AGE-RELATED CHANGES IN ORO-FACIAL MOTOR PERFORMANCE

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The following faculty have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Arts with a major in Communication Sciences and Disorders.

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ABSTRACT

Older adults speak 20-30% slower than younger adults. A decline in articulatory speed capacity has often been suggested; however, direct investigations on speech motor performance have rarely been conducted. Therefore, this study sought to determine if jaw speed capacity is reduced in older adults.

This study included 36 female participants in four age groups: young adult, middle-aged, young-old, and very old. Each participant completed a jaw oscillation task at seven metronome paces. Similar to previous studies on upper limb speed capacity, participants were asked to tap a fixed target with their jaw at each metronome beat. The metronome pace determined the jaw movement duration and the target determined the jaw movement excursions during the experimental conditions. Jaw peak speeds, excursion, and movement durations during the jaw closing strokes were compared between the four age groups.

Study outcomes showed that jaw speed capacity was significantly lower in the youngest age group relative to all other age groups. Jaw speed capacity did not significantly differ between middle-aged, young-old, and very old adults. These findings contrasted previous reports of aging studies on limb speed capacity. Further, these findings on jaw speed capacity suggested that jaw peak speed may not be a factor that contributes to a slowed speaking rate in older adults. In the future, jaw speed capacity of male speakers needs to be investigated. Further, aging-related changes in tongue and lip speed capacities also should be determined to gain more comprehensive insights in physiologic factors that may affect speaking rates of older adults.

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CHAPTER 1

LITERATURE REVIEW

Introduction

The world's demographic distribution is changing. By the year 2050, one person in four will be over the age of 65 in the more developed regions of the world, including the United States of America (United Nations, 2002). Furthermore, the number of Americans aged 65 and older is projected to be 88.5 million in 2050, more than double its projected population of 40.2 million in 2010 (Vincent & Velkoff, 2010).

As the number of older adults increases, various aging-related diseases, such as Alzheimer's and Parkinson's disease, are expected to increase. During the early stages of these degenerative diseases, disease-related symptoms such as mild forgetfulness or slower movement speeds during walking or reaching can mimic changes seen in typical (non-disease related) aging. In order to maintain the best quality of life with advanced age, it is crucial to diagnose and treat aging-related disease as early as possible. To accomplish this, health professionals must distinguish typical aging processes from early symptoms of age-related degenerative diseases.

While investigators have made significant advances in understanding aging effects on motor performance in the limbs, few have focused on investigating aging effects in the cranial system. In 1981, Kahane asserted, "There are numerous facets of aging of the peripheral speech mechanism that must be studied and be more clearly understood (p. 39)." Unfortunately, the same can be said 30 years later. Therefore, it is worthwhile to review the current body of knowledge regarding aging and its effects on speech. In the following pages, aging effects on the respiratory, phonatory, articulatory, and nervous systems will be examined with regard to speech motor control.

Aging Effects on the Respiratory System and Speech Breathing

The respiratory system, also known as the breathing apparatus, is frequently likened to a biomechanical air pump (Hixon, Weismer, & Hoit, 2008). This pump supports speech by generating the airflow that vibrates the vocal folds. Actions of the breathing apparatus may affect the intensity and frequency of voice production, as well as prosody, the rhythm of speech.

Aging changes the structure and function of the respiratory system. For example, the breathing apparatus becomes stiffer and the respiratory muscles become weaker (Huber, 2008). These changes affect the passive and active forces at work within the breathing apparatus. One source of passive force is the natural recoil of muscles, cartilages, ligaments, and lung tissue (Hixon, Weismer, & Hoit, 2008). These recoil pressures are determined by the degree of structural elasticity. Structural elasticity also determines the amount of compliance. Compliance of the chest wall decreases with age (Frank, Mead, & Ferris, 1957). Conversely, compliance of the lungs increases with age (Turner, Mead, & Wohl, 1968). The decrease in chest wall compliance and the increase in lung compliance are thought to underlie the observed decline in natural recoil of the chest wall during expiration (Huber & Spruill, 2008).

Whereas recoil pressures are partly responsible for passive forces, respiratory muscles are solely responsible for generating the active forces within the breathing apparatus. Enright, Kronmal, Manolio, Schenker, and Hyatt (1994) demonstrated that both inspiratory and expiratory muscle strength diminish with increasing age. Because recoil (passive) and muscular (active) forces of the breathing apparatus drive phonation, the aforementioned aging effects within the respiratory system may affect how the breathing apparatus generates the necessary subglottal pressure for speech. Specifically, investigators have documented three primary effects on speech breathing in older adults as a result of changes to structure and function of the breathing apparatus: (1) Older persons tend to begin speaking at a higher lung volume, (2) they use a greater percent of their lung volume per speech breath and per syllable, and (3) they produce fewer syllables per breath than younger adults (Hoit & Hixon, 1987; Hoit, Hixon, Altman, & Morgan, 1989; Huber & Spruill, 2008; Sperry & Klich, 1992). In addition, a reduction in functional reserve volume has been reported in older adults (Huber, 2008; Tolep & Kelsen, 1993). Older adults also may fatigue more easily as speech increases in length and/or intensity (Huber, 2008).

Aging Effects on the Larynx and Phonation

Nested within the cartilaginous laryngeal framework are the vocal folds. Vocal fold vibration is the source of human sound production. This vibration is complex, and includes the approximation of the vocal folds as well as a mucosal wave within the folds. The subsequent vocal quality is perceived as a reflection of the integrity of all laryngeal structures and functions. For example, when the vibration of the vocal folds is disturbed, vocal quality can be perceived as harsh, hoarse, or breathy. Thus, changes in vocal quality are associated with changes in the anatomy or physiology of the larynx and/or respiratory system.

Aging changes the structure and function of the larynx; however, these changes may differ for men and women. In general, the cartilages that constitute the laryngeal framework become increasingly stiff and brittle (Hixon et al., 2008). Certain cartilages ossify (turn to bone) and become less flexible, while others calcify (turn to salt) and may be more susceptible to change; both processes occur earlier and are more pronounced in males than in females (Hately, Evison, & Samuel, 1965). Particular age-related changes have been noted in the cricoarytenoid joints, which limit the approximation of the vocal folds (Kahane, 1988). In addition, an age-related decrease in the number of mucous glands causes dehydration of the laryngeal mucosa leading to an increased viscosity (thickness) of the vocal folds, further affecting vocal quality (Weismer & Liss, 1991). Male vocal folds lengthen with increasing age (Hixon et al., 2008). The length of female vocal folds remains relatively stable, although postmenopausal women may gain vocal fold mass, primarily due to edema (Hixon et al., 2008; Weismer & Liss, 1991).

Cumulatively, these age-related changes may have a strong effect on voice quality. The terms *presbylarynx*, *presbylarynges*, and *presbyphonia* now are being used in speech pathology literature (Hooper & Cralidis, 2009). The prefix "presby" describes the larynx, as changed by the anatomic and physiologic effects of aging. However, there is a lack of consensus as to which perceptual and acoustic correlates are concomitant with presbyphonia. Furthermore, voice quality is particularly affected by one's health and habits (i.e., smoking), and may be more altered more by biological aging rather than chronological aging (Gorham-Rowan & Laures-Gore, 2006).

Investigators have demonstrated that listeners can distinguish between the voice production of older and younger speakers during tasks ranging from sustained phonation to conversational speech (Ptacek & Sander, 1966; Ryan & Burk, 1974; Ryan & Capadano, 1978; Shipp & Hollien, 1969). Reported perceptual differences in the voices of older adults include harshness, breathiness, and hoarseness (Gorham-Rowan & Laures-Gore, 2006; Honjo & Isshiki, 1980; Ryan & Burk, 1974). Furthermore, irregularities in the vibratory pattern of the larynx can create acoustic instability. The acoustic descriptors for these irregularities are jitter, or pitch perturbation, and shimmer, or amplitude perturbation. Although vocal instability is reported as a characteristic of older voices, measures of jitter and shimmer in older adults have yielded conflicting results (Gorham-Rowan & Laures-Gore, 2006). Fundamental frequency, perceived as a person's pitch, also differs with increasing age. Whereas men's fundamental frequency generally increases, women's decreases (Honjo & Isshiki, 1980). In addition, fundamental frequency is more varied and less stable among older adults of both sexes (Gorham-Rowan & Laures-Gore, 2006; Linville, 1988).

Aging Effects on the Supraglottic Structures and Articulation

Following laryngeal production, the voice is modified through resonation and articulation. During resonation in the pharynx, nasal cavity, and oral cavity, some frequency components are attenuated, while others are enhanced. The filtered acoustic signal also is modified through articulatory movements of the pharynx, soft palate, hard palate, mandible, teeth, tongue, lips and cheeks in the production of speech sounds.

Aging changes the placement and structure of resonators and articulators. The laryngeal framework descends and the pharynx lengthens (Hixon et al., 2008). As the intrinsic laryngeal musculature weakens and atrophies, the pharynx widens and becomes more compliant (Huang et al., 1998; Israel, 1973; Zaino & Benventano, 1977). Further, the epithelial lining of the pharynx thins, and sensory innervation and discrimination both decrease (Ferreri, 1959).

The oral cavity also changes with age. The oral epithelium becomes thinner, less elastic, and less firmly attached to adjacent bone, muscle, and connective tissue (Squier, Johnson, & Hoops, 1976). Salivary gland functioning slows, saliva becomes thicker and less acidic (Chauncey, Kapur, Feller, & Wayler, 1981), and oral mucosa become less lubricated.

In addition, the temporomandibular joint (TMJ) deteriorates during aging (Weismer & Liss, 1991). The TMJ is the point where the mandible, or lower jaw, articulates with the temporal bone on either side of the skull. Here, the head of the condyle, the more posterior of the two mandibular processes, articulates with an elliptical-shaped cavity referred to as the glenoid fossa, or mandibular fossa. In between the condyle and glenoid fossa is a cartilaginous crescent called the articular disc. Deterioration, or regressive remodeling, of the TMJ is characterized by resorption of the condyle and glenoid fossa (Kahane, 1981). This resorption reduces the height of the condyle and reestablishes the articular surface at a lower level (Kahane, 1981). Additional modifications of the TMJ include a gradual reduction in the size of the mandibular condyle, flattening of the articular surfaces of the joint, and marked thinning of the glenoid fossa with age (Blackwood, 1969). Regressive remodeling is believed to result, in part, from increasing masticatory forces on the TMJ with increasing age (Kahane, 1981). Teeth and their supporting tissues typically help to absorb masticatory forces and redirect them through the facial skeleton. However, aging-related teeth and tissue loss may inhibit absorption of these forces; subsequently, they may be directly transmitted to the TMJ (Blackwood, 1969).

The mandible (lower jaw) lengthens with age (Israel, 1973), and can become thinner due to bone resorption related to tooth loss in the alveolar region (Klein, 1980). As a result, the points of attachment for masticatory and facial muscles may be altered, which may reduce their biomechanical efficiency during speech (Kahane, 1981).

In general, the muscles of the tongue, lips, and jaw become atrophied and fibrotic with age (Weismer & Liss, 1991). Though the tongue does not decrease in size, there is a reduction in muscle mass (sarcopenia) and muscle tone (Bassler, 1987; Kahane, 1981). Furthermore, there is thinning of the surface epithelium of the tongue (Bassler, 1987; Kahane, 1981). In addition, fiber type composition changes as age increases. In skeletal muscles, it has been shown that fast-twitch type II fibers degenerate before slow-twitch type I fibers; this process partially explains aging related motor slowness in the limbs (Ketcham, Seidler, Van Gemmert, & Stelmach, 2002). However, cranial muscles differ from limb fibers in their fiber type composition. For example, jaw elevators such as the masseter have few isoform fiber types such as fast-twitch type II fibers or slow-twitch type I fibers. Rather, such muscles consist of hybrid fibers with intermediate contractile properties (type IM/IC). Aging has been shown to affect cranial muscle fibers differently than skeletal fibers. For example, in the masseter muscle there is a decrease in slow-twitch type I fibers, and an increase in fast-twitch type II fibers (Monemi, Eriksson, Kadi, Butler-Browne, & Thornell, 1999).

Because of structural changes with age, the function of the resonators and articulators also changes. Changes in pharyngeal muscles and nerves may impede older speakers' ability to alter the pharyngeal tube (Weismer & Liss, 1991). The tongue may lose mobility and range of motion (Sonies, Stone, & Shawker, 1984). The lips also may be affected. The ability to seal the lips may diminish, and reflex responses of lip muscles may be reduced in older adults (Hixon & Hoit, 2005; Wohlert, 1996b). Baum and Bodner (1983) documented that older persons were more likely to exhibit alterations in the Lip Posture Index than their younger counterparts. The Lip Posture Index comprises a subjective evaluation of circum-oral tone, the posture of the lips, presence of drooling, and the ability to purse the lips symmetrically.

Sensation within the oral cavity also declines with advancing age. Baum and Bodner (1983) reported that older adults had more difficulty discriminating form, pressure, touch, and vibration than their younger peers. Further, spatial acuity on the surface of the lips is significantly poorer in older adults than younger adults (Wohlert, 1996a; Wohlert & Smith, 1998). Such findings indicate degradation of peripheral and/or central sensory function for orofacial structures (Weismer & Liss, 1991).

The effects of aging on supraglottic structures have multiple implications for speech. Any modification of the pharyngeal-oral airway, or the oral cavity, has the potential to alter the resonance characteristics of an individual's speech. For instance, because the pharynx and oral airway increase in size, vowel formants generally shift to lower frequencies in older individuals (Hixon et al., 2008). Also, degeneration of nerves and atrophy of pharyngeal muscles may affect resonance quality, velopharyngeal closure, and vowel and consonant articulation (Weismer & Liss, 1991). Atrophy of the oro-facial muscles may reduce articulatory speed. Indeed, reports have indicated slower diadochokinetic repetitions as well as speaking rate decline in older adults (Ptacek, Sander, Maloney, & Jackson, 1966; Ramig, 1983). Finally, deterioration of sensory capabilities (e.g., hearing, proprioception, touch) can influence articulatory feedback (Kahane, 1981).

Aging Effects on the Nervous System and Speech Motor Control

Aging changes the structure and function of the nervous system. Gross anatomic changes in the central nervous system include decreased brain weight, gyral atrophy, vascular anomalies, and ventricular dilation; microscopic changes include neuroglial cell loss, myelin loss, senile plaques, and amyloid deposits (Weismer & Liss, 1991). In a longitudinal study, Raz et al. (2005) found that changes in the brain volume of aging adults varied by region, and from one individual to the next. Relative to young adults, the greatest difference in volume was observed in the caudate nucleus, cerebellum, hippocampus, and tertiary association cortices, with diminution in the hippocampal and cerebellar regions progressing most rapidly with age. Cross-sectional evidence also suggested that age-related volume reduction was pronounced in the prefrontal lobe and only minimally observed in the sensory and entorhinal cortices (Raz, 2000).

Investigators using PET scans also have identified age-related changes in neuronal activation patterns. Specifically, these scans have indicated that older adults activate more and different areas than younger adults during cognitive-linguistic tasks (Reuter-Lorenz & Park, 2010). This age-related overactivation may be a symptom of cognitive decline; an alternative view is that overactivation indicates compensatory processing (Reuter-Lorenz & Park, 2010). Although individual regions of the brain atrophy, the brain may be able to compensate functionally.

Several structures within the nervous system are of particular importance to the motoric act of speech. The primary motor cortex in the frontal lobe is the origin of the majority of descending axons to the motor neurons. Investigators have demonstrated changes in the Betz cells, the large neurons of the primary motor cortex. Findings have included irregular swellings of the somata and large dendrites, degeneration of dendrites, and fewer synapses (Adams, 1987; Scheibel, Tomiyasu, & Scheibel, 1977).

Additional structures important to the refinement of motor speech control are the cerebellum and basal ganglia. Age-related changes to the cerebellum include histological alterations, such as a loss of dendrites, and changes in neurotransmitter systems (Willott, 1999). Scientists have used animal models to study typical age-related processes and pathological processes in the basal ganglia, such as Parkinson's disease. These experiments have demonstrated declines in synthesis, receptor number, functional activity, and other aspects of the cholinergic and dopaminergic systems in typically aging rodents and rodents with pathological basal ganglia processes (Morgan & May, 1990; Rogers & Bloom, 1985). Further, in studies on healthy older humans, a reduction in dopamine content and a decrease in various markers of dopaminergic activity, including dopamine transporters, have been reported (DeKosky & Palmer, 1994; Bannon & Whitty, 1997). Researchers concluded that certain symptoms common in older adults and persons with Parkinson's disease, such as rigidity, bradykinesia (motor slowness), tremor, and problems of gait and balance, may have the same underlying nigrostriatal dysfunction, and/or altered dopaminergic systems (Hindle, 2010; Kubis et al., 2000). However, older people with Parkinson's disease will exhibit the additional symptoms of resting tremor and lack of response to dopaminergic therapy (Hindle, 2010). Furthermore, in individuals from 44 to 110 years of age, Kubis et al. (2000) found no significant loss of mesostriatal dopaminergic neurons, which are typically affected in Parkinson's disease. This study provides support for the hypothesis that Parkinson's disease is not simply a disorder of accelerated aging.

In the peripheral nervous system, aging effects have been observed in the motor units. A motor unit consists of the lower motor neuron, the axon and dendrites of the motor neuron, and its associated muscle fibers. Each muscle fiber is innervated by only one motor neuron, although each motor neuron can innervate several muscle fibers. A motor neuron contracts all muscle fibers as a unit; it cannot selectively activate muscle fibers.

The number of motor neurons decreases with age, with losses estimated as high as 1% per year beginning as early as the third decade of life and accelerating after age 60 (Willott, 1999). In skeletal muscles, fast-twitch type II motor neurons are more vulnerable to attrition (Willott, 1999). Interestingly, the degree of motor neuron loss may vary by body area. In research conducted on mice, Sturrock (1996) demonstrated a significant loss of neurons in the facial cranial nerve (CN VII), but not the trigeminal cranial nerve (CN V). Because of the slow motor neuron degeneration, motor units undergo change with increasing age. Motor unit remodeling refers to the natural cycle of degeneration, axonal sprouting, and re-innervation of the muscle fiber. In older adults, re-innervation continues to occur, although there may be diminished sprouting (Kanda & Hashizume, 1991).

Anatomic and physiologic differences in the aging nervous system may explain several changes in older people's speech and language. For instance, evidence indicates deterioration of memory and cognitive-linguistic functions, such as impaired lexical access and retrieval (Burke

& Shafto, 2004; Burke, Mackay, Worthley, & Wade, 1991). Furthermore, studies have documented reduced speaking rates of older adults (Amerman & Parnell, 1992; Smith, Wasowicz, & Preston, 1987; Ramig, 1983).

Research Motivation

All major components of the peripheral speech mechanism and the nervous system are affected by aging. However, as Weismer and Liss noted in 1991, "To date, no extant theories of speech production have addressed aging effects, probably because of the absence of relevant data, especially on supraglottal articulatory function in the aged" (p. 221). Although the slowing of cognitive, linguistic, and motor processes remains a hallmark of aging, the precise contribution of each of these domains to the changes in speech production remains unexplained.

One particularly interesting aspect of age-related change in speech production is the decline in speaking rate. Studies have shown that older adults speak slower during conversational speech, paragraph reading, and syllable repetition tasks (Amerman & Parnell, 1992; Duchin & Mysak, 1987; Goozee, Stephenson, Murdoch, Darnell, & Lapointe, 2005; Ramig, 1983; Ryan, 1972; Smith et al., 1987). Slower speaking rates may be evidence of reduced articulatory movement speeds. However, because speaking rate is a product of both motor performance and high-level cognitive function, other factors also may contribute to this decline. For example, older adults' slower speaking rate may be at least partially determined by reduced processing speed (e.g., slower lexical access and retrieval; Burke & Shafto, 2004; Burke et al., 1991). In addition, diminished sensory feedback and changes to the oral environment (dentures; decreased saliva) may cause older adults to articulate more carefully (Amerman & Parnell, 1992).

A direct assessment of speed capacity in older adults would be an important first step to delineate the underlying factors of slowed speech in older adults. To date, direct studies on speech movements of older speakers are rare. Goozee et al. (2005) studied tongue and lip movements of younger and older speakers during syllable repetitions at fast and slow rates. They compared the displacements, speeds, and movement durations between the two age groups and found that during fast speech older speakers produced larger excursions with their tongues and lips than younger speakers. Consequently, syllable repetitions of older speakers were slower than those of younger speakers.

One limitation of the study by Goozee et al. (2005) was that speakers self-selected their slow and fast syllable repetition rates. It remains unknown whether older adults' relatively slow syllable repetitions during the fast rates were due to a physiologic decline of motor performance, or an articulatory strategy to increase speech precision in the presence of declining sensory feedback (Amerman & Parnell, 1992). Thus, to address whether the ability to complete fast syllable repetitions declines with age, repetition rates should not be self-selected but provided, as in metronome paces.

The present study aimed to identify factors that contribute to speaking rate decline in older adults. Specifically, this study focused on jaw speed capacity as a potential factor of slowed speaking rates. Currently, little is known about aging effects on jaw speed capacity as age increases. In the limbs, aging-related motor slowness has been well documented (i.e., Cooke, Brown, & Cunningham, 1989; Ketcham et al., 2002; Walker, Philbin, & Fisk, 1997; Welford, 1977). For example, investigators have shown that older adults walk and reach with slower movement speeds than younger adults (Haaland, Harrington, & Grice, 1993; Himann, Cunningham, Rechnitzer & Paterson, 1988). Research on cranial muscles is less extensive than research on the skeletal muscles, mostly because technology to assess speech movements has been developed only recently.

To achieve fast speech, speakers commonly reduce articulatory displacements while maintaining articulatory speed (Westbury & Dembowski, 1993; Goozee, Lapointe, & Murdoch, 2003; Kuehn & Moll, 1976, Mefferd & Green, 2010). This strategy of displacement reductions is thought to be an attempt to economize articulatory effort and accomplish “smooth speech” (Ballard, Robin, Woodworth, & Zimba, 2001; Lindblom, 1990; Perkell et al., 1997). Thus, to assess a speaker’s jaw speed capacity, articulatory displacement must be experimentally controlled during metronome-paced syllable repetitions.

A fixed-target task allows researchers to experimentally control displacement. Such fixed-target tasks commonly have been used to assess upper limb speed, but rarely have been used in the bulbar system. Mefferd, Green, and Pattee (2012) used a fixed-target task to detect minimal changes in motor performance at the early stages of Amyotrophic Lateral Sclerosis (ALS, also known as Lou Gehrig’s disease). Results demonstrated that the fixed-target task was highly sensitive to small changes in jaw and lower lip speeds.

Therefore, the present study will use a metronome-paced fixed-target task approach to test the following research question: Can older adults move the jaw as fast as younger adults? Because of the anatomic and physiologic differences between skeletal and cranial muscles and the differential effect of aging on these muscles, it is hypothesized that jaw speed capacity will not be reduced in older adults. A non-significant finding of age would suggest that slowed speech in older adults is not due to a physiologic speed constraint.

CHAPTER 2

METHODOLOGY

Participants

A total of 36 participants completed this study. Participants were divided into the following age groups: *young adults* (n = 10; Mean age = 23.8 years; Range = 22-27 years), *middle-aged adults* (n = 9; Mean age = 50.5 years; Range = 45-55 years), *young-old adults* (n = 10; Mean age = 68.5 years; Range = 65-74 years), and *very old adults* (n = 7; Mean age = 90.3 years; Range = 87-95 years). To minimize within-group variability, only females were examined in this study. Inclusion criteria are specified in Table 1.

Table 1.

Participant Inclusion Characteristics

Eligibility
1. English as the primary language
2. No diagnosis of a neurological condition
3. No history of speech or language therapy
4. Appropriate hearing*
5. Well-fitting dentures or partials (if applicable)
6. No missing front teeth

*pass a pure tone hearing test at 35dB at 0.5kHz, 1kHz, 2kHz, 3kHz, and 4kHz for adults without a hearing aid or report an annual check-up at an audiology clinic for adults who wear hearing aids

Experimental Task

To begin, the participants were fitted with a head gear device that had vertical rods attached on the right and left sides. A small horizontal bar connected the ends of the rods. A strike target, mounted on a lever arm, was attached to the horizontal bar. The lever arm was placed underneath the jaw (see Figure 1).

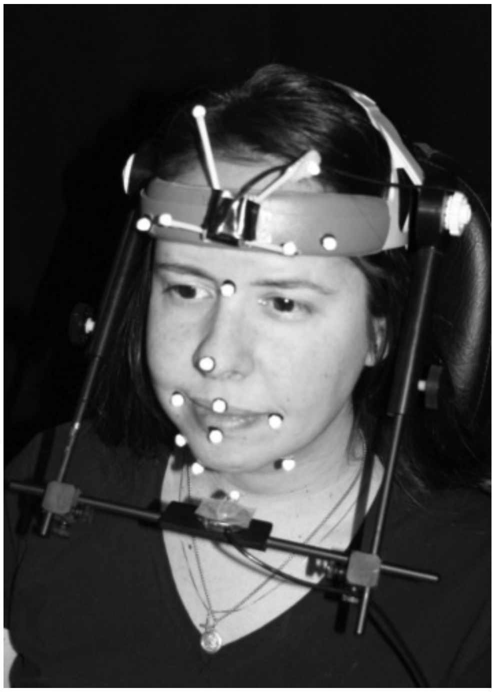

Figure 1. Experimental set-up

Next, participants were asked to repeat the syllable “fuh” and tap their jaw against the strike target with each beat of a metronome. The syllable "fuh" was chosen because the upper central incisors provide a hard upper boundary for jaw movements during oral closure. The metronome was a free software program (“weird metronome” www.pinkandaint.com/weirdmet.shtml). Metronome paces were provided via desktop loudspeakers at a comfortable hearing level. The distance between the jaw and strike target was determined by each participant’s jaw displacement during the slowest metronome pace (1.7 Hz). The distance to the strike target was not changed further during the experiment.

All participants started with the slowest metronome pace (1.7 Hz). Participants were instructed to listen to the metronome and start with syllable repetitions when they felt that they were familiar with the pace. The metronome was increased in a stepwise fashion six times

(2.5Hz, 3.3 Hz, 4.2Hz, 5Hz, 5.8Hz) to the fastest pace (6.7Hz). This range of metronome paces was selected based on previous studies (i.e., Hertrich & Ackermann, 2000; Kuehn & Moll, 1976; Perkell & Zandipour, 2002). Each pace was recorded for approximately 15 seconds. This equaled approximately 20 repetitions at the slowest pace; each subsequent pace contained substantially more repetitions. Participants were encouraged to rest between paces if needed. None of the participants requested rest periods. During data collection, marker tracking was monitored on a computer screen. Simultaneously, task performance was monitored, and the participant was encouraged to reach the strike target during the fast metronome paces.

Data Collection

Jaw movements were captured using a 3-dimensional optical motion capture system (Motion Analysis, Ltd.) consisting of four infrared Eagle cameras with a resolution of 1.3 million pixels at 1280 x 1024 full resolution. The movements were sampled at a frequency of 120 Hz. Four small (4mm) reflective spheres were placed on the participant's lips and two reflective markers were placed approximately 3cm away from the midline on the right and left side of the jaw. Eight reflective reference markers were placed on the tip of the nose, nose bridge, and forehead as reference markers (see Figure 1). Only the right jaw marker and the right bottom head reference marker were analyzed for the purpose of this study. The right jaw marker was used because previous analyses have shown that markers located off-midline, away from the fleshy part of the chin, are less affected by skin and tissue movements during speech compared to the marker placed at the center of the chin (Green, Wilson, Wang, & Moore, 2007). A miniature microphone was mounted on the head strap of the fixed-target device to record the audio signal (see Figure 1). The audio sampling rate was 44.1 kHz.

Data Analysis

The 3D Euclidean distance signal between the right jaw marker and right bottom head reference marker was used to calculate the peak speed, maximum displacement, and movement duration of the jaw during the closing stroke of each syllable repetition. The maximum and minimum displacements of the lower lip indicated the beginning and ending of each "fuh" syllable, respectively.

It was theorized that participants may have difficulty refraining from using a displacement reduction strategy, especially during the fastest metronome paces. Therefore, at each pace, the 10 oscillations that contained the largest articulatory displacements were selected for analysis. This approach was chosen to capture participants' best efforts to reach the target (Figure 2).

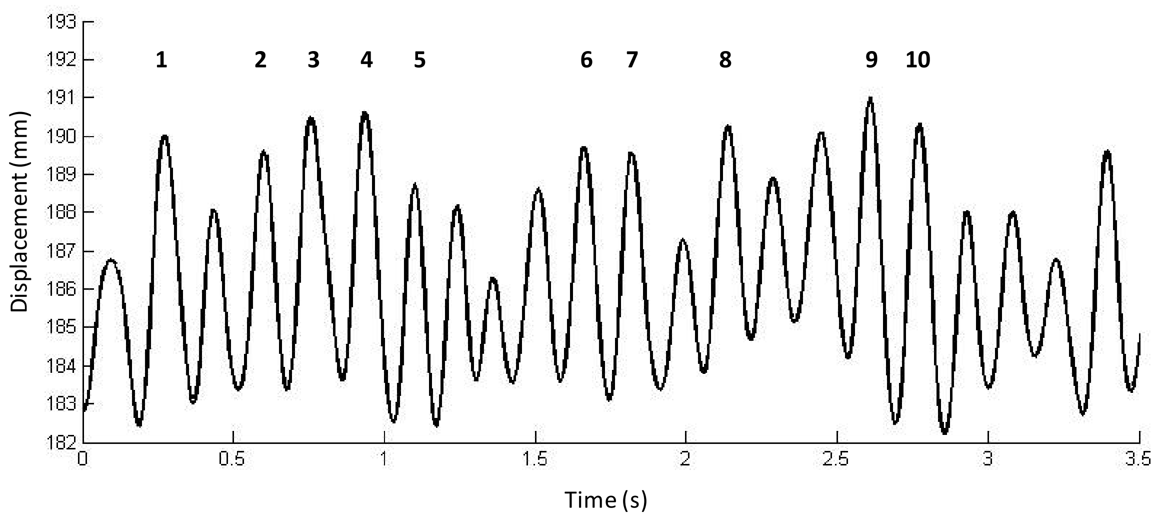

Figure 2. Example of jaw movements during very fast (6.7Hz) metronome pace

Statistical design

For statistical analysis, only four [*slow* (1.7Hz), *moderate* (3.3), *fast* (5Hz), *very fast* (6.7)] of seven metronome paces were compared statistically to reduce the number of post-hoc comparisons within each age group. To test the hypothesis that jaw speed capacity will not be reduced in older adults, mean jaw peak speeds were submitted to a repeated measures ANOVA as the within-subjects variable, and age groups were submitted as the between-subjects variable. Further, to verify that participants maintained the same displacements across metronome paces, and to test for potential group differences in displacement, maximum jaw displacements were submitted to a repeated measures ANOVA with maximum jaw displacement as the within-subjects variable, and age group as the between-subjects variable. Additionally, to verify that participants shortened movement duration according to metronome pace, movement durations were submitted to a repeated measures ANOVA as the within-subjects variable, and age group as the between-subjects variable.

Post-hoc comparisons were completed using Tukey's HSD (honest significant difference) procedure with a set critical alpha level of $p = .05$. The HSD approach was chosen to correct for an alpha inflation due to multiple pairwise comparisons. An outlier analysis was completed on all dependent variables before submitting the data to statistical analysis. An outlier was defined as a measured value being above or below 1.5 x the spread of the 25^{th} to 75^{th} percentile based on Tukey's hinges (Wilcox, 2005). Identified outliers were then winsorized by replacing the extreme values with the corresponding lowest or highest values calculated for the distribution.

CHAPTER 3

RESULTS

Task Performance – Durational Changes

An outlier analysis was conducted and yielded two extreme high values for the young age group, three extreme high values for the middle-aged group, four extreme high values for the young old age group, and two extreme high values for the very old group. These values were replaced by the calculated upper bound values of each group's distribution. Figure 3 shows group means and standard errors for each age group as a function of metronome pace. Mean movement durations were submitted to a mixed-group 4x4 factorial ANOVA. Results yielded significant main effects of pace on movement duration, $F(3,96) = 632.829$, $p < .001$, as well as a significant pace x age interaction, $F(9,96) = 3.03$, $p = .003$.

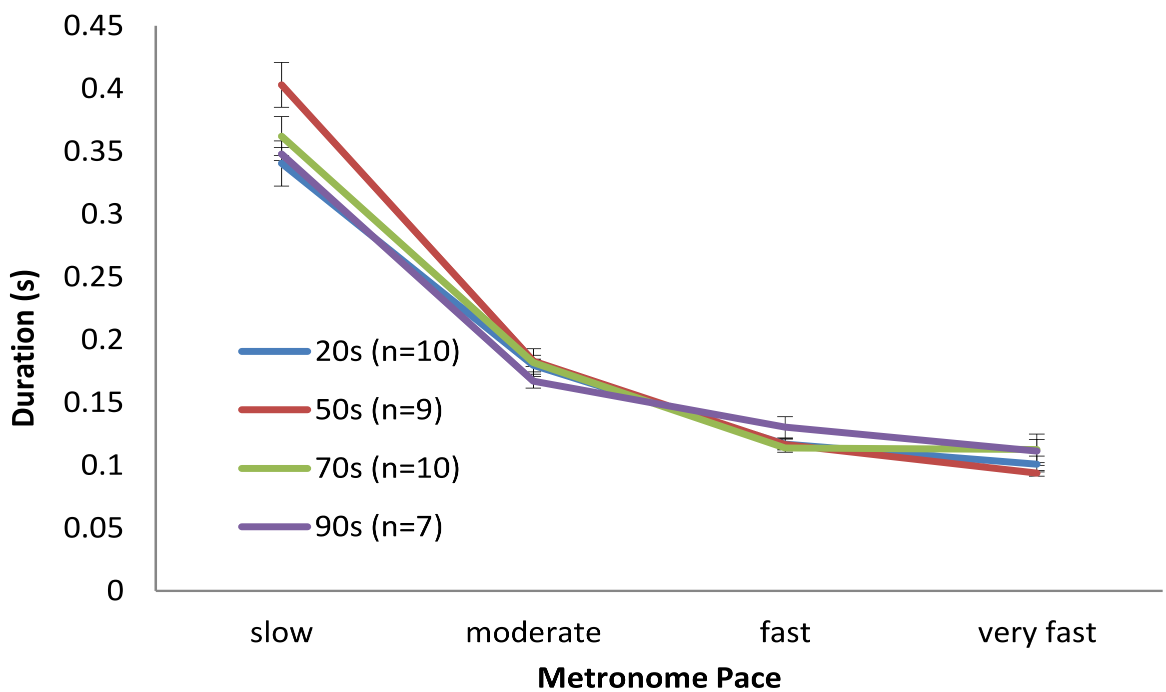

Figure 3. Mean movement durations for each age group as a function of metronome pace

Simple between-group and within-group comparisons were completed using the Tukey's HSD procedure with a set critical alpha level of $p = .05$. Table 2 displays significant between-group comparisons for movements and their corresponding metronome paces. In general, significant age group differences in movement duration were observed only during the slow metronome pace. Specifically, participants in the middle-aged group averaged significantly longer movement durations than participants of all other age groups ($p < .05$).

Table 2

Significant Between-Group Comparisons for Movement Durations

Comparison	Metronome Pace	Mean Difference (mm/s)
Middle-aged vs. young	slow	0.063
Middle-aged vs. young old	slow	0.041
Middle-aged vs. very old	slow	0.055

Simple comparisons of metronome pace effects on movement durations within each age group were only completed for adjacent metronome paces. Significant changes in movement durations were found between slow and moderate paces as well as moderate to fast paces in young adults, middle-aged adults, and young old adults ($p < .05$). In very old adults, movement durations changed significantly only between the slow and moderate paces ($p < .05$).

Task Performance – Jaw Displacements

An outlier analysis was conducted and yielded three extreme high and two extreme low values for the middle-aged group and one extreme high value for the young old group. These values were replaced by the calculated upper and lower bound values of each group's distribution. Figure 4 shows group means and standard errors of maximum jaw displacement for each age group as a function of metronome pace.

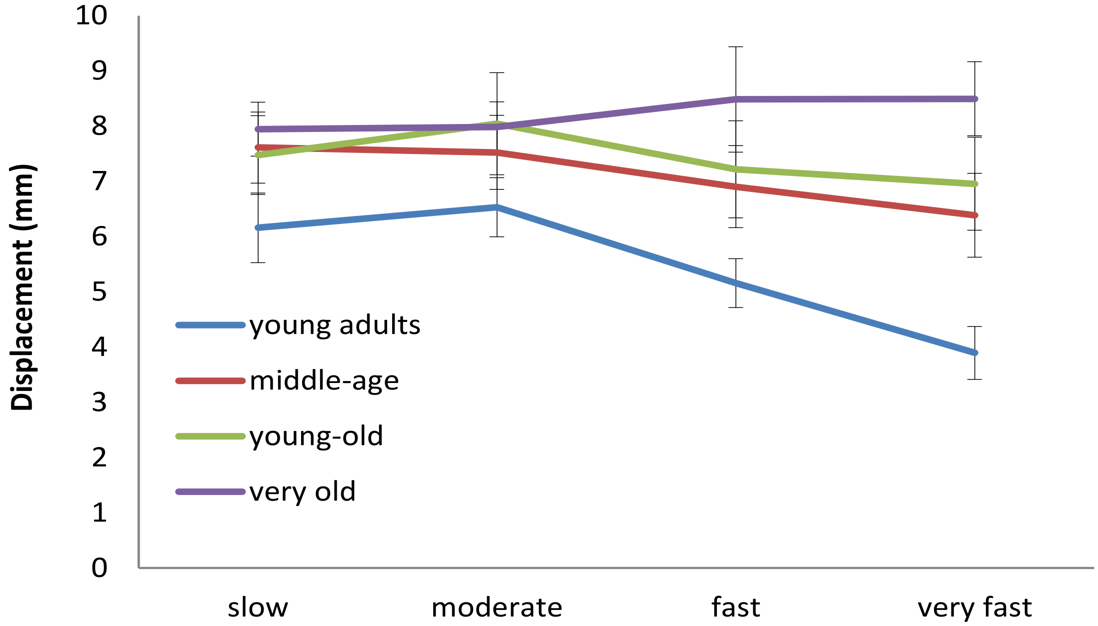

Figure 4. Mean jaw displacements for each age group as a function of metronome pace

To determine if participants completed the fixed-target task correctly by maintaining consistent jaw displacements across metronome paces, each participant's mean of maximum jaw displacements for each metronome pace was submitted to a mixed-group 4x4 factorial ANOVA. Results yielded significant main effects of pace, $F(3,96) = 7.992$, $p < .001$, and age, $F(3,32) = 3.270$, $p = .034$, on jaw displacements as well as a significant pace x age interaction, $F(9,96) = 3.141$, $p = .002$.

Simple between-group and within-group comparisons were completed using the Tukey's HSD procedure with a set critical alpha level of $p = .05$. Table 3 displays significant between-group comparisons for jaw displacements and their corresponding metronome paces. In general, jaw displacements of young adults were significantly smaller than those of participants of all other age groups during most metronome paces ($p < .05$). Interestingly, middle-aged adults and young old adults also had significantly smaller jaw displacements than very old adults during the fast and very fast metronome paces ($p < .05$).

Table 3

Significant Between-Group Comparisons for Jaw Displacements

Comparison	Metronome Pace	Mean Difference (mm)
Young vs. middle-aged	slow	-1.45
	fast	-1.75
	very fast	-2.49
Young vs. young old	slow	-1.32
	moderate	-1.51
	fast	-2.06
	very fast	-3.06
Young vs. very old	slow	-1.78
	moderate	-1.45
	fast	-3.32
	very fast	-4.60
Middle-aged vs. very old	fast	-1.58
	very fast	-2.11
Young old vs. very old	fast	-1.26
	very fast	-1.54

Simple comparisons of metronome pace effects on maximum jaw displacements within each age group were only completed for adjacent metronome paces. Significant changes in jaw displacements were only found in young adults for comparisons between the moderate and fast paces as well as the fast and very fast paces ($p < .05$).

Jaw Peak Speed

An outlier analysis identified two extreme high values in the young adult group and one extreme high value in the young old group. These values were replaced by the calculated upper bound values of each group's distribution. Figure 5 shows the group means and standard errors of jaw peak speeds for each age group as a function of metronome pace. To determine the pace and age effects on jaw peak speed, a 4x4 mixed-group factorial ANOVA was completed. There were significant main effects for pace, $F(3,96) = 69.226$, $p < .001$, and age group, $F(3,32) = 3.065$, $p = .042$. A significant pace x age group interaction was also found, $F(9,96) = 3.163$, $p = .002$.

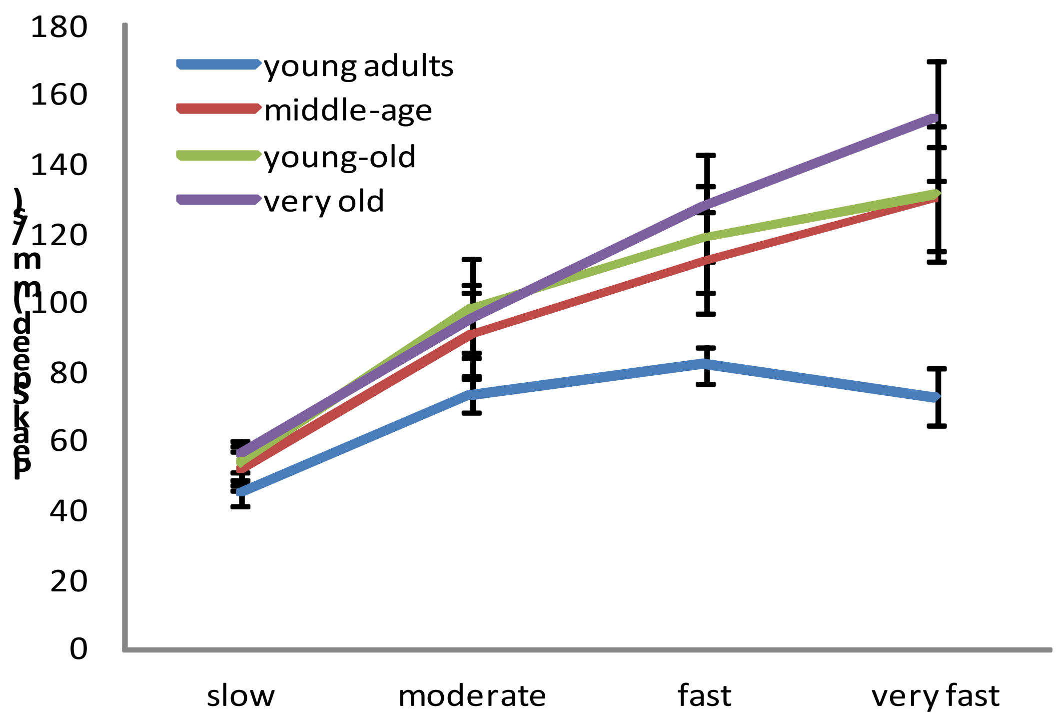

Figure 5. Mean jaw peak speeds for each age group as a function of metronome pace

Simple between-group and within-group comparisons were completed using the Tukey's HSD procedure with a set critical alpha level of $p = .05$. Significant between-group comparisons and corresponding metronome paces are displayed in Table 4. In general, younger adults were significantly slower than all other age groups during the fast and very fast metronome paces ($p < .05$).

Simple comparisons of metronome pace effects on jaw peak speed within each age group were only completed for adjacent metronome paces. Within each age group, jaw peak speed increased significantly only from the slow to the moderate metronome pace (p < .05). Further, very old adults also showed a significant increase in jaw peak speed from the moderate to the fast metronome pace ($p < .05$).

Table 4

Significant Between-Group Comparisons for Jaw Peak Speeds

Comparison	Metronome Pace	Mean Difference (mm/s)
Young vs. middle aged	fast	-29.84
	very fast	-57.12
Young vs. young old	fast	-36.17
	very fast	-58.69
Young vs. very old	fast	-45.26
	very fast	-80.14

CHAPTER 4

DISCUSSION

The aim of this study was to determine if older adults have a reduced jaw speed capacity when compared to younger adults. A total of 36 participants belonging to four different age groups (young, middle-aged, young old, very old) completed a metronome paced fixed-target task that elicited increases in jaw speed while maintaining consistent jaw displacements. It was hypothesized that jaw speed capacity would not decline with age based on reported motor unit remodeling of slow-twitch to fast-twitch muscle fibers in aging jaw muscles. Results showed significantly greater jaw speed capacities in the oldest age group relative to young adults. Jaw speed capacity did not significantly differ between middle-aged, young old, and very old adults.

The lack of aging-related motor slowness in the jaw contrasts with reports of aging studies on the limbs, which have found reduced movement speeds in older adults during reaching, grasping, and walking (Bellgrove, Phillips, Bradshaw & Gallucci, 1998; Ketcham et al., 2002; Welford, 1977, 1984). This discrepancy may be explained by differences in the underlying neuromuscular changes with age. For example, in the limbs, the number and size of fast-twitch type II fibers decrease with age, whereas in the jaw an increase in fast-twitch fibers has been found (Monemi et al., 1998, 1999).

It was found also that, in general, jaw displacements increased with advanced age. Specifically, significantly larger jaw displacements were observed in the very old age group relative to all other adults during the fast and very fast paces. Large displacements have been previously reported for speakers with motor speech impairments, such as persons with traumatic brain injuries (Bartle, Goozee, Scott, Murdoch, & Kuruvilla, 2006; Kuruvilla, Murdoch & Goozee, 2007) or ALS (Mefferd et al., 2012) and have been discussed as indicators of deficient fine force control. Thus, these findings suggest that as people get older, their fine force control of jaw movements may deteriorate.

Finally, it was found that movement durations were not significantly different between age groups. Paces were pre-determined by the researchers, rather than self-selected by the participants. Goozee et al. (2005) demonstrated that syllable repetition rates were slower for older adults compared to younger adults. This experiment establishes that this is due to preference, not speed limitations.

Because movement duration did not differ between younger and older adults, but jaw excursions differed significantly between these age groups, it can be inferred that these participants adequately adjusted their jaw speed with their jaw displacements. For example, older adults moved further, but with greater speed, whereas younger adults made smaller jaw excursions at lower speeds. The scaling of displacement and speed is consistent with previous studies that demonstrated a strong association between speed and displacement (Ostry, Keller, & Parush, 1983) unless the motor system is compromised by a physiologic speed constraint (i.e., ALS, Mefferd et al., 2012).

Displacement reductions in young adults were observed, despite the use of a fixed-target task designed to maintain consistent displacements. One explanation for this may be that younger adults are unable to overcome their bias toward displacement reductions to control movement durations. Another explanation, perhaps related to the first argument, is that younger adults control durations by changing their muscle stiffness. As muscle stiffness increases, movement duration will decrease, because movement excursion decreases as well. In that case, younger adults may not be able to refrain from reducing their displacements to match the very fast metronome paces. In older adults, however, the ability to increase muscle stiffness may be diminished and these adults may not be able to control excursions as well as younger adults. This may explain the preference for slower speaking rates often observed with increases in age.

Traditionally, studies have compared young college students with older adults. One implication of the current study, however, is that motor control and motor performance continue to change across the lifespan. Based on findings in this study, it is crucial to include a middle-aged group to fully understand how performance changes with advanced age.

In the future, jaw speed capacity also should be studied in males to determine potential interactions between sex and aging effects on orofacial motor performance. Furthermore, longitudinal research studies during the early and late adult years may further shed light on physiological changes that may have an effect on speech motor control. In addition, future studies also should investigate the effects of physical fitness on jaw speed capacity. Especially in older adults, there is increased heterogeneity amongst participants due to variability in health status. Therefore, measures, such as vital capacity, percent body fat, blood pressure, and blood oxygen levels may provide a means to quantify physical fitness and allow comparisons between participants on the low and high ends of the physical fitness continuum. Finally, future studies are needed to evaluate lip and tongue speed capacities during fixed-target tasks to see if similar patterns of aging effects on speed capacity emerge.

In summary, no evidence of aging-related motor slowness in the jaw was found. This has important clinical implications because previous studies have shown that jaw speed capacity declines in persons with motoneuron degeneration due to ALS (Mefferd, Green, & Pattee, 2012). The differences between persons who are healthy and those with diseases point to the sensitivity of the fixed-target task to detect underlying neuromuscular pathologies. In the future, this fixed-target task may help to identify preclinical conditions in persons with progressive neurological diseases, such as ALS and Parkinson's disease, and expedite diagnosis and effective treatment.

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