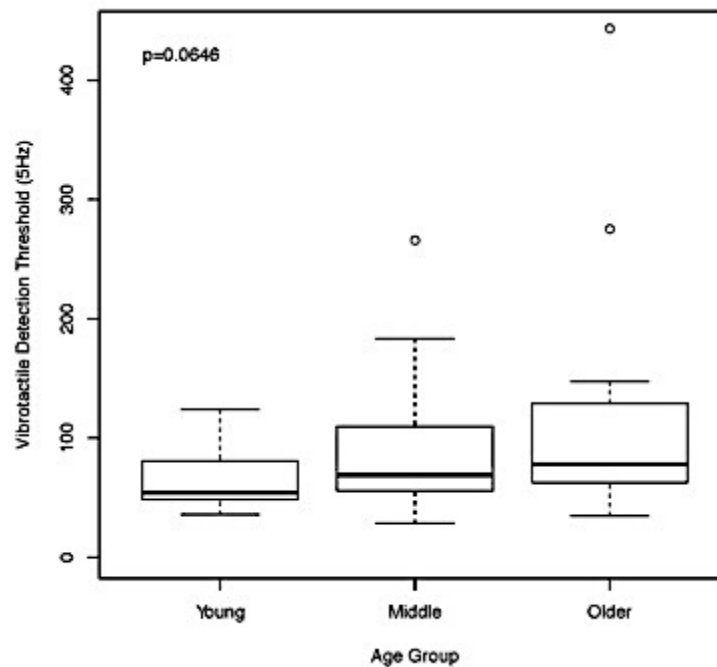


Figure 14: 5 Hz Vibrotactile Detection Threshold by Age

Boxplot showing medians and ranges of the 5 Hz test frequency thresholds for the young, middle, and older participants.

Low-level Skilled Force Assessments. Although testing protocols collected force endpoints from 0.25-2.0 N, only the 0.5 N endpoint will be presented at this time. Non-parametric Kruskal Wallis tests with an alpha set at 0.1 were used to compare the group variables of age, sex, speech usage, and smoking history for accuracy measures for dynamic force and reaction time, rise time, peak force,

and mean hold force for time 1 and 2 for the static, fast ramp (0.5N/s) and the slow ramp (0.25N/s) force test conditions.

Dynamic Force. There were no significant differences in the average dynamic force measures when compared to age ($p=0.3202$, figure 15), sex ($p=0.9313$), speech use ($p=0.7505$), or smoking history ($p=0.8882$). However, when the overall difference from the dynamic force signal was compared, significant effects were identified. A significant difference was identified between sexes with a p-value of 0.0447. There was a significant difference between age groups ($p=0.0786$); with the participants in the Middle age group demonstrating significantly decreased overall difference from the signal than the Young or Older participants. There was no significant difference identified for either speech use ($p=0.6284$) or smoking history ($p=0.9049$). See Table 7 for p-values for each measure by group for the dynamic force condition. For all tables in this section, significant correlations at $p<0.05$ are highlighted in red, with significant correlations of $p<0.1$ highlighted in blue.

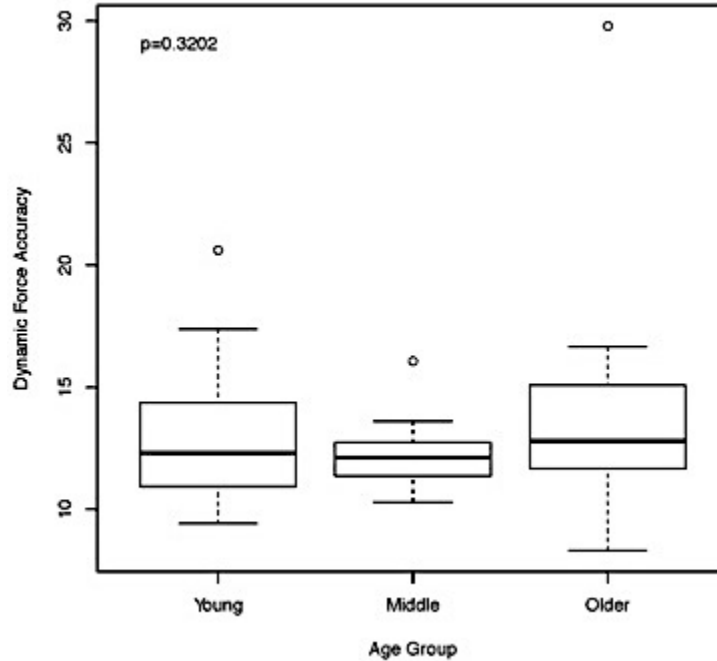


Figure 15: Dynamic Force Accuracy by Age

Accuracy in matching a 2 Hz dynamic force task by group: young, middle, and older. No significant differences were identified by group.

Table 7: P-values for Group Variables for the Dynamic Tracking Condition.

Dynamic force tracking accuracy and absolute difference from reference signal by demographic variables. Significant differences between groups were identified using $p < 0.05$ are highlighted in red; significant differences of $p < 0.1$ are highlighted in blue.

Dynamic Force	Average RMS	Difference from Reference Signal
Age	0.3202	0.0786
Sex	0.9313	0.0447
Speech	0.7505	0.6432
Smoking	0.8882	0.7355

Static Force Condition. Significant differences in the static force condition by age were identified for the mean force hold phase of time 1 ($p=0.0467$) and rise time ($p=0.0039$). See Figures 16-19 for boxplots of rise time, peak force, and mean force hold for time phase 1 and 2 for the static condition.

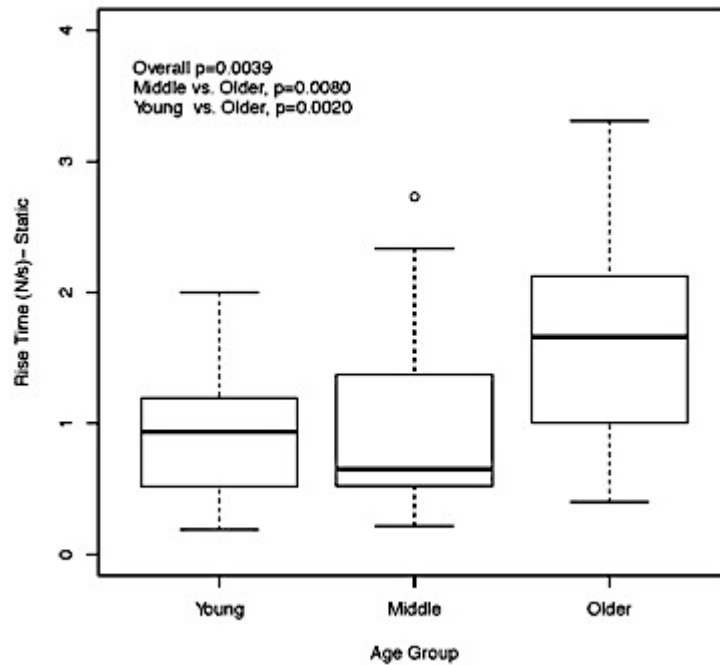


Figure 16: Rise Time Static Condition by Age

Boxplot showing medians and ranges of rise time during the static condition for the young, middle, and older participants.

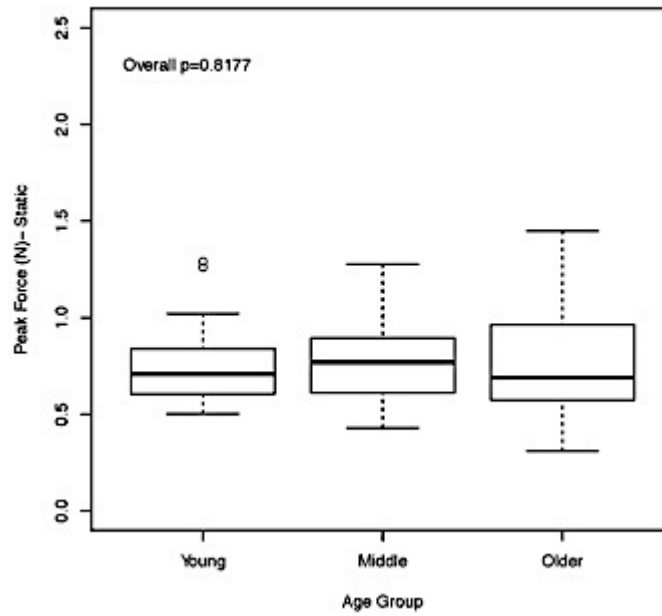


Figure 17: Peak Force Static Condition by Age

Boxplot showing medians and ranges of peak force during the static condition for the young, middle, and older participants.

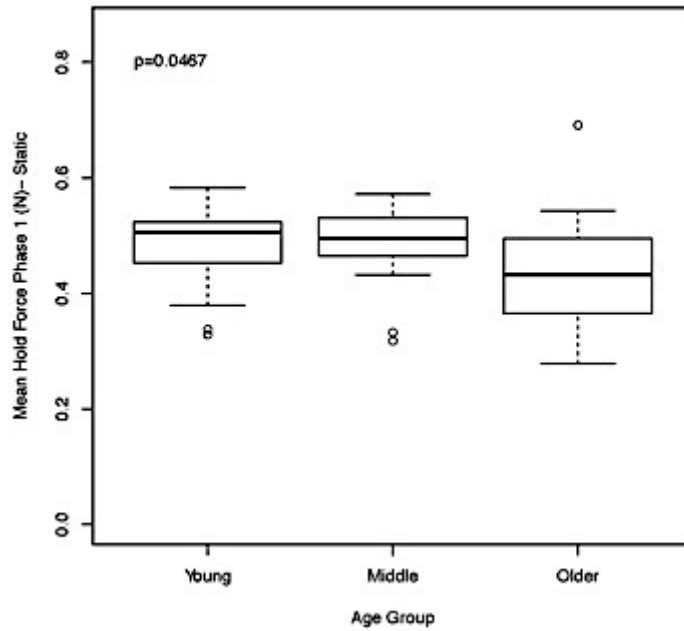


Figure 18: Mean Force for Time Phase 1 Static Condition by Age
 Boxplot showing medians and ranges of mean force during time phase 1 during the static condition for the young, middle, and older participants.

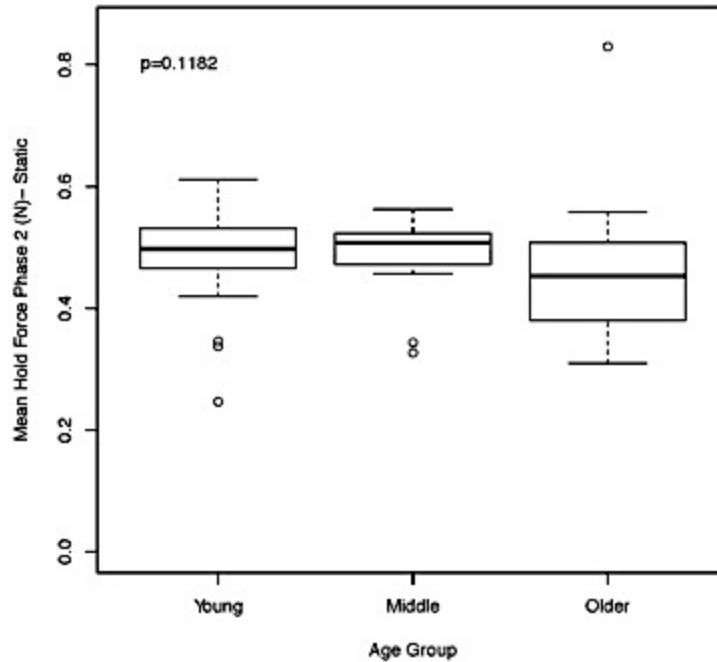


Figure 19: Mean Force for Time Phase 2 Static Condition by Age

Boxplot showing medians and ranges of mean force during hold phase 2 during the static condition for the young, middle, and older participants.

The group variable of smoking history identified significant differences in the mean force hold phase for time 1 ($p=0.0297$, Figure 20), as well as reaction time ($p=0.0386$, Figure 21). This data indicates that current smokers had significantly decreased ability to maintain the correct force endpoint during a hold phase and had significantly increased reaction times.

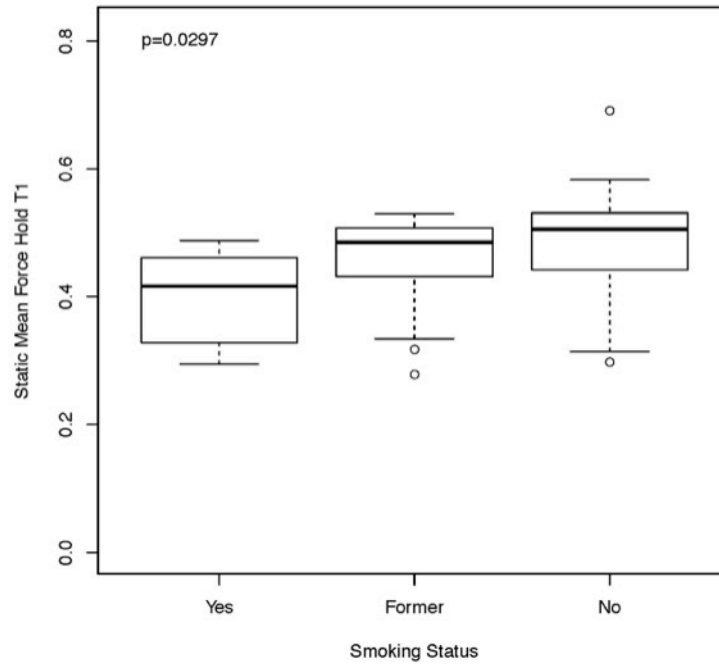


Figure 20: Static Condition Mean Force Hold Time Phase 1 by Smoking Status
 Boxplot showing medians and ranges of Mean force during hold phase 1 during the static condition for current, former, and non-smokers.

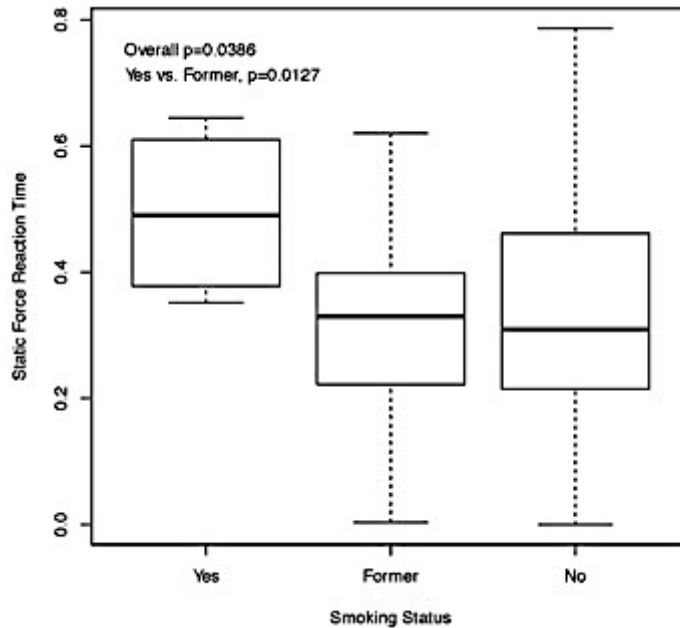


Figure 21: Static Condition Reaction Time by Smoking Status

Boxplot showing medians and ranges of reaction time during the static condition for current, former, and non-smokers.

Two variables demonstrated significant differences by speech usage category: mean force hold for time phase 2 ($p=0.0658$, Figure 22) and reaction time (0.0726 , Figure 23). Individuals with increased speech usage (categories 4 and 5) were significantly different than the less talkative individuals (categories 2 and 3) for maintaining mean force during hold phase 2. No sex differences were identified for any of the measurements in the static condition. See table 8 for p-values for each measure by group for the static condition.

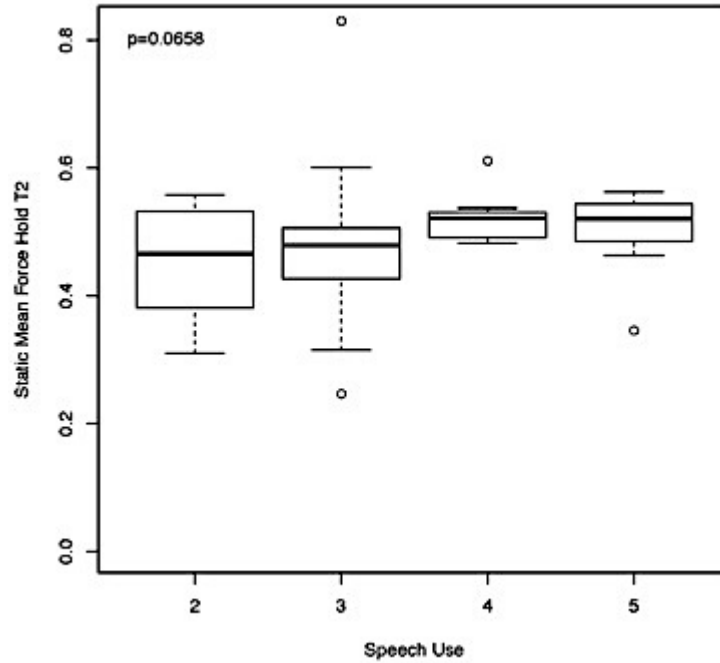


Figure 22: Static Condition Mean Force Hold for Time Phase 2 by Speech Use
 Boxplot showing medians and ranges of mean force during time phase 2 during the static condition by speech use. Higher numbers in “speech use” indicate an increase in self-reported daily talking.

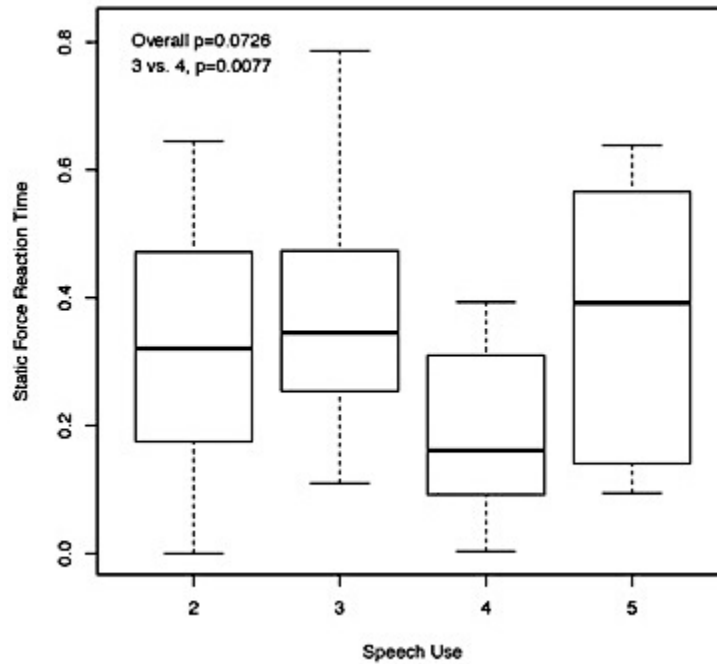


Figure 23: Static Condition Reaction Time by Speech Use

Boxplot showing medians and ranges of reaction time during the static condition by speech use. Higher numbers in “speech use” indicate an increase in self-reported daily talking.

Table 8: P-values for Group Variables for the Static Force Condition.

Associations between static force variables by demographic variables. Significant associations at $p < 0.05$ are highlighted in red; significant correlations of $p < 0.1$ are highlighted in blue.

Static Force	Mean Phase T1	SD - Phase T1	Mean Phase T2	SD - Phase T2	Peak Force	Reaction Time	Rise Time
Age	0.0467	0.4629	0.1182	0.6193	0.8177	0.3499	0.0039
Sex	0.204	0.3884	0.3799	0.3884	0.3468	0.6324	0.5408
Speech	0.1088	0.7737	0.0658	0.7747	0.1268	0.0726	0.2215
Smoking	0.0297	0.7632	0.1134	0.7767	0.4395	0.0386	0.6428

Fast Ramp-and-Hold (0.5N/s) Condition. See Figures 24-27 for boxplots of rise time, peak force, and mean force hold for time phase 1 and 2 for the fast ramp-and-hold (0.5 N/s) condition. Two statistically significant variables were identified for the fast ramp of 0.5N/s test condition for grouped data. Mean force hold during phase 2 was significant by age at $p=0.0467$. Peak force by sex was significant at $p=0.0132$. There were no statistically significant differences for any other fast ramp force conditions for speech usage or smoking history. See Table 9 for p-values for each measure by group for the fast ramp condition.

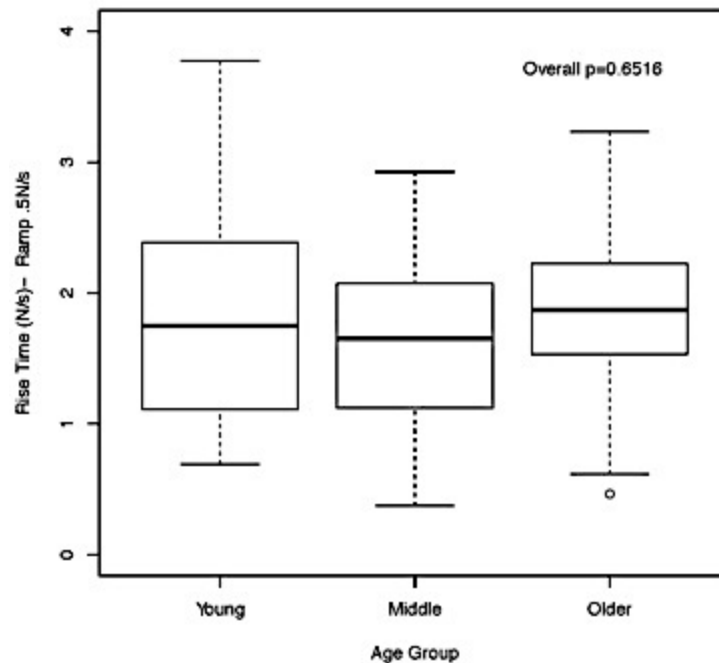


Figure 24: Rise Time for Fast Ramp-and-Hold (0.5 N/s) by Age
 Boxplot showing medians and ranges of rise time during the fast ramp-and-hold condition for the young, middle, and older participants.

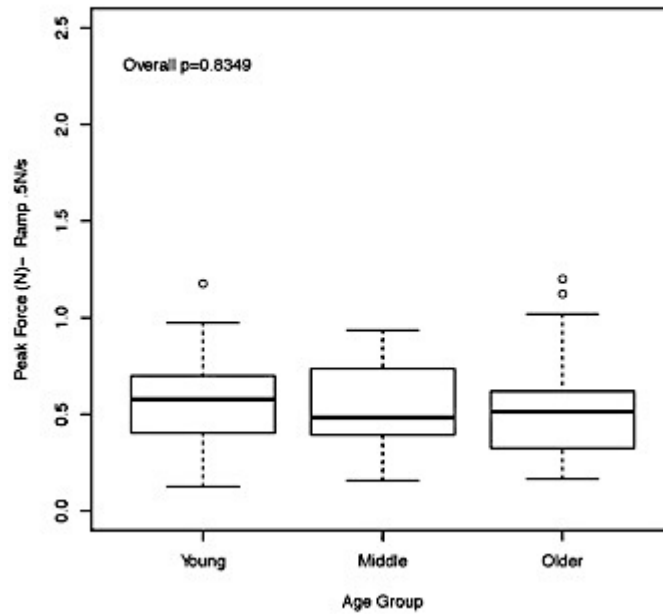


Figure 25: Peak Force for Fast Ramp-and-Hold (0.5 N/s) by Age
 Boxplot showing medians and ranges of peak force during the fast ramp-and-hold condition for the young, middle, and older participants.

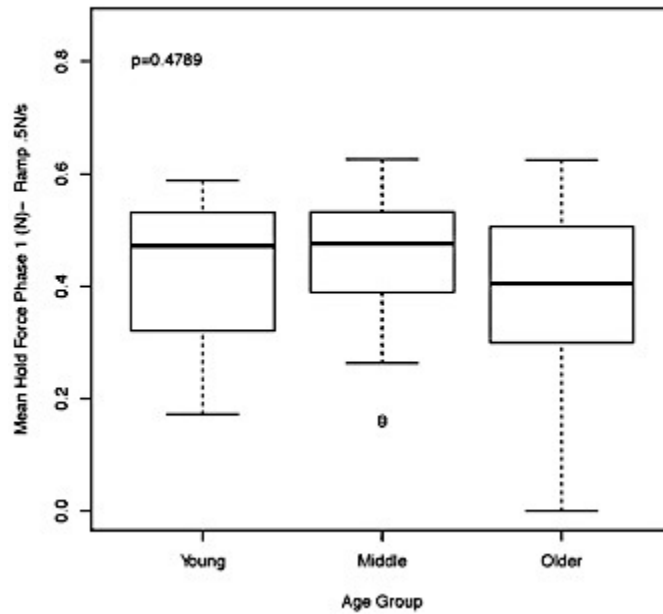


Figure 26: Mean Force for Time Phase 1 for Fast Ramp-and-Hold (0.5 N/s) by Age
 Boxplot showing medians and ranges of mean force for hold phase 1 during the fast ramp-and-hold condition for the young, middle, and older participants.

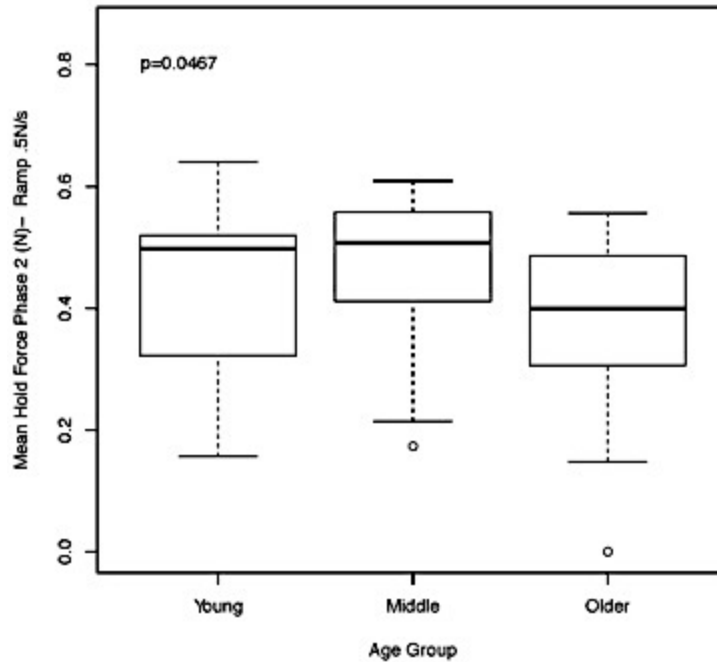


Figure 27: Mean Force for Time Phase 2 for Fast Ramp-and-Hold (0.5 N/s) by Age
 Boxplot showing medians and ranges of mean force for hold phase 2 during the fast ramp-and-hold condition for the young, middle, and older participants.

Table 9: P-values for group variables for the fast (0.5N/s) ramp force condition.
 Significant associations at $p < 0.05$ are highlighted in red; significant associations of $p < 0.1$ are highlighted in blue.

Fast Ramp Force	Mean Phase T1	SD - Phase T1	Mean Phase T2	SD - Phase T2	Peak Force	Reaction Time	Rise Time
Age	0.4789	0.3396	0.0467	0.3176	0.8349	0.1803	0.6516
Sex	0.3549	0.4902	0.8385	0.6892	0.0132	0.3631	0.2792
Speech	0.4967	0.7300	0.9837	0.7548	0.5078	0.6041	0.3751
Smoking	0.9498	0.3014	0.4784	0.2407	0.4312	0.1477	0.5871

Slow Ramp-and-Hold (0.25N/s) Condition. See figures 28-31 for boxplots of rise time, peak force, and mean force hold for time phase 1 and 2 for the the slow ramp-and-hold (0.25 N/s) condition. A significant difference was identified at the mean force for time 1 ($p = 0.0812$) and the standard deviations for time phase

1 and 2, at $p = 0.0957$ (figure 32) and 0.0586 (figure 33), respectively. Sex differences were nearing significance for the rise time at $p = 0.0777$. No significant group differences for speech use or smoking history were identified for measures in the slow ramp 0.25N/s condition. See table 10 for p-values for each measure by group for the slow ramp condition.

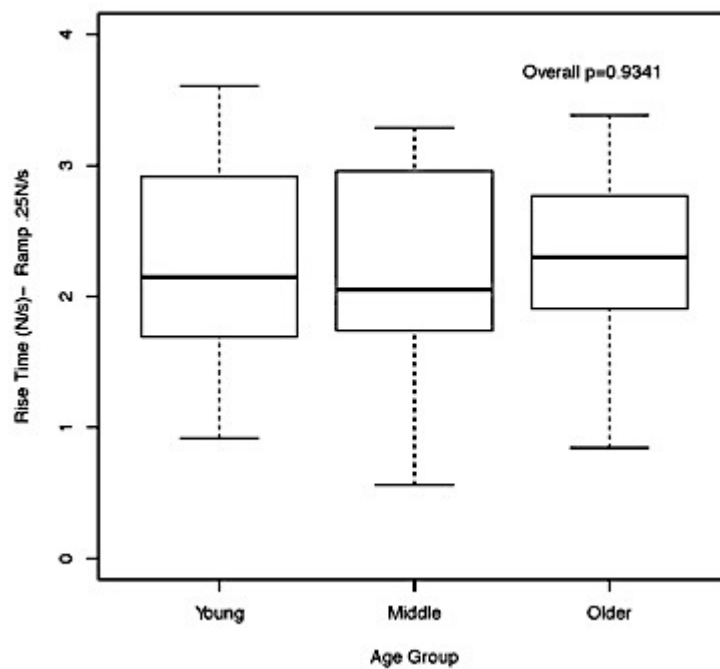


Figure 28: Rise Time for Slow Ramp-and-Hold (0.25 N/s) by Age
Boxplot showing medians and ranges of rise time during the slow ramp-and-hold condition for the young, middle, and older participants.

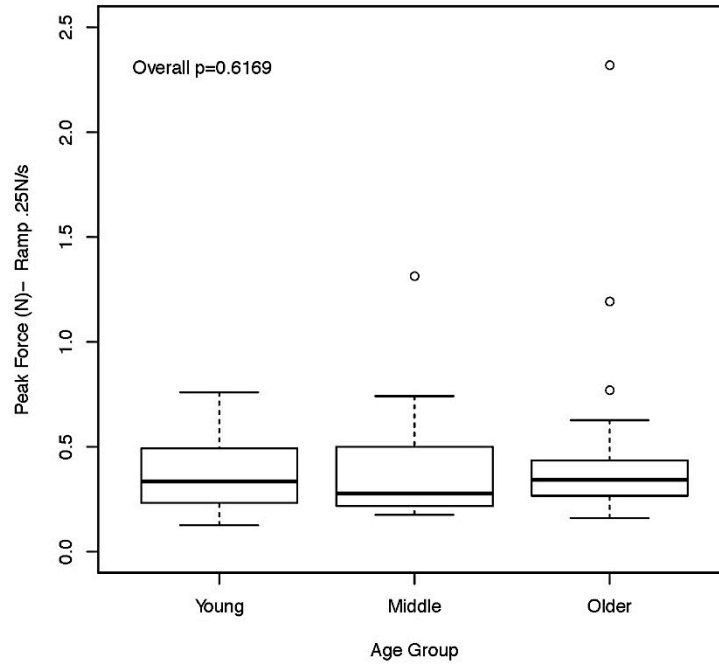


Figure 29: Peak Force for Slow Ramp-and-Hold (0.25 N/s) by Age
 Boxplot showing medians and ranges of peak force during the slow ramp-and-hold condition for the young, middle, and older participants.

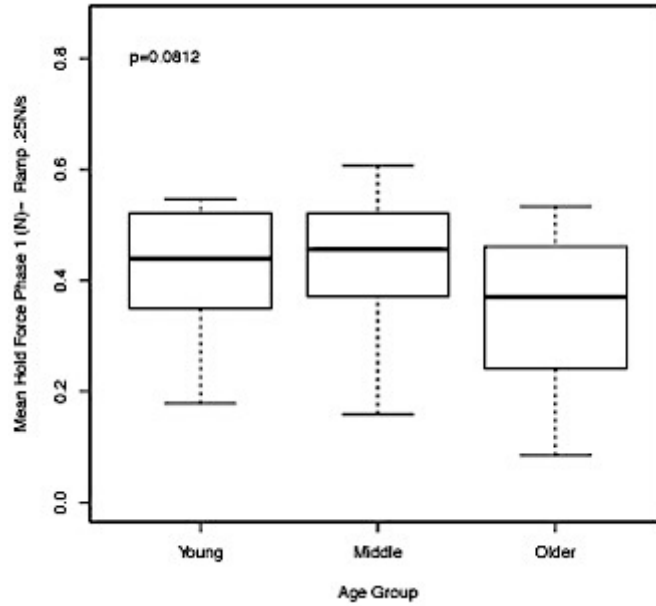


Figure 30: Mean Force for Time Phase 1 for Slow Ramp-and-Hold (0.25 N/s) by Age
 Boxplot showing medians and ranges of mean force for hold phase 1 during the slow ramp-and-hold condition for the young, middle, and older participants.

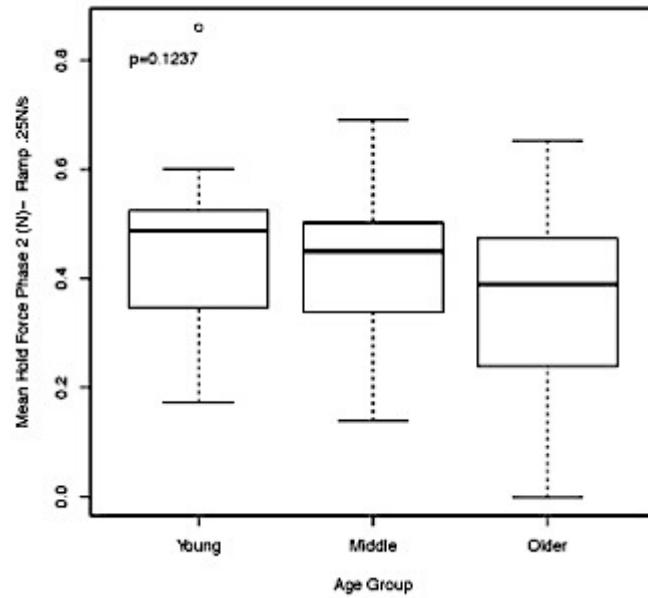


Figure 31: Mean Force for Time Phase 2 for Slow Ramp-and-Hold (0.25 N/s) by Age
 Boxplot showing medians and ranges of mean force for hold phase 1 during the slow ramp-and-hold condition for the young, middle, and older participants.

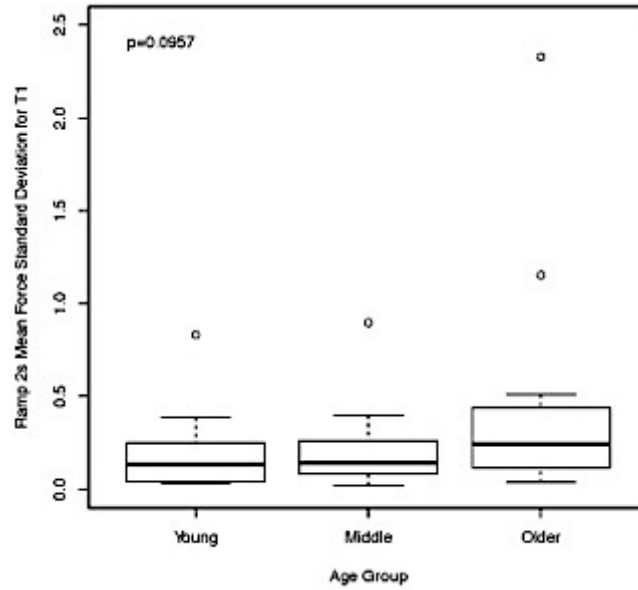


Figure 32: Slow Ramp-and-Hold (0.25 N/s) Standard Deviation for Mean Force Hold Time Phase 1 by Age

Boxplot showing medians and ranges of the standard deviations for mean force for hold phase 1 during the slow ramp-and-hold condition for the young, middle, and older participants.

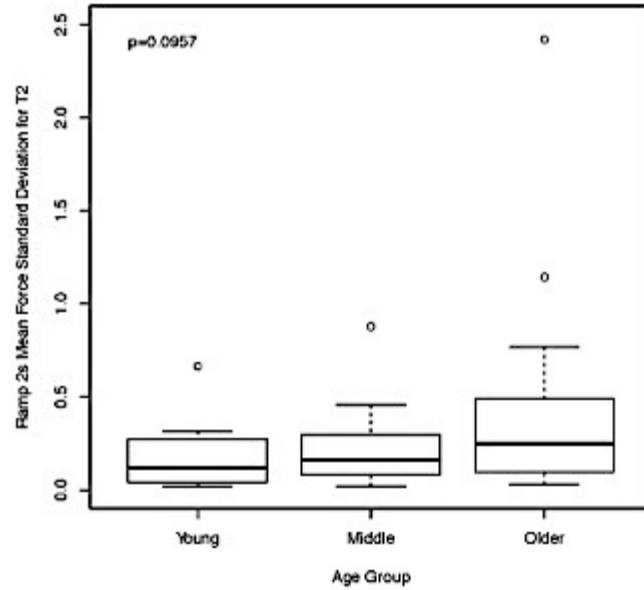


Figure 33: Slow Ramp-and-Hold (0.25 N/s) Standard Deviation for Mean Force Hold Time Phase 2 by Age

Boxplot showing medians and ranges of the standard deviations for mean force for hold phase 2 during the slow ramp-and-hold condition for the young, middle, and older participants.

Table 10: P-values for Group Variables for the Slow (0.25N/S) Ramp Force Condition. Significant associations at $p < 0.05$ are highlighted in red; significant associations of $p < 0.1$ are highlighted in blue.

Slow Ramp Force	Mean Phase T1	SD - Phase T1	Mean Phase T2	SD - Phase T2	Peak Force	Reaction Time	Rise Time
Age	0.0812	0.0957	0.1237	0.0586	0.6169	0.4761	0.9341
Sex	0.9250	0.1582	0.7301	0.2656	0.2934	0.2333	0.0777
Speech	0.3100	0.7305	0.3798	0.7198	0.8663	0.1064	0.8592
Smoking	0.2487	0.4031	0.7060	0.5688	0.2823	0.7499	0.3441

Chapter Five

Discussion

The central aim of this dissertation study was to begin to identify the relationship between labial sensation and low-level speech-like force production (as theorized by the DIVA model) and to characterize how this relationship may change as a function of increasing age. The purpose of this observational study was to begin setting the foundation for using this relationship to guide future assessment and treatment of speech dysarthria after non-progressive neurologic injury based on objective measures of sensation and force production.

Correlation analyses have identified a significant relationship between the vibrotactile detection threshold at the 5 Hz test frequency and accuracy in maintaining the mean force hold for phases 1 and 2 in the static and slow ramp (0.25 N/s) force control condition in community-dwelling adults. Our findings align with our initial hypothesis that there is a negative correlational relationship between labial somatosensation and low-level force production ability with vibrotactile detection thresholds increasing with age and accuracy in achieving a low-level force endpoint decreasing with age.

Alterations in Orofacial Sensory Capacities

Unfortunately, little is currently known about the functional effect of decreased somatosensory capabilities and the impact this reduction may have on behaviorally-related processes underlying the performance of common orofacial activities in the aging population. Some clues may be obtained from studies such as those that have demonstrated that alterations in sensation (using

vibrotactile detection sensitivity) in human foot sole may be a contributing factor to changes in postural and gait patterns.^{154,231} The age-related perceptual changes observed in our current study may have a similar effect as it pertains to behaviors such as speech production. As sensory experiences in the orofacial region are primarily the result of self-generated action, ongoing learning and updating of central orofacial sensorimotor representations are influenced by self-generated sensory experiences.¹⁰⁵ In studies by Ito and Ostry, these researchers identified the reciprocal relationship between speech production and perception.^{40,73} The researchers applied a stretch perturbation to facial areas while participants listened to speech sounds. Participants identified perceptually hearing a different speech sound based on the direction of skin stretch to the orofacial area, however no changes were identified when skin stretch perturbations were applied to the palm or forearm.⁷³ These studies support the application of the DIVA model in that auditory, somatosensory and motor associations learned during speech development and previous experience combine to aide in speech perception and action in older adults.

Our findings indicating that older adults have decreased labial sensitivity is consistent with increased somatosensory thresholds identified throughout the body in aging populations.^{150,155,232} The results of this investigation are consistent with previously published data by our lab group highlighting labial vibrotactile detection threshold changes in community-dwelling older adults.²²⁶ In our previous study, significant differences were noted for the 5 and 10 Hz test frequencies, whereas in our current study significant differences were observed

at the 5 Hz test frequency. This discrepancy may be partly explained by changes in our methodologies as the previous study employed a modified von Bekeky (staircase) method to identify thresholds, versus our current 2-alternative forced choice method. Additionally, the previous study used a small cohort of young individuals (average age of 22 years) as a comparison group to the older adults.

In healthy aging, increased perceptual thresholds may be attributed to physiological changes in oral and perioral skin, mucosa and muscle structure.^{159,162,233,234} For example, the orbicularis oris muscle thins²³³ while mechanosensitivity thresholds in the oral mucosa increase in healthy aging.¹⁶¹ Healthy skin, regardless of sun exposure, demonstrates a progressive alteration in thickness and elasticity.^{159,234,235} Aging skin is characterized by a flattening of the underside of the epidermis, a spreading out of the superficial blood vessels, thickening terminal elastic fibers, and decreased hydration at the skin surface. These changes result in the characteristic dry and sagging appearance of older skin.^{159,234} Any of these physiologic changes in aging muscle, mucosa or skin could be contributing to the results of this study.

Alterations in Orofacial Motor Activities

Previous reports described above have demonstrated that assessments of individual parts of the orofacial system may reveal adequate strength or range of motion in static positions or during the performance of gross motor movements. However, people with speech dysarthria may not be able to accomplish the overall speech goal when it comes to intelligible production of speech sounds that involves the interplay between these systems. In work by Barlow and

Burton,³⁶ four individuals with dysarthria after traumatic brain injury completed low-level force assessments using similar methodologies to the current study. The results from their study indicated a decreased ability to grade and fractionate movement. Participants in our older age group had significantly increased reaction times during the static force conditions. The older adults tended to take a more hesitant and slow approach to increasing target force. Taking a slower, more cautious approach to force adjustments may be an indication of needing more time to process sensory feedback to complete the desired task. In our current study, the older adults may have used decreased speed as compensation for decreased sensory thresholds. Individuals with speech dysarthria have also been known to use a slower rate during speech to compensate for weakness, fatigue, decreased sensation or the need for increased temporal processing.²⁶ It is possible older adults in our study were compensating in a similar fashion.

Applications to Theoretical Perspective

Using pure tone hearing thresholds, labial vibrotactile detection thresholds and dynamic, static, and ramp-and-hold low-level force assessments, the results of this dissertation study support the application of speech motor control theories, like the DIVA model and DST, to clinical populations with speech dysarthria.

Applications of DIVA model

In alignment with principles of the DIVA model, there is a proposed interdependent relationship between the ability to use auditory and

somatosensory feedback to produce functional speech actions. This primary tenant of the DIVA model was consistent with our current findings. Changes in auditory and somatosensory threshold levels that were correlated with decreased low-level force control as identified in our aging population, may have an impact on functional movement, although not apparent at the functional speech level at this time.²³²

Feedback vs. Feedforward Control Systems

Feedback, or closed loop, systems rely on auditory and somatosensory information to learn new skills, maintain skills during internal and external perturbations, and potentially re-learn skills after injury. Our findings indicated significant differences between age groups for maintaining mean hold force during time 1 in the static and slow ramp-and-hold conditions, as well as significant correlations between the 5 Hz test frequency and the ability to maintain force during mean force during time phase 1 and 2. It is possible that participants in our study had to rely more on their somatosensory feedback systems to maintain the force endpoint in the slow and more controlled force tasks^{136,228} and therefore had decreased ability to maintain the low-level force endpoint as labial sensitivity decreased.

In a mature speaker, the orofacial system has completed a training process that matches the intended speech goal to an acoustic and tactile/proprioceptive target. At this time, the healthy, mature speaker can rely on feedforward, or open loop systems to maintain correct speech production. In our data, differences in ability to reach and/or maintain the 0.50 N endpoint were not

found between age groups during the fast ramp-and-hold condition, except for mean hold force during time phase 2. It is possible that participants were able to rely on their feedforward systems in a more ballistic fashion during the fast ramp-and-hold condition. It was not until the end of task (mean hold force during time phase 2) that participants began to use their feedback systems and older participants began to have significant differences due to their decreased labial sensitivity.

Applications of Dynamic Systems Theory

In DST, complex dynamic performances are described as emerging from the interaction of neurobiological networks and environmental affordances.^{27,52-54} Multiple degrees of freedom spontaneously arrange themselves to correctly produce the desired behavior. It is the complex interplay of multiple vocal tract structures that allows healthy speakers to produce highly coordinated co-articulations during running speech. More simply put, this means that speech production is greater than the sum of its parts.

Interpretation of r^2 values is a means of interpreting the amount of variance explained by one variable versus another. The r^2 values identified during our Spearman correlations are low. This is not a negative finding, but actually supportive of the application of DST to this study population and speech tasks. Low r^2 values may indicate that there is not one variable that explains speech behavior outcomes well. This finding suggests that future analyses and modeling should be completed using multivariate analyses to identify which combination or pattern of variables may be most predictive. It is our contention

that gradual and progressive alterations in sensory and motor capacity may result in a narrowing of reserve capacity (degrees of freedom) to functionally adapt to large-scale perturbations such as neurologic injury or disease states.

Clinical Implications and Applications

Interestingly, in spite of the significant increase in threshold level at the 5 Hz test frequency and decreased accuracy in maintaining a 0.50 N endpoint, all aging participants had perceptually normal speech intelligibility and reported no noticeable difficulties swallowing. Although this study is preliminary in nature with numerous follow-up studies required, it does begin to provide insight into labial sensorimotor interaction underling functional communicative and ingestive behaviors in healthy adults that may be extrapolated to the treatment of a disordered population.

Smoking Status

Significant group differences for smoking status were identified for pure tone hearing thresholds, mean hold force during time phase 1 and reaction time during the static condition. Current smokers demonstrated decreased hearing acuity, decreased ability to maintain hold force during time 1 and increased reaction time. Ototoxic effects of tobacco have been well documented;^{236,237} however, smoking and/or tobacco use effects on oral tactile sensitivities have had mixed findings.^{161,238} Even though smoking causes vasoconstriction and reduced blood flow to skin and extremities,²³⁶ there have been some conflicting arguments regarding the impact of smoking on tactile sensation in fingertips and

feet.^{239,240} In one study with negative findings, Gerr and Letz discuss their non-significant findings for difference in vibrotactile acuity in the finger and forearm of healthy individuals based on smoking status. They argue that their findings may have been confounded by their exclusion of adults with specific co-morbidities that may be related to tobacco use. There is a need for further research in this area; however, our findings suggest that patients with a significant smoking history may have even further difficulties using auditory and/or somatosensory feedback during speech therapy interventions.

Possible Treatments that Increase Sensory Saliency

Unfortunately, there is little research in speech dysarthria focusing on the use of neuroplasticity principles to improve intelligibility; however work by Ramig and colleagues using LSVT/LOUD therapy is beginning to bridge that gap through application of the neuroplasticity principles described by Kleim and Jones above.^{218,241-243} During LSVT/LOUD therapy, patients are given one salient feature of speech on which to focus; they are instructed to “Think Loud” in an attempt to increase volume and clarity by moving articulators more dramatically. Although originally designed for individuals with Parkinson’s disease, Wenke and colleagues²⁴³ demonstrated an increase in intelligibility for individuals with dysarthria after traumatic brain injury using the LSVT program. It is possible that the improvement in speech intelligibility of individuals with non-progressive speech dysarthria after interventions with LSVT are related to the level of attention and motivation integrated into the program.²⁴¹ Additionally, the focus on “loud” speech encourages patients to over-articulate and slow their rate which

may also provide the necessary time for processing somatosensory and auditory feedback information necessary for maintaining correct production, as hypothesized in the DIVA model. The LSVT/LOUD program also requires daily homework (increased intensity of practice) and the use of functional, patient-created phrases (increased specificity and saliency). The daily practice, motivation of using self-created and important sentences, and the focused attention to “think loud” may increase the engagement of participants during therapy sessions, possibly leading to improved outcomes.²⁴⁴ Part of the LSVT/LOUD therapy program is the focus on moving from blocked to random practice within the confines of each session. The use of principles of exercise science may add to the overall effectiveness of this program and could be adapted for use in future therapy programs for individuals with other types of speech dysarthria.

Discussions of Study Methodologies

Speech vs. Non-speech tasks

Studies in the field of speech dysarthria often raise questions regarding the different muscle activation patterns and neural structures involved in speech versus non-speech tasks. Given our assessment methodologies of using skilled, but non-speech tasks, it is important to make the distinction between these types of oromotor movements to place our findings in the greater context of the field. Imaging studies and cortical recordings of neural networks for motor control have shown a functional task-specific organization in primary motor cortices.^{245,246} In

recent work using BOLD fMRI during the production of nonsense vocal tract gestures compared to speech sounds, researchers found common neural substrates with overlapping activations for speech gestures and skilled non-speech movements.²¹³ In the current study, participants were asked to complete a dynamic non-speech, yet skilled oral task. Participants were asked to focus on saying the vowel sounds for words such as “movie” or “gooey” to maintain focus on completing the quick lateral stretch to medial compressive labial movements underling the force control task. The rationale for using a correlate to a real word was to give participants a sense of “intent” when producing the speech-like movements. Given that outside of sex differences there were no significant results to report for the dynamic speech task may indicate that our task was not sufficiently speech-like. It is possible that the dynamic task was too far outside the range of expected speech production gestures for participants. Future study designs may move from use of a simple sinusoidal tracking pattern to a more real word pattern and/or increase the speed of the task to have the behavior fall more into the range of velocities and acceleration/deceleration states used in speech.

Vibration as a Means of Sensory Assessment

As discussed in the Methods section, vibration is an excellent signal with which to assess labial tactile sensitivity. The rapid movements of the lower face during speech produce cutaneous and subcutaneous derived sensory feedback encoded by mechanoreceptors in the orofacial region.^{79,97,220,221} Although, the cutaneous mechanoreceptors of the face are sensitive to frequencies from just above DC to 150Hz,⁹⁸ the sensory feedback information provided by self-

generated speech kinematics spans a bandwidth from DC to ~20 Hz.^{86,97}

Therefore the use of 5 and 10 Hz test frequencies were well-suited to assess vibrotactile detection thresholds as speech-specific somatosensory input ranges. Additionally, using vibration as a means of assessment provides researchers with a high degree of resolution, manipulation and control, especially when compared to other sensory assessment measures, such as 2-point discrimination or von Frey probe assessments.⁷⁶

Vibrotactile Detection Threshold Testing Location

The lips are comprised of multiple muscles working together to create a functional speech gesture. The use of one site may be an adequate representation of the orofacial system. In a previous study by Andreatta and Davidow,⁹⁸ these investigators tested various locations of the upper and lower lip vermilion and found no significant differences in sensitivity as a function of laterality or between the upper lip and lower lip vermilion. Furthermore, as discussed earlier and referenced in Barlow and Burton,³⁶ force measurements in the lips are measures of resultant force. In vivo isometric measurements of the labial musculature are not feasible. In fact, given the co-dependence of lip motion, the composite anatomy of muscles surrounding the oral opening and the 3-D conformational changes undertaken by the orofacial area during functional speech gestures, isometric measurements are generally uninformative and not consistent with the biomechanical goals of the region. Therefore the use of one site to measure sensation and force are appropriate given the underlying anatomy, physiology and research questions.

Non-parametric Data Analysis

Nonparametric testing methods were chosen for this study for multiple reasons. First, in pilot testing of vibrotactile detection thresholds in aging adults, the test frequency variables did not maintain a normally distributed data range and therefore do not meet one of the required assumptions for parametric methodologies. Second, as this study was designed as a preliminary exploratory study, the use of nonparametric methods offers a more conservative approach, particularly given the smaller sample sizes. Of the variables collected, including group variables, somatosensation, and force, only five demonstrated normally distributed values. These variables were: Rise time in the 1 and 2 second force testing conditions and Reaction time in the 1 and 2 second and static force testing conditions. Given that only these five variables qualified for parametric testing, they were analyzed using non-parametric tests as well, to maintain consistency throughout our data analysis; however, parametric results for these variables had the same interpretative conclusions.

Internal and External Validity Measures

Although a sample size of 20 subjects per group (n=60) may be considered small, this study demonstrated adequate power at 80% for an alpha of 0.1. With this a priori power analysis and the use of conservative non-parametric analysis for all data, we can be confident in the significant findings identified in this report. This study was intended to be exploratory and a first step

towards justifying a larger more comprehensive study to include disordered participant groups. In light of our current findings, a larger study is easily justified.

Because this study is a pre-experimental, observational study (retrospective) predictions cannot be made at this time. Additional threats to internal validity exist due to study design. For static group comparisons, threats to internal validity for this study include: selection, randomization and blinding. Participants in this study consisted of a convenience sample of adults affiliated with the University of Kentucky's College of Health Sciences. Participants were community-dwelling adults who self-reported as "healthy" adults. Although specific exclusion criteria were followed, because biomarker and cognitive assessments were not taken as part of the study protocol, health status was subjectively identified by participants. It is possible that some study participants could have an undiagnosed mild cognitive impairment (MCI) that would act to confound the results. For example, increased reaction time is also associated with early MCI. Future studies may consider the use of a cognitive screening tool such as the MOCA – Montreal Cognitive Assessment.^{247,248} Participants were not randomized to groups, however their assessment orders were randomized.

There was no blinding in this study.

External validity assesses both population validity, ability to generalize across people, and ecological validity, ability to generalize across settings. As previously described, the majority of participants was a convenience sample and may not be representative of the larger population. Continued data collection will aim to increase variation in the sample to complete sub-analyses of effects of

speech usage, sex, and smoking status. Additionally, findings may not generalize across settings as all assessment and data collection was completed by the primary investigator in the same lab location. Test and re-test values and inter-intra-rater reliability measures should be completed in future studies.

Future directions

In this study, only the 0.5 N force data from a larger set of force targets was analyzed and compared across three conditions. The study protocol in fact included the collection of force endpoints of 0.25, 1.00 and 2.00 Newtons. Analysis of findings for these endpoints will be completed to identify differences in peak force, rise time, and hold phases between our group data. Analysis of all endpoints would also determine which force endpoint(s) may be most beneficial for future testing to provide researchers with the most efficient means to assess the relationship between sensory thresholds and motor movements across age groups. Future studies could focus on those select force endpoints identified as most beneficial.

Collecting increased background information regarding participant's oral history would be beneficial. For example, in our study, individuals who were currently smoking demonstrated increased vibrotactile detection thresholds and increased hearing thresholds for pure tone testing, indicating decreased sensitivity in both areas. Future studies will need to assess for other possible factors that could alter sensitivity, including brass instrument musicians, vocal training, professions with high loads of public speaking, alcohol and drug history,

and more information regarding current medications. Although our study protocol excluded individuals with recent dental visits, information regarding oral health and dental history may provide valuable data. It is possible that any of these factors may alter somatosensory levels, providing important information for future modeling of the relationship between labial/orofacial sensory and motor elements.

Continued collection using the current protocols can be completed to increase sample size, age ranges, and match for sex. In the previous chapter it was noted that sex differences were identified during select force data analyses. Increased sample size with equal sex distribution across groups to distinguish if sex differences are important for future research and/or provide important information for clinical application. Additional protocols may be added to assess differences during assessment of non-skilled/non-speech, skilled/non-speech, and skilled speech-like tasks, as well as assessment of vibrotactile detection thresholds during skilled non-speech or speech movement tasks.

The culmination of the normative data will be used to model the bidirectional relationship of perception-action in the orofacial system for healthy adults. Future modeling may be completed using multivariate means to capture the cooperative relationship among multiple vocal tract subsystems important for speech gestures. Additionally, factor analyses can be completed to identify which variables would be most important to assess clinically as well as which variables we can eliminate from future study protocols.

After collection of normative data is complete, study protocols should be completed with select motor speech disorders to characterize changes in sensory and low-level force control characteristics occurring after neurologic events, such as stroke or traumatic brain injury. Data can then be compared to normative values to begin descriptions of dysarthria based on sensorimotor characteristics. These descriptions of dysarthria can then be compared to the early foundational work of Darley, Aronson, and Brown in the Mayo Clinic Model to update their characterizations of dysarthria to objective, measurable variables.

Finally, although not attainable in the near future, the overarching objective of this research line is to better understand sensorimotor speech disorder for the design of future assessment and treatment protocols. At present there are no clinical means available to objectively measure labial sensorimotor skills as discretely as this study. Therefore, although this research provides important implications for clinical practice, research in this area will eventually need to concentrate on the development of sensory assessments that can be utilized fully in the clinical setting.

Conclusions

Overall, the decrease in labial vibrotactile sensitivity, coupled with decreases in pure tone hearing thresholds, and decreased force accuracy and reaction times leaves our healthy aging population with a distinct disadvantage in their use of incoming sensory information to control outgoing motor outputs and accuracy; all this before any neurologic injury. This means that before our older

patients even reach our inpatient rehabilitation units, they are already demonstrating significantly decreased sensorimotor capabilities. Even though perceptually older adults do not demonstrate decreased speech skills, the sub-clinical consequences of the collective changes noted in this dissertation may crucially impact the effectiveness of any future speech therapies delivered after a neurologic event.

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Education

Bachelor of Philosophy (Interdisciplinary Studies) - May 2007

Miami University, Oxford, Ohio, USA

Focus: Self- Designed focus in Speech Pathology and Educational Psychology

Senior Thesis: Adolescent traumatic brain injury sequelae: A resource guide for the transition back to school.

Mentor: Dr. Andrew Garrison

Master of Science (Communication Sciences & Disorders) - May 2009

University of Kentucky, Lexington, Kentucky, USA

Thesis: Defining the Lived Experience of Older Adults with Voice Disorders.

Mentor: Dr. Joseph C. Stemple

Externships

- Lexington Hearing and Speech Center, Lexington, KY
 - 1/2009-4/2009
- Central Baptist Hospital, Lexington, KY
 - 9/2008-12/2008
- Jewish Hospital Shelbyville, Shelbyville, KY
 - 6/2008-8/2008
- University of Kentucky, Communication Sciences & Disorders Clinic
 - 1/2008-4/2008
 - 9/2008-12/2008
 - 6/2007-8/2007

Work Experience

- Cardinal Hill Rehabilitation Hospital, Lexington, KY
 - Clinical Doctoral Fellow, June 2009-April 2013
 - Speech-Language Pathologist, April 2013 –April 2014
- Baptist Health Lexington, Lexington, KY
 - Speech-Language Pathologist, February 2013-April 2014
- Health Therapy Services, Lexington Kentucky
 - Speech-Language Pathologist, February 2013-February 2014
- Clinical Fellowship Year (CFY) supervisor
 - Gabby Gardner, Clinical Fellowship Year supervisor
 - 5/2012- 7/2012, completion of CCC
 - Ashley Hull, Clinical Fellowship Year supervisor
 - 6/2012- 4/2013, completion of CCC
- Clinical supervisor for graduate student externship
 - Jen Larsen 8/2012-12/2012
 - Lauren Cosentino 1/2013- 4/2013

Presentations

International/National

Etter, N., Stemple, J., Thomas, L., & Howell, D. (June 2009). Defining the living experience of older adults with voice disorders. Oral presentation at the 38th Annual Symposium: Care of the Professional Voice, The Voice Foundation. Philadelphia, PA.

Etter, N. & Andreatta, R. (November 2011). Perioral Vibrotactile Detection Thresholds in Healthy Aging Adults. Poster presentation at the Annual National Convention of the American Speech-Language and Hearing Association. San Diego, CA.

Etter, N., Stemple, J., & Howell, D. (November 2011). A Three-Phase Quality of Life Scale Development for Dysphonic Aging Adults – Phase I Results. Poster presentation at the Annual National Convention of the American Speech-Language and Hearing Association. San Diego, CA.

Maddy, K., Hctor, M., & Etter, N. (September 2011). Creating an Intensive Aphasia Program Close to Home. Poster presentation at the American Medical Rehabilitation Professionals Educational Conference. Miami, FL.

Etter, N., Danzl, M., Andreatta, R., & Kitzman, P. (2013). Using Principles of Engagement to Increase Participation in Speech-Language Neurorehabilitation. Oral presentation accepted at the Annual National Convention of the American Speech-Language and Hearing Association, Chicago, IL.

Etter, N., Van Meter, E., & Andreatta, R. (2013). The Relationship Between Orofacial Vibrotactile Detection Thresholds & Force Control Capabilities in Healthy Adults. Poster presentation accepted at the Annual National Convention of the American Speech-Language and Hearing Association. Chicago, IL.

Etter, N., Van Meter, E., & Andreatta, R. (2014) Orofacial Vibrotactile Detection Thresholds and Low-level Force Control Capabilities in Healthy Young and Aging Adults. Poster presentation accepted at the Motor Speech Disorder Conference. Sarasota, FL.

State

Joshi A., Etter N., & Stemple, J. (February 2010). The Changing Voice of the Older Adult. Oral presentation at the Kentucky Speech, Language and Hearing Association (KSHA) Annual State Convention. Lexington, KY.

Etter, N. & Andreatta, R. (March 2012). Orofacial Somatosensory Perception in Healthy Aging Adults and those with Acquired Dysarthria of Speech. Poster presentation at the Annual Center for Clinical and Translational Science (CCTS). Lexington, KY.

Etter, N., Van Meter, EM., Flynt, KF., Roe, AA., & Andreatta, R. (March 2014). Orofacial Vibrotactile Detection Thresholds and Low-level Force Control Capabilities in Healthy Young and Aging Adults. Poster presentation at the Annual Center for Clinical and Translational Science (CCTS). Lexington, KY.

Local

Etter, N. (April 2011). Sensori-Motor Integration in Speech Dysarthria: Research Agenda and Preliminary Findings. Oral presentation. Cardinal Hill Rehabilitation Hospital Lunch and Learn, Lexington, KY

Danzl, M and Etter, N. (February 2012). Facilitating NeuroRehabilitation through Principles of Engagement. Oral presentation. Cardinal Hill Rehabilitation Hospital Lunch and Learn, Lexington, KY

Etter, N and Andreatta, R. (September 2011, September 2012, and September 2013) Anatomical and Functional Considerations of Speech Production. Invited Lecture. CD 277: Introduction to Communication Disorders. Lexington, KY

Etter, N. and Danzl, M. (August 2012 and August 2013). The Role of Rehabilitation in Neuroplasticity. Invited Lecture. Neuroplasticity for the SLP. Lexington, KY.

Etter, N. and Danzl, M. (March 2013). Neuroplasticity and Stroke Rehabilitation. Invited Lecture. Montgomery County Stroke Support Group, Dayton, OH.

Etter, N. and Danzl M. (May 2013). Healing of Magic: Using Magic to Engage Patients in Therapeutic Settings. Oral presentation. Cardinal Hill Rehabilitation Hospital Lunch and Learn, Lexington, KY

Etter, NM. (2014) How to assess and treat dysarthria: A review of evidence for the practicing clinician. Invited lecture. Cardinal Hill Rehabilitation Hospital. Lexington, KY.

Workshops

Etter, N. (September 2013). Using principles of Engagement to improve neuroplasticity during rehabilitation. University of Kentucky, 1st year graduate students, Lexington, KY.

Teaching Experiences

Andreatta, R. and Etter, N. (Fall 2012). CD 571: Neural Bases of Speech and Hearing. Teaching Assistant. Lexington, KY.

Peer-Reviewed Publications

Etter, NM, Van Meter, EM, & Andreatta, RD. *Labial Vibrotactile Somatosensory Perception: A pilot study in healthy aging versus young adult participants. Perceptual & Motor Skills*. Accepted for Publication.

Etter, NM, Stemple, JC, and Howell, DM. (2013). Defining the Lived Experience of Older Adults with Voice Disorders. *Journal of Voice*. 27 (1): 61-67.

Danzl, M.M., Etter, N.M., Andreatta, R.D., & Kitzman, P.H. (2012). Facilitating Neurorehabilitation through Principles of Engagement. *Journal of Allied Health*. 41 (1): 35-41.

Etter, N.M. (2010). What have we learned from physiological approaches to characterizing dysarthrias and other speech production disorders. *Perspectives: Speech Science and Orofacial Disorders*, 20(2) 25-54.

Student Mentoring Experience

- Anna-Kathryn Kline, Graduate Student Thesis Mentor, 7/2009 to 2/2010
- Sarah Groppo & Jill Branski, Undergraduate Research Assistants, 8/2009 to 11/2009
- Ashley Westerman & Taylor Ogburn, Undergraduate Research Assistants, 1/2012 to 5/2012
- Allison Roe, Undergraduate Research Assistant, 5/2013 to present
- Katelyn Flynt, Undergraduate Research Assistant, 8/2013 to present

Professional Service

- Ad hoc reviewer for International Journal of Speech-Language Pathology – 1/2013
- Reviewer for South Plains Foundation for Texas Tech University Health Sciences Center – 6/2013

Awards

- Endeavour Research Fellowship, Australian Government, Department of Education - 2014
- College of Health Sciences Robinson Graduate Award for Research Creativity - 2014
- Student Travel Award, University of Kentucky Graduate School – 2009
- Student Travel Award, University of Kentucky Graduate School – 2011
- Student Travel Award, University of Kentucky Graduate School – 2013
- College of Health Sciences Student Grant - 2009
 - Pilot funding for “Sensorimotor Profiles of Dysarthric Speakers”
- ASHA Foundation Mentor-Mentee Travel Research Award - 2010

Professional Certifications and Memberships

- ASHA Member – 2009 – Present
- Society for Neuroscience Member – 2010 – Present
- Certificate of Clinical Competence in Speech-Language Pathology – 2010 – Present
- Kentucky Licensure – 2009 – Present
- ASHA NOMS certified – April 2011
- McNeil Dysphagia Therapy Program Provided – certified April 2011