QUANTIFYING SPEECH AND VOICE IMPAIRMENT IN INDIVIDUALS WITH A HISTORY OF SPORTS-RELATED CONCUSSION

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ABSTRACT

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Researchers suggest that the following areas are affected by both acute and non-acute Sports Related Concussion (SRC): neurometabolic function, balance, vestibular/ocular function, cognition, and motor movement of the limbs. However, significant gaps in our knowledge still exist regarding the potential speech production effects of concussion. Additionally, the effect of concussion in complex speech contexts has gone largely unreported in published research. This dissertation set out to determine how the speech production of individuals with a history of concussion is affected. It also examined speech production between these groups during increasingly complex contexts: single syllable alternating motion rate (AMR) diadochokinetic (DDK) tasks, real and non-word multisyllabic sequential motion rate (SMR) DDK's, reading passages (Rainbow and Caterpillar), and spontaneous speech. Data was gathered from 30 individuals with a history of concussion and 30 matched controls with no history of concussion to understand potential speech differences. The primary purpose of this study was to investigate potential speech timing and acoustic differences between individuals with a history of concussion (one or more previous concussions) measured during speech tasks. Speech timing and acoustic differences have not yet been reported between those in the with a history of concussion and individuals with no history of concussion. The secondary purpose of the current study was to explore the potential perceived speech production differences of those with a history of concussion and those without a history of concussion to fill the research gaps that currently exist. Limited research is available on the perceived speech effects of concussion history. While previous research addresses speech intelligibility several unanswered questions remained, which are addressed in this dissertation. Results revealed a significant interaction effect of concussion status and speech timing analysis method where both objective ($p<.001$) subjective ($p=.041$) timing analysis were significantly different between participants with a history of concussion and those with no history of concussion. This and future work stemming from this dissertation will focus on standardizing measures for the potential use of identifying individuals at risk of long-term functional damage and those with acute speech production issues.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

KEY TO ABREVIATIONS

AMR – Alternating Motor Rates

ANCOVA – Analysis of Covariance

CPPs – Smoothed Cepstral Peak Prominence.

f_0 – Fundamental Frequency

mTBI – Mild Traumatic Brain Injury

SIS – Second Impact Syndrome

SMR – Sequential Motion Rate

SLP – Speech Language Pathologist

SRC – Sports Related Concussion

CHAPTER 1: Introduction

The Evolving Definition of Concussion

For several years, the terms mild Traumatic Brain Injury (mTBI) and concussion have been used interchangeably. However, some researchers have begun to distinguish the two(Laker, 2011; McCrory et al., 2017). Therefore, for the purposes of this dissertation, mTBI will encompass all non-sport related head injuries and concussion or Sports Related Concussion (SRC) will refer only to those sports-related head injuries.

Defining concussion has been extremely difficult due to competing terminology (mTBI vs concussion), as well as the lack of a reliable biomarker for concussion. Additionally, reported signs and symptoms of concussion have been extremely variable. This variability has been noted in the onset, duration, and severity of concussive symptoms. Further, most definitions of concussion and much of the diagnostic criteria rely heavily on patients self-reported symptoms, which are considerably varied and can be unreliable (Gabbe, Finch, Bennell, & Wajswelner, 2003; Shrier et al., 2009; Valuri, Stevenson, Finch, Hamer, & Elliott, 2005). In order to bring some consensus to the identification and treatment of concussion as it relates to those that occur during sports play, several of the world’s leading clinical professionals and researchers in the field of head injury established the following definition of SRC:

> *SRC may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head. SRC typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously. However, in some cases, signs and symptoms evolve over a number of minutes to hours. SRC may result in neuropathological changes, but the acute clinical signs and symptoms largely reflect a functional disturbance rather than*

> *a structural injury and, as such, no abnormality is seen on standard structural neuroimaging studies.*
> *SRC results in a range of clinical signs and symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive features typically follows a sequential course. However, in some cases symptoms may be prolonged (McCrory et al., 2017, pg. 839).*

The remainder of this chapter will discuss the prevalence of concussion, the dangers of playing sports with a concussion and briefly introduce areas where extensive amounts of research have generated much of what we know concerning the physiologic effects of concussion. These areas will be discussed in further detail in Chapter 2. This chapter will conclude by addressing the significant gaps in research regarding the speech of individuals with a history of concussion which this study attempts to fill.

Prevalence

The number of reported SRC's has increased to an epidemic level over the last decade, with some research estimating 19.5% of the adolescent population in the US having sustained at least one diagnosed concussion in their lifetimes (Veliz, McCabe, Eckner, & Schulenberg, 2017). As the prevalence of these reported concussions continues to rise, there has been an increase in concussion research within a number of medical and health related fields (Gilchrist, Thomas, Wald, & Langlois, 2007). Nevertheless, there is a need for more efficient and effective ways to assess and identify concussions (Harmon et al., 2019; Noble & Hesdorffer, 2013), including the determination of biomarkers of concussions. Recent research suggests that concussions and mTBI may negatively affect the cognitive abilities and the quality of life of over 3 million people nationwide (Gilchrist et al., 2007; Langlois, Rutland-Brown, &

Wald, 2010). With such a vast number being affected by concussions in some way, research regarding the potential speech effects of concussion is warranted.

Dangers of Playing Sports with a Concussion

Several notable phenomena have been investigated for their potential relationship to concussions. Two of these are second impact syndrome (SIS) (Saunders & Harbaugh, 1984) and chronic traumatic encephalopathy (CTE) (Baugh et al., 2012; A. C. McKee et al., 2013; Omalu et al., 2005). Research has concluded that the cause of SIS is swelling of vasculature within the brain immediately following multiple concussions within a short time period, causing pressure on or displacement of the brainstem, and subsequent shutdown of several important body systems including consciousness, respiration, and cardiac function (Cantu, 1998). After sustaining a concussion, the brain remains in a vulnerable state where further, more devastating and potentially long lasting damage may be done (Laurer et al., 2001; Maugans, Farley, Altaye, Leach, & Cecil, 2012; Stiefel, Tomita, & Marmarou, 2005; Cantu, 1998; Dessy, Rasouli, & Choudhri, 2015). This period of increased sensitivity to damage is likely caused by the metabolic cascade following head injury The effects of this cascade may last for 2-4 weeks after initial injury (Laurer et al., 2001; Maugans et al., 2012; Stiefel et al., 2005).

Another potentially devastating result of concussions is CTE, a degeneration of and buildup of tau proteins in the brain leading to a number of cognitive and physical signs and symptoms similar to those found in Alzheimer’s disease (Baugh et al., 2012; McKee et al., 2013; Omalu et al., 2005). Thus, researchers suspect CTE is a result of repeated concussive and sub-concussive injuries sustained over several months or years, particularly at times when the brain is in a vulnerable metabolic state. Due to the potential short and long-term phenomena surrounding concussion, recent research in the field has focused heavily on finding a reliable biomarker for SRC.

What We Know About Concussion

During the span of the last several years, several non-invasive techniques to evaluate head injury have been the focus of research. One area of research where significant contributions have been made is regarding the neurometabolic effects of head injury. To evaluate more accurately some of the metabolic disturbances caused by the neural cascade triggered after a head injury, several neuroimaging techniques have been employed. The following methods have been used to detect the structural and functional effects of mTBI: Computed tomography scanning (CT or CAT) magnetic resonance angiography (MRA), positron emission tomography (PET), diffusion tensor imaging (DTI) and functional magnetic resonance imaging (fMRI) (Ghajari, Hellyer, & Sharp, 2017; Wu et al., 2017). However, with relation to concussions, these neuroimaging techniques have been largely inconclusive as there are often no structural abnormalities noted in the brains of concussed individuals, only extremely variable functional deficits (McCrory et al., 2017). Current guidelines in concussion assessment suggest that the above mentioned neuroimaging techniques be used after one or more of the following specific criteria is met: 1) 30 seconds or more of loss of consciousness, 2) altered mental status, 3) motor issues (i.e. paralysis or weakness in a focal region indicative of central nervous system impairment), 4) seizures, and 5) worsening of any of the above symptoms over time (McCrory et al., 2017, 2013). Once a head injury meets these criteria, however, it is more likely to be a serious form of TBI rather than a concussion. Furthermore, signs and symptoms of a head injury that meet the above criteria are unlikely to demonstrate themselves only functionally and will likely have caused structural damage to the brain. For this reason, the above guidelines, while helpful in some cases, are generally not sensitive enough to detect the functional effects of concussion and thus, are inadequate (Jeter et al., 2012).

Subsequently, several physiologic effects of concussion have been investigated to provide a more reliable means of identifying individuals who have sustained a concussion. One area which is frequently assessed and is commonly negatively impacted by concussions (especially soon after injury) is balance (Howell, Osternig, & Chou, 2018; Murray, Ambati, Contreras, Salvatore, & Reed-Jones, 2014; Riemann & Guskiewicz, 2000). Often, those who have sustained a concussion report and demonstrate postural instability which can at times be severe especially during the acute stage of concussive events. Balance will be discussed in detail, including limitations in its ability to assess individuals with SRC.

Recently, vestibular and ocular assessments have been employed as a multifaceted means of both detecting concussion and tracking functional improvement over time following injury. Mucha and colleagues' recent work in this area has shown that during several different motion sensitivity, ocular reflex, saccade, and distance convergence tests, youth who have recently suffered a concussion (within about 6 days) perform predictably lower on these tasks compared to controls (Mucha et al., 2014). However, this work has been limited in its long-term application and has rarely been applied months after sustaining a concussion.

Additionally, cognitive testing is among the more popular tools currently used in concussion assessment. In many cases, even mild concussions can cause cognitive impairment in several areas such as attention, executive function, memory, and visual acuity. These effects may last for several days and in many cases weeks (Bleiberg et al., 2004; Wasserman, Kerr, Zuckerman, & Covassin, 2016). However, it has been suggested that these cognitive tests (e.g., response time, processing speed, memory, and attention) along with many of the balance tests detailed can be subverted by athletes during prescreening. While not extremely common, this is done at times to feign improvement or no change at re-screening for a head injury (Alsalaheen, Stockdale, Pechumer, & Broglio, 2016). While individuals who engage in this deceptive activity are generally looking to return to sports and physical activity, evidence suggests that this early return to activity may be largely responsible for further, potentially catastrophic damage to the brain (Laurer et al., 2001). In addition, research indicates that the utility of some commonly used sideline balance and cognitive assessments, "appear to decrease significantly 3-5 days after injury" and thus, are not sensitive enough to detect concussions days after it is sustained (McCrory et al., 2017). For this reason, many of the most effective assessments include a multifaceted approach to identifying the functional, objective, and subjective effects of concussions.

Gaps In Our Knowledge

Limited research has attempted to quantify the effects of concussion on speech production and examine speech analyses as a means of identifying individuals with concussions. In response, a recent publication by the *American Medical Society for*

Sports Medicine (*AMSSM*) called for further research into the potential use of speech measures to identify individuals with concussions (Harmon et al., 2019).

Speech production is an extremely complex and sensitive process requiring the comprehensive integration of a number of areas of the brain in order to perform even simple speech acts (Guenther, 2006; Harmon et al., 2019; Tourville & Guenther, 2011). Research has indicated that in acute concussions, speech may be affected (Echemendia et al., 2017; Gallagher, Mias, & Kipps, 2017; McCrory et al., 2002). However, these largely anecdotal and patient-reported references to speech production changes immediately following a concussion have generated the publication of only a handful of studies specifically addressing the assessment of speech production in the concussed population (Daudet et al., 2016; Dolan, 2013; Hewitt, 2015; Peiffer-Lapid, 2016; Phan, 2016a; Xia, Xia, Daudet, Poellabauer, & Schneider, 2016). Many of these studies are incomplete and limited in their scope. This dissertation fills the current gap in our knowledge surrounding how the speech production of individuals with a history of concussion is affected in non-acute cases compared to those without a history of concussion. It also examines speech production between these groups during increasingly complex contexts: single syllable Alternating Motion Rates (AMR), real and non-word multisyllabic Sequential Motion Rates (SMR), reading passages (Rainbow and Caterpillar), and spontaneous speech. Limited reports exist concerning the effect of concussions on speech production beyond simple non-word diadochokinetic (DDK) speech investigations. The next chapters provide a detailed description of how this dissertation addressed these gaps.

CHAPTER 2: Literature Review

As discussed in the introduction, the search for a universally applicable definition for concussion has led to a drastic increase in research and a significant increase in our knowledge increase concerning the neurologic and subsequent physiologic effects of concussion. It has also produced a large number of potential assessments for use in acute and non-acute stages of concussion. The remainder of the chapter discusses several of the areas where research over the two last decade has been focused related to the neurometabolic and other physiologic effects of concussion. The neurometabolic effects of concussion are reported to be, at least in part, responsible for many of the physiologic effects of concussion. The physiologic effects of concussion explained in this chapter are specifically relevant to work of speech and language pathologists (SLPs). The speech relevant physiologic effects are mainly discussed in terms of recent research into their potential use in assessing and identifying individuals with concussion and tracking improvement following injury. Finally, gaps in our knowledge concerning the physiological effects of concussion, especially as they relate to speech production, are explained.

Neurologic Effects of Concussion

The neurologic effects of concussion have been a primary focus of research over the last several years. Researchers have revealed that, immediately after a concussion is sustained, notable neurometabolic changes occur and can develop over minutes or days (and in some rare cases up to a week) to become fully apparent (Dashnaw, Petraglia, & Bailes, 2012; Frattalone & Ling, 2013). This section will explain the chemical and metabolic changes associated with brain injury including concussion.

Upon sustaining an impact to the head, a complex neuro-metabolic cascade develops. This cascade is described as a significant release of neurotransmitters including amino acids such as glucose and glutamate (Hovda et al., 1995). Cascades are also often referred to as pathways or signaling pathways. Once the cascade is triggered, the complex neurometabolic process begins to unfold.

First, a major change in the electrical charge of affected and surrounding brain tissue develops (Farkas, Lifshitz, & Povlishock, 2006). The brain is a complex and generally adaptable structure. However, in terms of electrical charge or polarization, the brain prefers a state of balance called “homeostasis.” (Giza & Hovda, 2014; Stiefel et al., 2005). Many of the chemical control mechanisms in the brain (which directly affect its electrical state) are themselves controlled by electrical charge. For this reason, when a concussion is sustained, a process called depolarization (increase in positivity) occurs across cell membranes in that region (Giza & Hovda, 2014). During depolarization (and subsequent increase in negativity outside cell membranes in the affected region), an increased efflux of potassium (K+) to the extracellular fluid and influx of sodium (Na+) into the cell is initiated (Giza & Hovda, 2014). This change in the polarization of the cell reaches a point where the chemical control mechanisms, called “ion gates,” responsible for maintaining homeostasis within the brain, begin to activate, exchange charged ions, and further polarize the cell membranes in the area surrounding the injury (Farkas et al., 2006). Along with the efflux of K+ is the efflux of the amino acid glutamate. The magnitude of this polarization process is directly related to the severity of the head injury, where the more severe cases result in a greater polarization of the membranes and a greater efflux of K+ and glutamate. The increase in glutamate and K+ into the extracellular space results in the overactivation of glutamate receptors and calcium (Ca^{2+}) ion channels. These Ca^{2+} channels open and begin to allow large amounts of Ca^{2+} into the cell in an attempt to restore homeostatic balance to the system (Casson, 2006; Giza & Hovda, 2001; Zetterberg, Henrik, Smith, & Blennow, 2013). Calcium plays a major role in regulating polarization in several cellular events in the brain however, when high concentrations of Ca^{2+} are found in the brain over extended periods of time, research indicates it can lead to several dangerous phenomena including the breakdown of crucial brain structures, difficulty in intercellular communication and eventually tissue death (Dominguez, 2004; Dominguez, Lopes, Holland, & Campbell, 2011). Importantly, this accumulation of Ca^{2+} over time (and multiple injuries) can also lead to waste buildup and the impairment of metabolic function (Dashnaw et al., 2012; Giza & Hovda, 2001; Signoretti, Lazzarino, Tavazzi, & Vagnozzi, 2011).

Another notable characteristic in the neurometabolic cascade is the cellular metabolism of glucose. Following the process described above, the homeostasis of the cells in the affected region of the brain have been disrupted to a point where adenosine triphosphate (ATP)-dependent pumps begin to activate in an attempt to regulate the cellular system (Glenn et al., 2003). These pumps perform an important function, however, they require relatively high levels of energy, gained from the break-down of glucose, to complete their intended role. This demand on the glucose storage of the brain eventually depletes the supply nearly completely, initiating what has been termed an “energy crisis” (Giza & Hovda, 2014). This oversimplified description of the breakdown of glucose to create the energy needed to activate the ATP-dependent pumps is called glycolysis (Dorfman, 1943). Glycolysis is the initial pathway that converts glucose into high energy precursors that will lead to the formation of ATP. In the absence of sufficient oxygen, for example during the energy crisis in concussion, glucose is instead shunted (redirected) into lactic acid. Much like the acids produced in muscles with extreme exercise, this lactic acid, if produced at high levels within the brain can lead to large amounts of swelling and accumulation of fluids in the brain. Under normal circumstances, this process of glycolysis and lactic acid production is helpful and safe, however, at extreme levels such as those found after concussion it can lead to impaired transport of messages and nutrients within the brain (including oxygen), damage to axons, and cell death (Banks & Domínguez, 2019; Giza & Hovda, 2001; Signoretti et al., 2011; Vagnozzi et al., 2010).

Glycolysis and lactic acid accumulation lead to the collapse and breakdown of parts of the axons of the affected cells (called neurofilaments, microtubules, etc.) and the resulting breakdown in axonal function of cells. The swelling produced by the buildup of lactic acid, water, and other ions in the brain can increase pressure on and eventually cause lasting damage to cell axons in the brain. After a single head injury, research indicates that this pressure can last for several hours (Maxwell & Graham, 1997). The pressure then causes a disruption of transport within the cell and abnormal accumulation of protein within cells begins. As Ca^{2+} levels within the axon are already elevated as described above, a process called phosphorylation begins (Giza & Hovda, 2014). During phosphorylation, Ca^{2} ions encourage the turning on and off the proteins which have accumulated in the axon. This process leads to the final major hallmark of the neuro-metabolic cascade: decrease in cerebral blood flow (Banks & Domínguez, 2019; Domínguez & Raparla, 2014). As axons become weaker they begin to collapse and breakdown (Giza & Hovda, 2001; Nakamura et al., 1990; Sternberger & Sternberger, 1983; Zetterberg, Henrik et al., 2013). This process will in turn quickly decrease cerebral blood flow and thus, oxygenation levels within the brain (Domínguez & Raparla, 2014). As noted previously, oxygen is needed during glycolysis in order to prevent the buildup of lactic acid. Thus, reduced blood flow in the brain continues the cycle of lactic acid buildup and further potential for short and long-term damage to the brain. The entire process can continue for 2-4 weeks after initial injury and can leave the brain at significantly higher than normal risk for further, more devastating injury (Laurer et al., 2001; Maugans et al., 2012; Stiefel et al., 2005).

In order to conduct much of the research which has yielded the knowledge above, tissue measures must be performed directly. Several researchers have attempted to establish a less invasive biomarker for identifying concussion which incorporate means of measuring the “functional disturbances” noted by McCrory and colleagues (2017). These attempts have been met with varying levels of success, however, to date there is no reliable means of identifying concussion. Further, the issue exists that many of the more commonly used metrics for identifying concussion are only somewhat reliable within the first few days after a concussion is sustained. These therefore cannot be used to track improvement following SRC over time. Due to the overwhelming amount of research in this field over the last two decades, publications on several potential biomarkers have been printed in journals around the world. Neuroimaging has been a common area where researchers have sought to gain more understanding surrounding the nature of concussions.

Neuroimaging

Several neuroimaging techniques have been employed to evaluate the structural and metabolic disturbances caused by the neural cascade triggered after head injury. The following methods have been used to detect concussion in an attempt to explain its functional effects: Computed tomography scanning (CT or CAT; comparable to a 360 degree x-ray image giving stationary pictures of tissue), positron emission tomography (PET; specifically used to track glucose metabolism of the brain especially areas of elevated activity, though, like x-rays, overexposure can be harmful), diffusion tensor imaging (DTI; a type of MRI which measures the diffusion of water throughout the brain) and functional magnetic resonance imaging (fMRI; used to image changes in the blood flow within the brain) (Ghajari et al., 2017; Wu et al., 2017).

Studies using CT scans: Computed tomography has long been used to image the brains of individuals following head injuries of varying severity. However, over the last few decades, the use of CT scans has been called into question and in fact, research has begun to call for its elimination in mild head injury including concussion (Miller, Holmes, & Derlet, 1997). This is due to the often times inconclusive nature of CT scans and the lack of structural damage noted in this population (Paul McCrory et al., 2017).

Studies using PET: Another area where several researchers have focused their efforts is in looking for glucose metabolism by the brain at rest and during a number of cognitively tasking activities. Using PET, research has revealed that at rest, there may be no difference in the amount of glucose absorbed by many areas of the brain (Chen, Kareken, Fastenau, Trexler, & Hutchins, 2003). However, this same study suggested that working memory tasks induced smaller blood flow increases in concussed individuals as well as areas of increased glucose metabolism compared to healthy controls. Findings detailed in Chen et al.'s research (and other studies), however, suggest that these findings are highly dependent on the severity of the head injury and thus, a more severe concussion results in more significant changes both at rest and during cognitive activity (Bergsneider et al., 1997).

Studies using DTI: Neuroimaging methods have attempted to expand the utility of MR images to give more insight into the functional properties of the brain. Many studies have examined the directionality of diffusion of fluids (mostly water) through the cerebral structures of individuals with concussion using a type of magnetic resonance image: diffusion tensor. These studies have focused mainly on two different measures: fractional anisotropy (FA; variability of fluid diffusion based upon the direction which it is measured) and mean rate diffusivity in various white matter structures of the brain. Generally in the concussed population, increased FA is reported often in addition to a decreases in mean flow rate (Lipton et al., 2009; Michael McCrea et al., 2016). Results of these studies while informative, must be examined carefully as many other studies report opposing findings with increased severity (Cubon, Putukian, Boyer, & Dettwiler, 2010) and pediatric populations (Maugans et al., 2012). Other measures of diffusivity along varying dimensions, such as the radial and axial, have demonstrated inconsistent results in the concussed population (Chamard, Lefebvre, Lassonde, & Theoret, 2015; Pasternak et al., 2014; Sasaki et al., 2014).

Studies using fMRI: fMRI has often been used in an attempt to quantify change in cerebral blood flow following a variety of head injuries. This technique has been examined during both resting state and a variety of physical and cognitive activities.

Some researchers have found that there may be an association between reduced blood flow in some areas of the brain and concussed individuals self-reported cognitive function (J. Chen, Johnston, Collie, McCrory, & Ptito, 2007). However, a recent review of the literature by McCrea and colleagues has discovered a large amount of variability in fMRI studies concerning concussed individuals (Michael McCrea et al., 2016). McCrea's work has called into question the reliability and interpretation of fMRI as it applies to those with SRC.

Recent research has indicated though, that many of the neuroimaging methods described in this section lack the requisite qualitative and quantitative detail regarding the pathophysiology of concussion and use protocols which are not clinically relevant (Ellis et al., 2016). The metabolic changes discussed earlier in this research are difficult to perceive using current neuroimaging techniques particularly in vivo. Another important consideration with neuroimaging is that most methods are expensive, non-mobile, and unable to detect the often functional rather than structural nature of concussion (McCrory et al., 2017). Further, due to the nature of many of the neuroimaging techniques, radiation is a concern for individuals being subjected to them; especially repeatedly, over short amounts of time. Importantly, much of the research described above reinforces the ideas that: 1) effects of concussion are more often functional rather than structural, and 2) variability in brain structure and functional regions person-to-person make it very difficult to identify concussion using neuroimaging. Finally, much of the research described above comes from the examination of non-human models as well as humans postmortem. Due to the difficulty in obtaining data from live subjects, many researchers have attempted to quantify less invasive physiologic and functional deficits in the concussed population. Below, many of the most common physiologic effects of concussion of particular interest to SLP's are discussed as well as their associated assessment methods.

Physiologic Effects of Concussion

Balance

One of the more commonly studied physiologic effects of concussion is a change in balance. For several decades, studies have attempted to quantify changes in vestibular function related to balance as a potential biomarker for concussion. Several studies have found that after sustaining a concussion, many individuals suffer transient (and in some cases long-term) postural instability as a result of functional damage to the balance centers of the brain (Riemann & Guskiewicz, 2000). Many researchers have worked to develop tools to reliably identify changes in balance which occur following a concussion. Among the most common are the Romberg Test, the Balance Error Scoring System (BESS), and the Clinical Test of Sensory Organization and Balance (CTSIB).

The Romberg test of balance and postural stability was used for several years to clinically assess balance in individuals suffering from neurogenic balance issues (DeJong, 1979). Traditionally, the Romberg balance test examines individuals ability to maintain balance when the feet are placed together, arms are placed at the side, and the eyes are closed (Bohannon, Larkin, Cook, Gear, & Singer, 1984; DeJong, 1979). Individuals who are unable to complete this task showing sway or fall behaviors are said to have a "positive Romberg sign." Recent research by Guskiewicz and colleagues has indicated that the Romberg sign is present in 30% of individuals and is even less common in high level athletes who's natural balance abilities are above average

(Guskiewicz, 2011; Guskiewicz, Weaver, Padua, & Garrett, 2000). The Romberg test, Guskiewicz states, is not objective or sensitive enough to evaluate concussion status.

Developed as a more comprehensive means to identify vestibular disfunction in various neurogenic disorders, the CTSIB examines balance abilities during a number of surface and visual conditions (i.e., hard vs. soft surface; no blindfold, blindfold etc.) (Shumway-Cook & Horak, 1986). As with other balance assessments, results of this test should be interpreted carefully as there may extraneous factors (general sensory and motor ability for example) which may affect performance on this test.

The BESS is often considered an acceptable non clinical means of assessing balance (Riemann & Guskiewicz, 2000). During the BESS, participants are instructed to perform a number of standing postures (one and two footed, eyes open or closed, etc.) while raters stand by and evaluate their performance based on a number of criteria (ex. sway, stability, number of errors, etc.). Several studies have examined the use of this balance scoring system in a range of head injured populations and have found a striking amount of variability of individuals within differing populations (Bell, Guskiewicz, Clark, & Padua, 2011; Sirmon-Taylor & Salvatore, 2012). This variability makes providing definitive interpretation of balance scoring difficult.

While useful in some cases, the practice of assessing balance in cases of concussion has been called into question. Murray and colleagues recently found a significant lack of reliability and sensitivity in many assessments used in cases of concussion (Murray et al., 2014). Specifically, they report that the Romberg Test and the CTSIB (among other balance assessments) lack enough information regarding their reliability for evaluating balance after concussion. Further, Murray et al.'s review of the literature indicates a low ability to identify concussion (sensitivity), at only 34%.

In addition to the questions of reliability and sensitivity associated with many of the current balance assessments, it has been suggested that outcomes of these balance tests along with many of the cognitive tests (response time, processing speed, etc.) can be faked during prescreening in order to feign improvement or no change with a head injury (Alsalaheen et al., 2016). Conservative estimates of "sandbagging" behaviors on concussion testing have been reported between 6-33% (Erdal, 2012; Schatz, Elbin, Anderson, Savage, & Covassin, 2017; Szabo, Alosco, Fedor, & Gunstad, 2013). This "sandbagging" by athletes on pre-injury concussion screenings, researchers say, results in non-significant differences in post injury concussion screening scores compared to their falsified pre-injury scores. No flags are raised therefore, and athletes return to play having successfully gotten through the system undiagnosed. This return to play without sufficiently healing, is the most dangerous and likely cause of issues such as second impact syndrome and perhaps even chronic traumatic encephalopathy (Gavett, Stern, & McKee, 2011; McKee et al., 2010). Balance alone, it seems is not an adequate means of identifying and assessing individuals following a suspected concussion.

Cognition

Several studies have indicated that secondary to the metabolic and resulting hemodynamic changes in the brain following concussion, general cognitive function is often impaired. These cognitive effects have the potential to last several days (Bleiberg et al., 2004). The cognitive areas most commonly affected are attention, executive function, memory, and reaction time.

Several areas of attention have been examined as potentially being affected by concussion. Researchers have found that on selective attention tasks, individuals with concussion perform significantly worse than healthy controls (Gentilini et al., 1985). Visuospatial attention may also be affected following a concussion (Cremona-Meteyard & Geffen, 1994). Some researchers have examined attention abilities in individuals following a concussion using dual task attention and motor tasks and found more reliable results than those gained from studies using a single isolated cognition task (Howell et al., 2018). Auditory stroop tasks using congruent and incongruent auditory stimuli have also been used to identify deficits in attention several weeks after a concussion is sustained (Białuńska & Salvatore, 2017).

Changes in executive function have also been examined as a possible means of identifying individuals who have a concussion (Belanger, Curtiss, Demery, Lebowitz, & Vanderploeg, 2005). However, because of the integrated nature of executive function tasks (often requiring several different cognitive domains at once such as attention, reasoning, memory, etc.), meta-analyses have demonstrated weak relationships between concussion and deficits in executive function (Belanger & Vanderploeg, 2005).

Reaction time has been included in several experiments as a means of identifying potential location and extent of damage to the brain in concussion. Several researchers have investigated measures of reaction time and found that those who have sustained a concussion, demonstrate prolonged reaction times compared to healthy controls (Jakobsen, Baadsgaard, Thomsen, & Henriksen, 1987). Jakobsen and colleagues reported that following concussion, reaction time was significantly prolonged compared to healthy non-concussed individuals

McCrea and colleagues have examined memory abilities in a large number of concussed individuals using the Standardized Assessment of Concussion or SAC (M. McCrea et al., 1998; Michael McCrea, Kelly, Kluge, Ackley, & Randolph, 1997). The SAC has been incorporated into the Sport Concussion Assessment Tool-5 or SCAT-5 and is commonly used to assess neurologic function immediately following a suspected concussion (for example on the sideline of a sporting event) (McCrory et al., 2017). McCrea and colleagues' research, standardized on a relatively small sample of concussed individuals (n=33), revealed that memory (as well as concentration and orientation) scores of those who had sustained a concussion were significantly lower than their healthy controls and significantly lower than their own pre-injury scores.

While helpful in identifying deficits in individuals following a concussion, researchers have examined the potential of physical activity interfering with cognitive abilities of athletes. Covassin and colleagues have discovered that following strenuous physical activity, verbal memory scores (used in the SAC and SCAT-5; both immediate and delayed verbal recall) are significantly lower than controls who did not perform maximum physical activity (Covassin, Weiss, Powell, & Womack, 2007). This, they say, indicates that immediate testing of memory following an SRC (often done on the sidelines of sporting events) may be invalidated due to the effect of physical activity on several cognitive domains. If used as an assessment tool, individuals should be allowed some time to rest following physical activity in order to give a more accurate indication of cognitive function.

Other limitations should be noted in the use of cognitive assessments with individuals following a concussion. First, it can be difficult to interpret if concussion is the cause of cognitive decline or abnormality following a concussion. For this reason, most current assessment protocols call for multiple assessments and screenings of concussed individuals over time. This however, leads to a second limitation in cognitive assessments generally which is, most are not sensitive enough to track or detect minor change (decline or improvement) over time (McCrory et al., 2017). Finally, researchers have used patients' self-reported cognitive function scores as a means to quantify abnormality. Relying on self-report of cognition may lead to inadvertent bias and can skew research results. Thus, the current consensus is that more sensitive objective assessments are needed in this population. Research regarding balance capabilities in those with acute and multiple concussion history has given rise to an emerging field of research: vestibular ocular abilities.

Vestibular/Ocular

Several researchers have found that vestibular and ocular systems are affected in concussion. There are two distinct systems of operation in the vestibular system: the vestibulo-ocular system (responsible for maintaining visual stability) and the vestibulospinal system (responsible for maintaining posture and balance) (Mucha et al., 2014). As described above, much of the research conducted over the last 20 years has indicated that vestibulospinal measures introduce too much uncertainty and are thus, not effective in assessing the physiologic effects of concussion (Guskiewicz, Ross, & Marshall, 2001; Riemann & Guskiewicz, 2000).

Subsequently, recent research has suggested that the ocular system of concussed individuals be assessed in addition to the vestibular system. Current cognitive assessments commonly used when a concussion is suspected, such as the SAC, SCAT-5, Balance Error Scoring System (BESS), and others, do not currently incorporate an evaluation of vestibulo-ocular function. Mucha and colleagues have investigated the vestibular and ocular abilities of young teens still in the relatively acute stages following an SRC (within 5.5 days of sustaining their injury). They found that concussed participants' horizontal vestibular ocular reflex and visual motion sensitivity were significantly decreased compared to non-concussed controls and that performance on these measures were reliably able to predict concussion status. Researchers have indicated that generally these symptoms tend to normalize after 50-75 days (Kostyun & Hafeez, 2014). These vestibulo-ocular assessments are thus more sensitive over time than most balance only assessments.

General Motor Movement

Much of the research to date concerning the effects of concussion are centered on the cognitive and vestibular effects. However, an impressive amount of research has examined the effect of concussion on general motor control especially as it relates to cortical structures of the brain. Motor control following a concussion has been examined from several perspectives. For example, transcranial magnetic stimulation (TMS), the process of stimulating specific cortical areas of the brain to contract muscles of the body and evaluate connectivity within the nervous system (De Beaumont et al., 2007; Miller et al., 2014; Tallus et al., 2011), has been used to measure muscular activity following a concussion. Using this technology, researchers have demonstrated that significant differences in timing and strength of the muscle contractions (usually of the hands, arms, or legs) occurs following both concussion and mTBI. Further, these studies have found that larger input from the magnetic stimulation units are needed in order to obtain the desired muscular response in individuals following a concussion.

Several studies have examined the effects of concussion on movements of the periphery especially arms, hands, and fingers (De Beaumont et al., 2007; Dolan, 2013; Miller et al., 2014; Phan, 2016; Tallus et al., 2011). These have found that peripheral motor movements are negatively affected by concussion. Specifically, Tallus and colleagues used transcranial magnetic stimulation (TMS) to determine motor thresholds (latencies) in individuals following concussion (referred to as both concussion and mTBI in the publication; participants were included if they fell between a 13-15 on the Glasgow Coma Scale following their injury). This study described increased motor threshold of neural stimulation required to induce a movement of a target intensity in the extremities (hands and digits). While these previous studies have important implications for deficits in speech timing due to potential articulatory motor changes following concussion, very little research has examined speech timing in individuals with SRC.

This dissertation proposes that the complex motor activity of speech be investigated by examining speech timing, acoustics, and perceived speech characteristics in greater detail. The rationale, physiological effects and gaps in the speech research regarding athletes with a history of sports related concussions is detailed below.

Respiration

Given that the purpose of this research study is to examine if concussion history affects speech production, it is important to consider if research reports significant deficits in the respiratory abilities of the concussed population. Research regarding changes in respiration after SRC are again relatively sparse. A study compared the effect of hypercapnia (holding ones breath) and hypocapnia (hyperventilation) between individuals with SRC and healthy controls (Len et al., 2011). Authors of this study reported that those with SRC took significantly longer than those without SRC to return to their normal resting respiration state. In addition to taking longer to return to a normal respiratory rate, this research also concluded that blood oxygenation levels took significantly longer to return to normal when performing hypercapnic (breath holding) and hypocapnic (hyperventilation) tasks for participants with SRC compared to those without. Interestingly, this research and others which have documented a decrease in oxygenation levels of the brain after SRC (Bishop & Neary, 2017) indicate the potential disturbance of respiration or the body’s difficulty in metabolization of respiratory oxygen following SRC during extreme respiratory situations. However, because the purpose of this research and the speech tasks involved were not meant to overly tax the respiratory system, it is anticipated that speech production differences noted between individuals with a history of concussion and controls with no history of concussion will not be caused by respiratory deficits in the concussed population.

Speech Production After Concussion

This section is a review of knowledge (and lack thereof) of concussions which is specifically related to the clinical and research work of Speech Language Pathologists.

Reviewed components include a comprehensive quantification of deficits in speech production as measures during real and non-word DDK tasks, read passages, and spontaneous speech. While some research has been performed aimed at quantifying differences between the motor speech rates of healthy controls and concussed individuals, each experiment performed to date has had significant limitations which may decrease the value of outcomes and generalizability of results. Additionally, there are many gaps in our knowledge of the voice production and perception of voice in the concussed population. Particularly, the gap in our knowledge of voice changes following a concussion is highlighted in pilot research done in a joint project between Notre Dame and MSU. Each of the above-mentioned gaps will be discussed in detail below.

Speech Timing After Concussion

Speech production is an extremely complex process which requires widespread integration of neural structures including multiple cortical and subcortical structures (Fiez & Petersen, 1998; Turkeltaub, Eden, Jones, & Zeffiro, 2002). Studies of change in motor function following concussion have focused heavily on limb activity to the exclusion of the speech system. These studies provide a great deal of evidence to suggest that several motor areas may be affected following a concussion. The remainder of this subsection will discuss findings of research involving motor control of several peripheral motor systems and then describe the little research which has been performed to date surrounding motor speech and timing following SRC.

Breedlove and colleagues have performed a number of studies investigating correlations between the magnitude and location of hits to the head and resulting functional brain activity in athletes of contact sports (primarily American football).

Results of two of these studies revealed that in several of the athletes who participated (ages 15-18), significantly more impacts were recorded to the front and side of the head. These impacts were hypothesized to be responsible for significantly altered blood flow in regions of the brain responsible for speech and voice production such as the inferior frontal lobe and the supplemental motor area (Breedlove et al., 2012; Talavage et al., 2010). In a related example, many of these brain areas have been implicated as playing a role in voice changes noted in individuals with Parkinson's Disease as well (Liotti et al., 2003). In most of the athletes who demonstrated cerebral blood flow changes, no clinically measurable changes in cognition were noted. Interestingly, despite blood flow changes to areas known for their involvement in speech, analysis of speech was not performed in these studies.

Changes in speech production (e.g., rate/timing, fluency and accuracy) has been noted, however, as an early sign of diseases of the nervous system and other motor-speech disorders (Duffy, 2013). Following severe TBI, articulatory function is commonly affected (Theodoros et al., 1994). Further, slurred speech has been noted as a potential effect of acute concussion (Echemendia et al., 2017; Gallagher et al., 2017; McCrory et al., 2002). However, few studies have examined articulatory ability of concussed individuals in either the acute stage or later stages of injury. A small number of researchers have found that motor speech rate may be negatively impacted by concussion (Hewitt, 2015; Peiffer-Lapid, 2016; Phan, 2016b).

Interestingly, motor limb, voice and speech articulation movements are located in adjacent (and possibly overlapping) anatomical locations of the cortex, which may contribute to coordinated functional declination of these systems following a concussion

(Brown, Ngan, & Liotti, 2008; Simonyan, 2014; Simonyan & Horwitz, 2011). This relationship is demonstrated in research which suggests that after severe injury, neural reorganization of motor areas for the hands and fingers may occur to incorporate function of the face (and visa-versa) (Cramer & Crafton, 2006). Research has also indicated that in more severe injury, motor cortex function (specifically of hands and wrists) can be affected long after acute symptoms have subsided (De Beaumont et al., 2007). It is important to note that objective analysis of motor movements of speech articulators (jaw, tongue, cheeks, etc.) has not yet been reported for individuals with a history of concussion.

The paucity of research regarding the effects of concussion on articulation during speech production is especially interesting given that it has been noted as an acute sign of concussion (Echemendia et al., 2017; Gallagher et al., 2017; McCrory et al., 2002). Most recent studies have attempted to quantify motor speech production changes in young athletes after concussion using diadochokinetic (DDK) rates and simple sentence repetition tasks. (Dolan, 2013; Hewitt, 2015; Peiffer-Lapid, 2016; Phan, 2016). Results of the studies above, while inconclusive and in some cases contradictory, generally suggest that although pyramidal tract fibers for motor limb (corticospinal) and motor speech (corticobulbar) terminate in different regions of the body, their neighboring cortical regions may be affected collectively by concussion (Duffy, 2013; Kuruvilla, Murdoch, & Goozee, 2012).

DDK speech tasks involve the production of repeated single and multi-syllable production such as “puh,” “tuh,” and “kuh” as quickly as possible (Ackermann, Hertrich, & Hehr, 1995). Like finger movements and tapping exercises used in previously outlined experiments, DDK speech involves repetition of speech sounds in order to establish a speech rate. From the DDK speech samples, alternating motion rates (AMR; “puh, puh, puh…”) and sequential motion rates (SMRs; “puhtuhkuh…”) can be obtained. Speech articulation rate can be estimated from analysis of DDK production rate (e.g. syllables per second). Several studies have attempted to establish normative values for DDK speech rates in healthy adults. Icht and Ben-David recently reported DDK norms for English at 6.23 syllables per second with low normal values being 5.4 and high normal being 7.5 per second for adults (Ben-David & Icht, 2017; Icht & Ben-David, 2014). Results of this research indicate that DDK speech rates vary significantly between languages (Greek: 4.32 syllables/s, Portuguese: 2.8 syllables/s, and Farsi: 4.16 syllables/s). More importantly though, Icht and Ben-David’s research results indicate that normal speakers rates across languages improve when using “real word” repetitions (e.g. Buttercup, Pattycake) rather than traditional non-word multi-syllable repetitions (2017). Also, of note, this research indicated that gender had no significant effect on DDK speech rates. Finally, in traditionally disordered speech populations, Ackermann and colleagues have shown that DDK rates are significantly affected in people with neurologic disease, including PD, ataxia, and cerebellar syndrome compared to normally healthy controls (Ackermann et al., 1995).

More recent work has investigated DDK rates in TBI and found several interesting patterns. Wang and colleagues found that following a TBI DDK syllables were lengthened, resulting in slowed AMR’s and SMR’s and lengthened pauses between syllables. Additionally, this research suggests that syllable rates during DDK tasks were comparable to that of conversational speech rate tasks and that significant differences in the perceptual analyses of TBI speech, voice production and quality (Y. Wang, Kent, Duffy, Thomas, & Weismer, 2004; Y.-T. Wang, Kent, Duffy, & Thomas, 2005). Dolan found significantly reduced DDK (AMR and SMR) rates in individuals diagnosed with concussion compared to healthy controls (ranging in age from 18-25 for both the SRC and control groups) (Dolan, 2013). While time post injury was not mentioned in this study, Dolan does indicate that all concussed participants had a current diagnosis of concussion. Dolan's research also examined peripheral motor movement (finger tapping) rates in these same athletes. Analysis of these data revealed significantly slower finger tapping rates in concussed individuals compared to healthy controls (again these controls were mostly non-athletes). In a follow up study using data collected by Dolan as well as a handful of newly concussed participants ages 13-19, time post injury for concussed participants in this study was recorded and ranged from 1 to 33 days (Hewitt, 2015). This study further examined speech rate and intelligibility during a sentence repetition task. As in the previously mentioned studies, Hewitt also reported that speech DDK (AMR and SMR) rates and motor limb duration times were significantly slower and longer respectively than normal controls. Importantly, regarding the perceptual analysis of the speech in the sentence repetition tasks, they found no differences in subjective ratings of intelligibility.

Building on these studies, Phan used much of the same speech dataset collected in Dolan and Hewitt's work (again, adding a handful of new concussed participants) and found few significant differences in rate of speech (both DDK productions and single phrases) between 13-23 year old concussed and healthy control participants (Phan, 2016). The impact of the reported differences was minimized because of the variability of the types of injury, ages of participants, and potential severity of injury. For example, the time post injury for concussed participants was recorded and ranged from 6 hours to 33 days, in which significant recovery can occur (Eisenberg, Andrea, Meehan, & Mannix, 2013; Michael McCrea et al., 2003) Additionally, careful examination of the generally non-athlete, age and gender matched control group shows that controls were not well age-matched and were generally younger than their concussed peers. Furthermore, this research did not include subjective analysis from trained and untrained listeners regarding speech production aspects of individuals with concussion, especially compared to healthy speakers. Finally, speech analysis only included DDK productions and not real-world speech production (read or spontaneous) samples. Some have argued that that DDK speech rates (especially SMR's) are similar enough to real connected speech to be analyzed in a similar way and thus, could be useful to in measuring complex speech production differences between individuals with a history of concussion and controls with no concussion history (Wang, Kent, Duffy, & Thomas, 2005).

However, it is reasonable to question if the inclusion of the estimated timing, acoustic and perceptual analyses of complex speech (real word SMR's, reading passages and spontaneous speech) will give the most accurate and comprehensive profile of the speech of participants with a history of concussion compared to those with no history of concussion in increasingly motorically demanding speech settings. The studies described in this section provided a preliminary first step to speech analysis in this population. However, a more in-depth examination of speech articulatory abilities in individuals with a history of concussion is needed.

In terms of motor speech movements, few studies have objectively quantified motor speech muscle output in individuals following a concussion (Powers et al., 2014). Research has also not attempted to correlate speech rate with changes in motor speech muscle activation. While the research cited in this section has examined motor speech function using diadochokinetic speech tasks, the current research aims to provide a more comprehensive speech evaluation of the population with a history of concussion that includes analysis of connected speech samples.

Voice After Concussion

The previous studies reviewed covered speech production via speech rate from DDKs and running speech. Speech production, in these cases, is primarily focusing on the overall speech system, primarily influenced by the coordination of the tongue and jaw. However, speech production includes other physiological components and their coordination, such as the pulmonary system (for breath support) and the larynx (for valving, phonation like pitch and quality). Studies have indicated that TBI is associated with decline in several areas of speech including voice (larynx) and speech articulatory function (Theodoros, Murdoch, & Chenery, 1994). Changes in voice and speech should affect speech analysis and speech acoustic analysis in particular, however, such analysis has been largely overlooked in concussion research. Acoustic analyses of the voice have long been used as means of both identifying and classifying both neurogenic and primary voice pathologies. Some of the more common neurologic conditions associated with a change in voice are Parkinson's Disease (PD), Amyotrophic Lateral Sclerosis (ALS), Essential Tremor (ET), and Spasmodic Dysphonia (SD) (Deuschl, Bain, & Brin, 1998; Perez, Ramig, Smith, & Dromey, 1996; Ramig & Shipp, 1987).

Several studies have reported on neural control mechanisms of voice production and have attempted to identify cortical regions responsible for voluntary motor control of the voice, with focus on a series of structures known as the “laryngeal motor cortex” or the “larynx-phonation area” (Belyk & Brown, 2014; Simonyan, 2014; Simonyan & Horwitz, 2011). Included in this region are the inferior portion of the precentral gyrus and inferior portion of the frontal lobe. Again as noted above, these areas suspected to be responsible for fine laryngeal control and thus voice production are common sites of impact in contact sports and areas where changes in cerebral blood flow are noted following a concussion (Breedlove et al., 2012; Talavage et al., 2010). Nevertheless, only a small number of studies have examined the potential effects of concussion on various acoustic parameters of the voice.

Recently, Poellabauer and colleagues performed a small series of studies investigating the possible use of acoustic analysis of voice as a potential means of assessing and identifying individuals who have suffered a concussion (Daudet et al., 2016; Falcone, Yadav, Poellabauer, & Flynn, 2013; Xia et al., 2016). Further analysis of the data collected in these studies was done in consultation with Michigan State and is discussed in the next chapter under pilot research, which setup some of the measures used in the method section. The analysis performed provides some evidence to suggest that significant acoustic voice changes occur in athletes with acute concussion.

Perception of Speech After Concussion

Perceptual evaluation of speech and voice is a common means of evaluating communication abilities in many populations including those affected by neurologic and neurodegenerative disease. Analysis of various aspects of speech is often performed in prior to, or in conjunction with other measures including speech, voice, and intelligibility. Often, where speech production differences are present, there are perceptually salient speech changes as well. For example, the speech of many dysarthric populations is frequently subjectively rated in the following dimensions: rate, loudness, pitch, word repetitions, stress, and articulatory accuracy (Kluin, Foster, Berent, & Gilman, 1993; Silbergleit, Johnson, & Jacobson, 1997). Subjective analysis of voice has long been used to describe perceptual features of disease and injury as well. For example, the Consensus Auditory-Perceptual Evaluation of Voice (CAPE-V) was created to evaluate several parameters of voice including overall severity, roughness breathiness, strain, pitch, and loudness (Kempster, Gerratt, Abbott, Barkmeier-Kraemer, & Hillman, 2009). As the gold standard, the CAPE-V is often used to evaluate the speech and voices of individuals prior to performing acoustic analysis. In this way, it serves as a preliminary analysis of voice that can lead to the objective acoustic analysis of voice in many populations. Similarly, the GRBAS scale was developed in order to evaluate several parameters of voice: grade, roughness, breathiness, asthenia, and strain (Hirano, 1981; Karnell et al., 2007). In some populations, notable changes in speech are frequently reported.

In the concussed population, few perceptual analyses of speech studies have been reported. Phan and Hewitt describe a perceptual analysis of speech intelligibility of athletes following a concussion (Hewitt, 2015; Phan, 2016). Results of their analysis did not find statistically significant differences in intelligibility between concussed and healthy athletes; however, ratings were performed by only two raters thus, severely limiting confidence in these results. Further, these studies lack a comprehensive subjective analysis of speech generally and do not include a subjective analysis of voice. Due to the variable nature of perceptual ratings (Eadie & Baylor, 2006), multiple raters are strongly advised to improve reliability and establish functional levels of the variables of interest. Additionally, Eadie and Baylor (2006) and others have found that training and providing moduli for raters significantly improves reliability within and between raters. The current research included six raters, trained on each measure of interest, provided with a modulus for each task and measure of interest. Further, the current research aims to gather and analyze auditory-perceptual data in a manner which may give insight into the perception of timing and acoustic characteristics of participants with a history of concussion compared to those with no history of concussion.

The Effect of Concussion History

As it is anticipated that concussion status (previous concussion history vs. no concussion history) will have an effect speech production across speech tasks, this section will detail recent research in the potential effects of concussion history. Studies in this section will focus primarily on those which included participants several months to years removed from their last concussion. It will also focus on studies which examined motor movement in those with a history of concussion.

In a study of over 2,500 retired professional football players, 61% sustained at least one concussion and 24% sustained three or more. In this study of former football players of average 53 years, participants had a five times higher likelihood of being diagnosed with mild cognitive impairment and an earlier onset of Alzheimer’s disease than the average American male (Guskiewicz et al., 2005). Additional recent research by Martini and colleagues (2017) investigated the potential cognitive effects of multiple concussions. They separated participants into 3 age groups: young (18-30 years), middle aged (40-50 years), and older (60 years and older). These groups participated in computerized neurocognitive assessments which included reaction time, working memory speed and accuracy, auditory timing, visual tracking, and attention tasks. They found that that when controlling for age and the number of concussions experienced by athletes, significant differences in working memory accuracy and attention were noted. The authors explained however, that their methods used may not have been sensitive enough to identify differences between concussed and normal healthy controls. However, Barker et al (2017) reported that male athletes from a variety of sports backgrounds (10-19 years old) reported a significantly higher rate of memory and concentrations problems on the Immediate Post-concussion Assessment and Cognitive Test (ImPACT) (Montenigro et al., 2017). While many of these studies did not find significant differences in cognitive functions, many athletes did report increased cognitive symptoms on the IMPact test (Brooks et al 2016; Howell et al 2017; Barker et al, 2017).

A considerable amount of the research regarding the long term motor effects use neuroimaging or neuromodulation techniques in an attempt to provide a neural basis to explain the motor deficits seen in this population (De Beaumont et al., 2007, 2009; Huang et al., 2016). Interestingly, De Beaumont and colleagues found that in concussed athletes who had suffered a previous concussion (1 year to 27 years prior) an increased cortical silent period (CSP) was noted. De Beaumont and colleagues described an increase in the cortical silent period following both a single SRC and in individuals who were at least nine months post sustaining their last of two or more concussions. The cortical silent period is a phenomenon reported in EMG signals during sustained voluntary contractions. When a cortical motor region of the brain related to a muscle is activated while that muscle is being contracted, a “silent period” or zeroing effect is seen in the EMG measure. Results of the De Beaumont and colleagues study indicate that in individuals with a history of concussions, this silent period is longer compared to those who have sustained only one or no concussions. This silent period, researchers hypothesize, reflects deterioration/disruption of the pathway from the cortex to the spine and to the extremities after injury. The CSP is said to be a measure of inhibition of the motor cortex. De Beaumont also found that athletes with concussion performed significantly slower on a diadochokinetic repetition task of the hands (repetitive finger tapping). A recent review of the concussion literature suggests that there may be a relationship between concussion history and long-term motor effects (Martini & Broglio, 2018). Howell and colleagues (2017) investigated the effects concussions on gait characteristics of adolescent athletes during a dual task experiment. They found that athletes who had experienced 2 or more concussions walked with significantly shorter strides and significantly slower gait speed than controls (no current or prior concussions). There was also a moderate correlation (not significant) in gate speed, where more concussions resulted in faster gait speed.

Summary

Previous research has examined the potential effects of multiple concussions on several different cognitive and motor parameters. Early research in this area by Guskiewicz et al. indicate that multiple concussions may cause mild cognitive impairment and executive dysfunction in retired elite athletes (Baugh et al., 2012; Gavett et al., 2011; Guskiewicz et al., 2005). These researchers have also found that multiple concussion may lead to an increased likelihood of persistent symptoms of concussion and may lead to personality changes and memory loss (A. McKee et al., 2009; Mez et al., 2017). Other research among these retired elite athletes suggests that symptoms similar to those common in certain types of dementia may also be a result of multiple concussions and/or sub-concussive events over time (Mez et al., 2017).

Previous research suggests that there are notable changes in the motor speech, voice and perhaps auditory-perceptual dimensions of speech production in the concussed population. Given the findings of these studies, it is anticipated that speech production generally and speech articulation specifically will be negatively impacted for individuals with a history of concussion. Therefore, it is hypothesized that athletes' AMR, SMR, and connected speech productions will be slower for individuals with a history of concussion compared to individuals without a history of concussion. This study aims to objectively gather and analyze data in a manner which may give insight into the speech production deficits of individuals with a history of concussion. Further, this research expands the work previously performed by Dolan, Hewitt, Peiffer-Lapid, and Phan by analyzing read speech and spontaneous speech, in addition to real and non-word DDK tasks. This information may provide further insights into the communication difficulties experienced by individuals following a concussion.

While the previous research has been helpful in drawing attention to motor control deficits and potential motor speech production changes following a concussion, there has been general a lack of sufficiently controlled participation, perceptual analysis of speech and voice, comprehensive design including broader speech contexts, and robust objective speech timing and acoustic voice analysis. This dissertation attempted to fill many of these gaps.

CHAPTER 3: Methodology

The overarching aim of this dissertation was to determine to what degree the speech production from a range of motorically complex speech tasks was or was not different when comparing individuals with a history of concussion and those without a history of concussion. Based on the knowledge gaps exposed in the literature review, two research questions were created which address more specific aspects of the speech production of individuals with a history of concussion compared to those with no history of concussion.

Question 1: Is there a significant difference in speech timing between those with a history of concussion and those with no history of concussion? Is that difference impacted by increasingly complex tasks or the method of assessment?

Question 2: Is there a significant difference in acoustic voice quality between those with a history of concussion and those with no history of concussion? Is that difference impacted by increasingly complex tasks or the method of assessment?

To respond to these two questions, two different types of speech stimuli (DDK and continuous/connected speech) were used to represent contexts of increasing linguistic and speech motor complexity. This was done to obtain a comprehensive profile of speech in the population of individuals with a history of concussion and those without a history of concussion. From the speech recordings from both groups of individuals, objective speech timing and acoustic metrics as well as speech timing and acoustic voice quality production ratings (via expert raters) were made. Per the review above and as will be outlined below, it was hypothesized that speech timing would show signs of slowing generally for participants with a history of concussion compared to matched controls. Finally, it was anticipated that judgements by trained SLP raters would demonstrate a decrease in articulatory precision, speech rate, rhythmic consistency, and voice quality for those with a history of concussion compared to those with no history of concussion. Below will outline the participant details, the speech stimuli, and the method of participation. Then presented will be the types of measures (objective and subjective) extracted and the statistical analysis method.

Participants

To answer the research questions, concussed and non-concussed matched controls were recruited. Based on previous research examining norms in DDK speech rates of English speakers, an a priori power analysis was conducted (Ben-David & Icht, 2017; Icht & Ben-David, 2014; Phan, 2016b). Results of the power analysis indicated that inclusion of 30 participants in each of two groups (history of concussion and controls with no history of concussion) has 80% power to detect a medium sized effect (.5 or higher Cohen's *d*) at a .05 criterion for determining statistical significance. Therefore, data were collected from 30 participants in each group.

The inclusion criteria for participants with a history of concussion were as follows:

1. Concussion(s) was sports related
2. sustained at least one concussion in the 2 years prior to participation in the current study (diagnosed by a physician or athletic trainer (AT))
3. native English speakers
4. between 19 and 22 years of age
5. no reported history of dyslexia
6. no reported history of neurological disorders
7. no reported loss of consciousness of more than 20 minutes at the time of the concussion event
8. no reported hospitalization for their concussion event.

Recruitment of matched controls (with no history of concussion) were first screen using inclusion criteria 3-6 above. Next, those passing the screening were individually matched to specific criteria of each participant with a history of concussion. Matching criteria included: height (+/- 2 inches, weight (+/- 10 pounds), education, age (+/- 2 years), and birth sex.

All 60 participants were recruited from a central research participant database in College of Arts and Sciences at Michigan State University called “SONA”. These participants set up private accounts containing their personal characteristics which are commonly used as inclusion and exclusion criteria. When researchers add studies to the SONA system they may include/exclude potential subjects from signing up for their study by checking boxes for desirable/undesirable characteristics. Inclusion goals for recruiting the concussed participants and the matching criteria for the controls were part of questionnaires during recruitment and also confirmed later during recording and analysis.

Speech Stimuli

To respond to these two questions, five different types of speech stimuli were acquired to obtain a comprehensive profile of speech in the population of individuals with a history of concussion. These five types of stimuli represent contexts of increasing linguistic and speech motor complexity. These stimuli can be generally divided into two broader speech tasks: repetitive motion DDK speech and continuous spoken phrases. Below are the types of stimuli and the justifications for them. From these stimuli, objective speech timing and acoustic metrics, as well as speech production ratings were conducted.

Diadochokinetic Speech (DDK): Real and non-word DDK tasks were included in the speech production collection protocol of this experiment. These were: (1) non-word single-syllable (*puh-puh…-puh, tuh-tuh…-tuh,* and *kuh-kuh…-kuh.)* AMR DDK, (2) multi-syllable (*puhtuhkuh-puhtuhkuh…-puhtuhkuh)* SMR DDK tasks as well as a (3) real word multi-syllable (*buttercup-buttercup…-buttercup* and *pattycake-pattycake…-pattycake)* SMR DDK.

Justification: Ackermann and colleagues have shown that DDK speech rates are significantly affected in people with neurologic disease, including PD, ataxia, and cerebellar syndrome compared to normally healthy controls (Ackermann et al., 1995). DDK rates have been used to evaluate the speech of individuals with dysarthria and speech motor disorders including those with concussion (Hewitt, 2015; Peiffer-Lapid, 2016; Phan, 2016).It has been reported non-word (*puhtuhkuh*) DDK productions may isolate more of the motor speech effects of speech disorders where real-word productions (*buttercup* and *pattycake*) may rely on language ability and motor speech ability to produce (Ben-David & Icht, 2017). More recent work has investigated DDK (both SMR and AMR) rates in TBI and found several interesting patterns. Wang and colleagues found that following a TBI, DDK productions were lengthened. Additionally, slowed rates were noted and pauses between syllables increased. Interestingly, syllable rates of DDK (AMR and SMR) tasks were comparable to that of participants' conversational speech rate tasks. Perceptual analyses of TBI speech revealed differences in speech and voice production and quality when comparing speech of individuals with TBI to normal healthy participants (Y. Wang et al., 2004; Y.-T. Wang et al., 2005). As the results of previous research suggest, there may be motor speech issues in the concussion population manifested in a decrease in timing measures on traditional and real word DDK (AMR and SMR) tasks. Finally, several studies have evaluated DDK's in athletes with concussion, however, they have not controlled for the time after injury when they participated in each study. This research attempts to control for these important factors. Given findings of previous research in the area of DDK productions and a range of TBI severities, the use of DDK's to measures speech rate in this population is justified and expected to provide meaningful outcomes. Specific hypotheses regarding DDK timing differences between those with a history of concussion and those without a history of concussion are detailed in the research questions and justifications section.

Continuous Speech: Two read passages and one spontaneous speech task were included in the speech production collection protocol of this experiment. The two reading passages, (1a) Rainbow Passage and (1b) Caterpillar Passage, are common passages used to evaluate speech and voice with a long history of documenting timing, acoustic and perceptual measures (Fairbanks, 1960; Patel et al., 2013). The passages can be found in Appendix A and B, respectively. The reading level of each passage is 5th grade and neither is designed to be difficult, but rather to elicit a diverse number of speech sounds. The last spoken passage was a (2) spontaneous speech task. Instructions to participants were to describe what their favorite room in their home or a relative's home looks like. They were encouraged to speak for one full minute thus eliciting a sample of continuous, non-read speech.

Justification: Previously, researchers have used these reading passages to evaluate global speech production metrics such as fundamental frequency and rate in several populations including those with acquired and degenerative brain disease (Patel et al., 2013; Solomon, McKee, & Garcia-Barry, 2001). The Caterpillar Passage specifically was chosen because it was standardized on a population of dysarthric and brain injured speakers. It also has been used to quantify many of the same fundamental frequency characteristics of the voice as the Rainbow Passage. Spontaneous speech can be more complex in that an increased number of brain regions are recruited in comparison to single word repetitions (Troiani et al., 2008). Previous research into the speech of concussed athletes only examined simple measures of timing (overall rate) and acoustics (fundamental frequency) (Falcone et al., 2013; Xia et al., 2016). These were all analyzed from single sentence readings and single word repetition tasks (counting to ten). Thus, to date, no objective timing, acoustic, or perceptual information regarding the speech of individuals with a history of concussion in a non-scripted elicitation mode exists. Further, the only perceptual analyses of concussed speech included intelligibility, rhythm, and rate evaluations of acutely concussed athletes from only two raters with a non-standardized, difficult to replicate assessment method (Peiffer-Lapid, 2016). Peiffer-Lapid notes this as a limitation to her work and thus, the inclusion of perceptual analysis of speech in this manner is justified.

Participant Engagement

Each participant was consented following an explanation of the research protocols. Participants were initially asked to complete a survey to determine their eligibility for inclusion in this study. Participants performed the speech and voice tasks described above. Each task participants performed are detailed below in the procedures and analyses section.

The speech tasks were all recorded using the same system. For consistency, the same three trained individuals were present during instruction and recording of all participants. Recordings were conducted in a double wall sound-sound attenuated booth (IAC Acoustics, North Aurora, Illinois) with internal dimensions of 88”x84”x80” and a natural background noise of 20 dB(A).The speech recordings were to extract timing and acoustic measures as well as for the auditory-perceptual judgment task. An omnidirectional head-mounted microphone (M80, Glottal Enterprise, Syracuse, NY, USA) and a digital recorder (Roland R-05, 44,100 Hz, 24-bit, wav file) recorded each participant’s speech. Additionally, the microphone (MIC) signal was simultaneously recorded by a PowerLab 8/35 (ADInstruments, New South Wales, Australia) connected to a laptop computer for redundancy. The different speech tasks were prepared for analysis using Audacity (audacityteam.org [Computer application]. Version 2.2.2).

All participants performed the following tasks: non-word DDK (AMR, SMR), real-word DDK stimuli (SMR), and continuous speech tasks (short paragraph readings and spontaneous speech sample elicited by an open-ended question: “describe your favorite room in your house or your parents’ house”; Figure 3.1). Each participant performed one of three randomizations of these tasks to offset any speech task order effect. Participants with no history of concussion were given the same randomization as the participant with a history of concussion to whom they were matched. DDK tasks were practiced once before the recording to ensure that all participants were able to perform them and reduce variability due to potential reading ability, lack of task familiarity, and/or lack of context familiarity. To improve the ability to compare timing measures extracted from the task, a time-by-count method was employed (Fletcher, 1972). This meant that participants were asked to repeat DDK target syllable ten times as quickly and consistently as possible. Prior to performing the recorded trial, a model was provided by the investigator and participants were allowed to practice each DDK task three times prior to performing the recorded trial. Times for each of the three sets of ten repetitions were collected for averaging in later analysis. Short paragraphs were read once aloud prior to recordings as practice and to clarify any new words or pronunciation if needed.

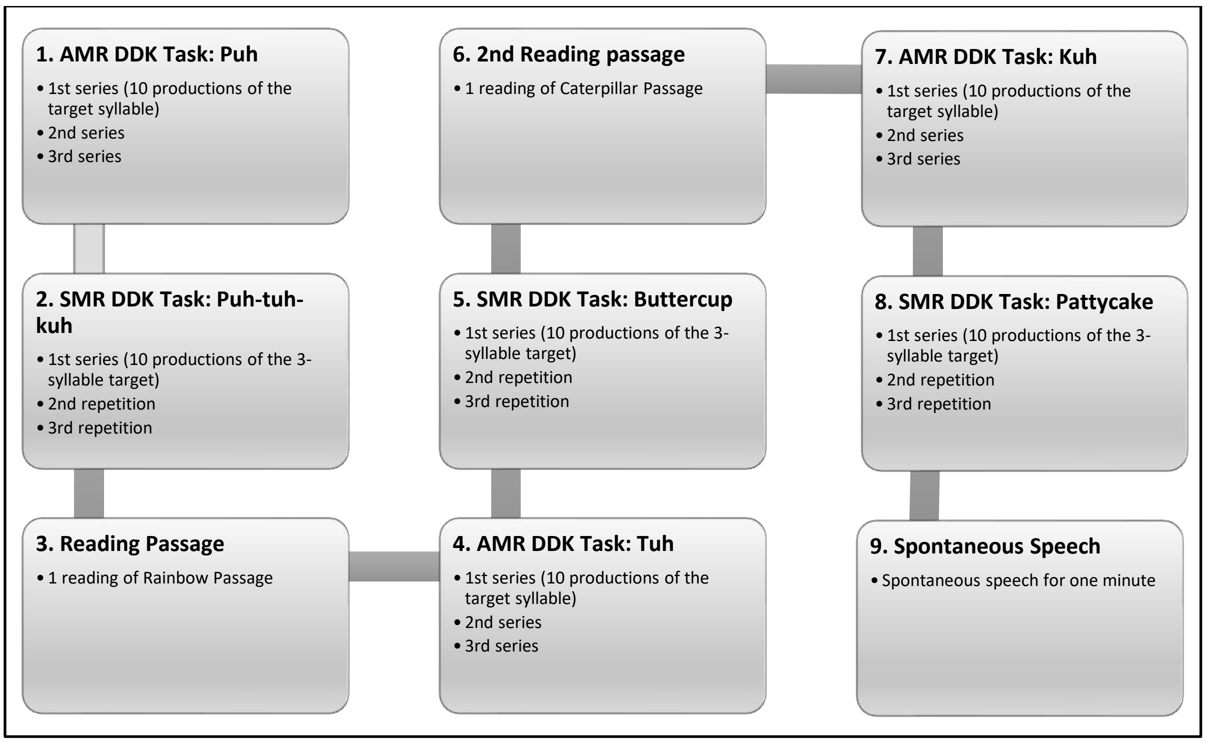

Figure 3.1. Description of one randomization of the possible three given to participants. All three randomizations included the same nine speech tasks; however, presentation order was randomized between them.

For analysis (objective and subjective) preparation, participant recordings were segmented by task and rendition. Segmentation was done in Audacity free audio manipulation software. During multisyllabic word productions (“puhtuhkuh”, “buttercup”, “pattycake”), only correct productions in a series were used in the analysis (example:

“puh-tuh-kuh, puh-*kuh*-tuh, puhtuhkuh, puh-*puh-kuh*” would exclude “puh-kuh-tuh” because the correct target is “puh-tuh-kuh”). However, such errors were tracked for future analysis. Sets of AMR and SMR productions were segmented following segmentation guidelines described by Dolan, Phan and Hewitt’s experiments described in previous chapters (2016). Three sets of ten correct repetitions were counted during each AMR and SMR task using audio and, when necessary, spectral and wave form settings in Audacity. These ten productions were used in the statistical analyses described below. Timing and acoustic measures for each set of 10 repetitions were then averaged and used in statistical analysis. Paragraph readings and spontaneous speech productions were segmented at the first sign of speech pulses in Audacity software and then at the end of speech. In accordance with previous research, only the second and third sentences of the Rainbow passage were included in each set of analyses (Awan, Roy, & Cohen, 2014; Gelfer & Schofield, 2000; Hillenbrand & Houde, 1996). This is also helpful in facilitating perceptual analysis.

Using the segmented speech recordings from each of the task types and repetitions, objective and subjective metrics were extracted. These included metrics which would capture both the timing and the quality of the produced speech.

Speech Timing Measures

Speech timing measures were extracted from the range of repeated motorically complex speech tasks (single AMR, multi-syllable SMR, and word production samples). While there are many timing measures which could have been included, the three chosen could be applied to all types of speech tasks. These include: Estimated Average

Time Per Syllable, Average Voicing Time per Syllable, and Average Non-Voiced Time Per Syllable. The latter two are estimates of speech length and pause length.

Average Time Per Syllable: Previous work has examined motor speech rate in individuals with severe TBI (Wang et al., 2005) with results indicating speech timing differences in individuals with more severe head injury and resulting dysarthria compared to normal uninjured speakers.

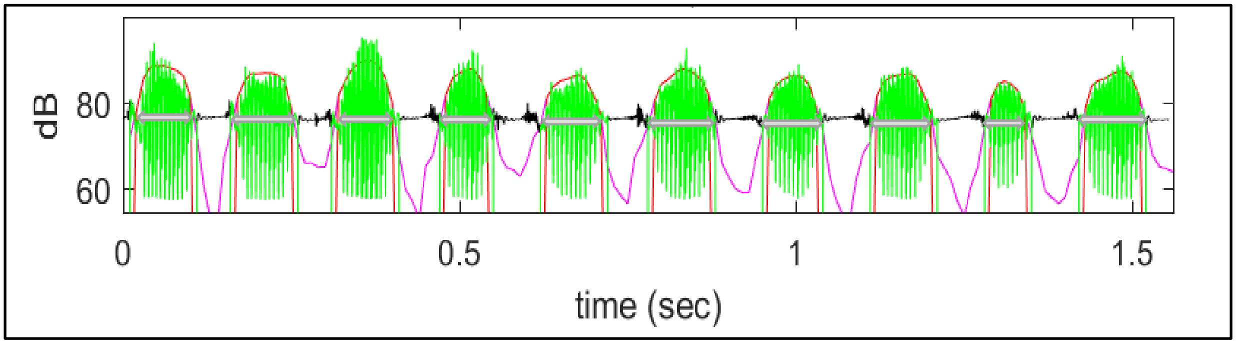

Figure 3.2. A sample wave form from male participant in this study. Green areas indicate 10 repetitions analyzed in a one bout of repetitions. Blue arrows indicate the rough areas making up the average voicing time per production.

Additionally, previous research has examined motor speech rate during DDK speech tasks in individuals with acute concussion only (Dolan, 2013; Hewitt, 2015; Peiffer-Lapid, 2016; Phan, 2016). This previous research, while inconclusive, has shown generally that speech rate may be affected by acute concussion. As previous research has indicated that motor speech rate is affected by acute concussion, the investigation of speech rate in those with a history of concussion compared to those with no history of concussion is justified. Participants were asked to produce 3 sets of at least 12 repetitions of each AMR and SMR sequence in order to assure that the requisite ten correct repetitions were produced for analysis. These recordings were then segmented as detailed below, and final segmentations included the 2nd -11th correctly produced target (Figure3.2). During spontaneous speech samples, 1 minute of speech was recorded and segmented. These segmented recordings were used as the basis for all timing, acoustic and perceptual analyses discussed. To calculate the estimated average time per syllable, the total length of the production (file length) of the ten repetitions of DDK word, reading passages and spontaneous speech were individually divided by the number of syllables produced in that file (10 syl. for AMR's, 30 for SMR's, 50 for the two included sentences of the Rainbow passage, 261 for the Caterpillar passage, and the total number of syllables produced during spontaneous speech; Table 3.1). Incorrect syllable productions were not counted toward the overall 10 or 30 needed in AMR and SMR tasks respectively. The number of errors produced in recordings was noted in order to account for its potential influence on outcomes. Due to the potential inclusion of artifacts (production errors, vocal fry, etc.) this measure establishes an estimation and is named as such. Thereby, an average time per syllable of each of the following was obtained: puh, tuh, kuh, puh-tuh-kuh, buttercup, pattycake, syllables produced during the reading of standardized passages and during spontaneous speech.

		Type	Production	Syl count
DDK	*3 renditions of 10 word sequence*	AMR AMR AMR	puh-puh-[…7 more…]-puh tuh-tuh-[…7 more…]-tuh kuh-kuh-[…7 more…]-kuh	10 10 10
		SMR SMR realword SMR realword	puhtuhkuh-puhtuhkuh-[…7more…]-puhtuhkuh pattycake-pattycake-[…7more…]-pattycake buttercup-buttercup-[…7more…]-buttercup	30 30 30
Spoken	*1 rendition*	Rainbow (Middle 2 Sentences)	"…The rainbow is a division of white light into many beautiful colors. These take the shape of a long round arch, with its path high above and its two ends apparently beyond the horizon…"	50
		Caterpillar	Do you like amusement parks? Well… memorable moment ever!	261
		Spontaneous	For 1 minute-- "describe your favorite room in your house or your parents' house"	variable

Table 3.1. Speech tasks and the number of syllables associated with each.

Estimated Average Time Per Syllable Hypothesized Outcome: It was hypothesized that individuals with a history of concussion would exhibit significantly slower speech rates compared to those with no history of concussion.

***Average Voicing Time Per Syllable*:** As highlighted previously, research has examined both the time per syllable production and unvoiced time in speech of individuals with TBI. To measure a true average time per syllable and pause would require a time marking of each production (60 subjects x 170 repeated syllables = 10,200 syllable to measure) and would be subject to human judgment of start and stop time. To reduce variability and be more systematic, the voicing time within the speech was utilized to estimate the length of a syllable (e.g. total voicing time of 10 puh repetitions divided by 10). Likewise, the unvoiced time per syllable could be estimated using the (total recording time – total voicing time) / 10 repetitions. As the average time per syllable measure (as performed in this dissertation) could have been affected by the amount of time the voice was engaged, the estimated average voicing time per syllable was calculated. In this way, this dissertation can provide a more comprehensive analysis of speech timing. Voicing time was estimated during the acoustic analysis of the recordings as it is a byproduct of speech fundamental frequency analysis. Therefore, the details of estimating voicing time are presented below in the Acoustic Speech Measures section. Nevertheless, given the estimated average time per syllable, the average voicing time per syllable was calculated by subtracting the total unvoiced time from the total length of each recording and subsequently dividing the output by the number of syllables calculated for each task. Figure 3.2 roughly depicts the voicing detection (blue marks that are segmented with the red vertical lines) that was included in the analysis of a male participants *kuh* productions.

Speech abnormalities in the concussion population have been noted as an acute sign of concussion but have not yet been quantified objectively or subjectively in those with a history of concussion compared with those who have no history of concussion (Echemendia et al., 2017; Gallagher et al., 2017; McCrory et al., 2002). These shortcomings coupled with previously mentioned research which details speech timing differences in those with more severe head injury provide the justification for the analysis of timing differences in those with a history of concussion (Wang et al., 2005).

Voicing Time Per Syllable Hypothesized Outcome: It was hypothesized that individuals with a history of concussion would demonstrate increased voicing time contributing to an overall increased average time per syllable compared to individuals without a history of concussion.

Average Unvoiced Time Per Syllable**:** Some researchers have examined speech pauses in individuals with TBI (Wang et al., 2005) This research found significantly increased unvoiced time for individuals with severe head injury and resulting dysarthria compared to normal uninjured speakers without dysarthria. However, pauses during motor speech tasks in individuals with a history of concussion compared to those with no history of concussion have not been accounted for in current literature (Dolan, 2013; Hewitt, 2015; Peiffer-Lapid, 2016; Phan, 2016). The lack of research regarding the effect of concussion history on unvoiced time was one justification for its inclusion in this research. Additionally, as unvoiced times have been shown to be affected by more severe brain injury, the examination of unvoiced times in SRC is warranted. Interestingly, recent research examining pause rates during speech in individuals with primary progressive aphasia (PPA) discovered a significant increase in pause rate when compared to healthy controls (Nevler, Ash, Irwin, Liberman, & Grossman, 2019). This increase in unvoiced time during speech were associated with two factors: 1) an increase in left inferior frontal cortex atrophy due to the progressive nature of PPA and 2) an increase in phosphorylated tau protein measured in the cerebrospinal. As these two factors are both associated with the effects of concussion, it is anticipated that increased speech pause lengths will be present in those with a history of concussion compared to those with no history of concussion. Pause length will be estimated using non-voice time per syllable.

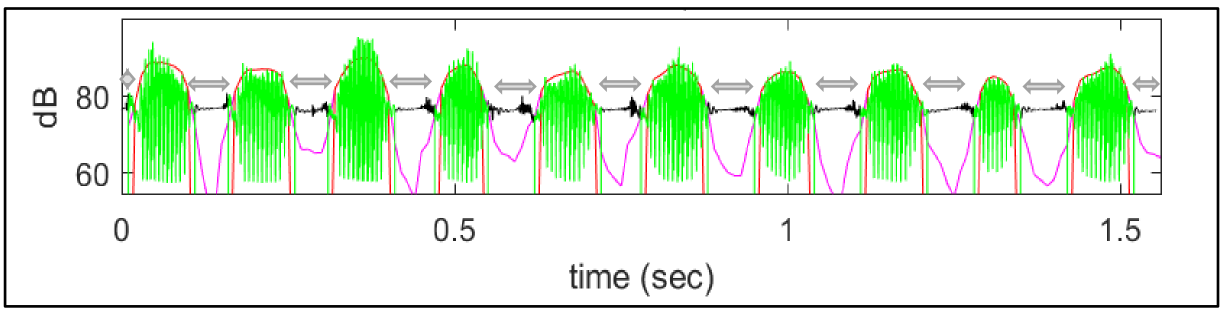

Figure 3.3. A sample wave form from male participant in this study. Blue arrows indicate the rough areas summed to make up the average total unvoiced time metric.

As the amount of non-voiced time (calculated in this dissertation as the time where voicing was not detected may have an effect on both average time per production and the perceptual analyses of the speech in those who participate in this research, the total unvoiced time of each recording was measured (e.g. total voicing time of 10 puh repetitions divided by 10). Additionally, the amount of unvoiced time could have an effect on the average time per syllable measure calculated in this dissertation, therefore, it was important to see if either unvoiced time, voiced time, or both might contribute to significantly longer general productions of syllables during speech tasks. This analysis was carried out using an automated Matlab script outlined in recently published literature (Bottalico, Astolfi, & Hunter, 2017; Picheny, Durlach, & Braida, 1986) using speech dB amplitude and frequency filters to establish where speech was likely present versus where pauses were present. Figure 3.3 shows the final analysis of a males' production of 10 *kuh* AMRs. The red vertical lines to the left and right of each voiced segment are the predicted voiced sections. Average unvoiced times per syllable were calculated as the space between sets of vertical red lines (highlighted below with blue arrows) and averaged over participants' three DDK productions. Each automated prediction of voicing performed in Matlab was manually reviewed for accuracy by the author.

Average Unvoiced Time Per Syllable Hypothesized Outcome: As previous research has shown that in severe and progressive brain injury, significantly longer unvoiced times are present compared to non-injured controls, it is anticipated that the same will be true of those with a history of concussion compared to those with no history of concussion. Specifically, it is hypothesized that the average total unvoiced time measured during recordings of DDK tasks, reading passages, and spontaneous speech will be longer for those with a history of concussion compared to those with no history of concussion.

Pilot Research in Speech Timing of Acute Concussion

In a pilot study conducted by the investigator, the acoustic speech characteristics of concussed athletes done in partnership with the University of Notre Dame the speech of concussed athletes were examined. Participants' ages and time after injury upon recruitment were not described, only that they were high school and college age student athletes in Midwestern United States who had ("within a few hours") or had not recently sustained a concussion. Speech recordings from 110 athletes in high schools and colleges throughout the Midwest were collected by Dr. Christian Poellabauer and his colleagues at the University of Notre Dame. All participating athletes responded to a brief survey eliciting basic demographic information: gender, age, place of origin, and whether or not they had sustained a concussion prior to participating in this study. Those athletes who had a history of concussions were not included. Youth athletes were predominantly male (86%, 14% female) football players, who ranged in age between 14 and 24 years. Other confounding factors that could affect the test results (e.g., medications, learning and neurological disorders, orthodontic treatment) were also identified (Collins et al., 1999) and used as exclusion criteria.

Each athlete who participated in this pilot study performed at least two sets of recordings: before the start of the sports season (baseline) and after sustaining a concussion. Athletes' concussions were diagnosed by an AT or a physician within an average of 20 hours of sustaining a head injury. When a head injury was sustained, athletes were recorded again and thus, a pre-injury (baseline) and post-injury recording were gathered.

Participating athletes completed a series of speech tests recorded via Apple iPad. These speech tests, though novel regarding the specific token used, were patterned after several common speech and articulation assessments designed to evaluate features of speech production such as stress, rate, clarity, and prosody (Karnell et al., 2007; Kempster, Gerratt, Abbott, Barkmeier-Kraemer, & Hillman, 2009;

Skodda & Schlegel, 2008). Participants performed 7 tasks, described below in Table 3.2 (adapted from Tao et al., 2016).

ID	STIMULUS	DESCRIPTION
Task 1	Participate, Application, Education, Difficulty, Congratulations, Possibility, Mathematical, Opportunity	Combination of front, mid, and back sounds phonemes
Task 2	*PUT* the book here, Put the BOOK here, Put the book HERE	Stress patterns
Task 3+	"We saw several wild animals"	Reading accuracy task
Task 4	Puh, Puh, Puh	Diadochokinetic (DDK) Tasks
Task 5	Kuh, Kuh, Kuh	
Task 6	Puh, Tuh, Kuh	
Task 7	Sustained "Ah" vowel	Common voice analysis

Table 3.2. Tasks analyzed in pilot voice research. (Tao et al., 2016).

Results indicated that athletes' post injury DDK tasks were produced at a significantly slower rate when compared to their preinjury DDK recordings. Figure 3.4 demonstrates the significant differences in the timing of DDK productions in this pilot research. This speech timing difference for athlete's post-concussion may indicate a decreased ability to turn the voice "off" after a concussion thus, resulting in longer DDK productions. It may also be evidence of a change in the neuromuscular activation of articulatory muscles used for speech production following a concussion. This would be similar to the decreased movement rates that have been described in the peripheral muscles of the hands of those with a history of concussion (De Beaumont et al., 2007; N. R. Miller et al., 2014). Speech timing results obtained from this sample of young adult provided rationale for a further, more in-depth investigation of speech timing differences between individuals with a history of concussion and those individuals who have never been concussed.

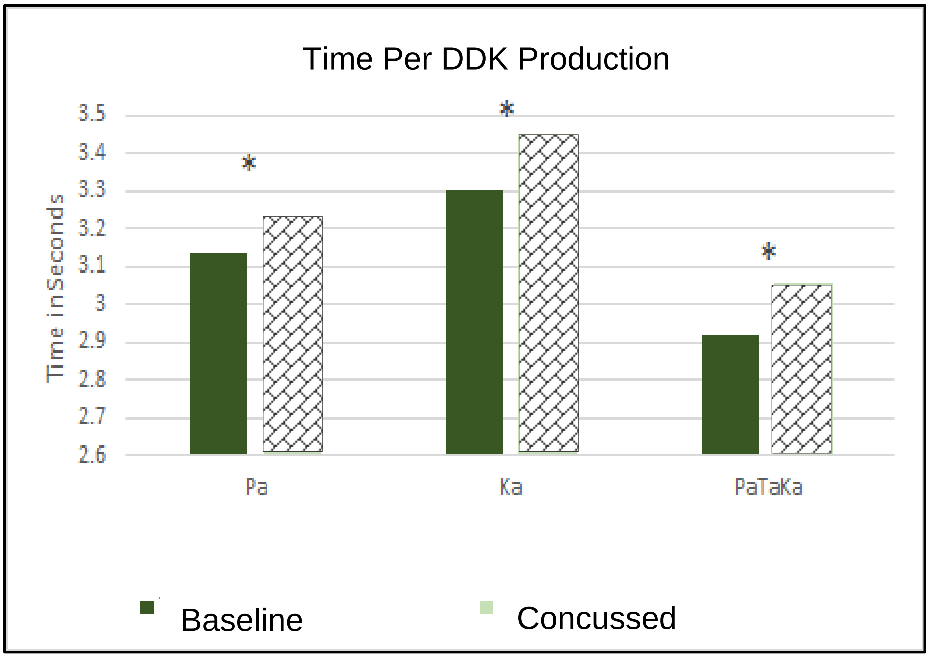

Figure 3.4. Results of pilot research for speech timing of athletes' DDK productions comparing baseline attempts to post concussion recordings of the same athletes.

Acoustic Speech Measures

Four acoustic speech measures were extracted from the range of motorically complex speech tasks (single AMR, multi-syllable SMR, and word production samples, read speech, spontaneous speech). These include: Speech Fundamental Frequency (f_0: mean and standard deviation), Smoothed Cepstral Peak Prominence (CPPs), and Pitch Period Entropy (PPE). Acoustic speech measures were extracted from speech recordings and were analyzed using custom Matlab (www.mathworks.com) scripts calling PRAAT software to perform some of the analysis (www.fon.hum.uva.nl/praat/). Use of these customized scripts has been reported elsewhere (Banks, Kleinfeld, Hunter, & Berardi, 2017; Cantor-Cutiva, Bottalico, Ishi, & Hunter, 2017; Kopf et al., 2017). Generally speaking, the scripts estimate speech regions in a recording and estimates of voicing (Figure 3.5, top graph, turquoise is voicing areas). Voicing was determined to be between 70-300 Hz for males and 100-350 Hz for females. Additionally, dB levels of speech and noise were measured for each recording, thresholds for each were established and together speech and pitch measures were used to determine if speech was present. Thresholds of speech dB were established and used to determine. Within these voicing areas, the speech fundamental frequency is estimated in 30 millisecond intervals (Figure 3.5, middle graph). Speech fundamental frequency estimators are more accurate when given a range near where an individual's vocal pitch occurs. These scripts automatically find the range for each individual, therefore all recordings had their own unique search range. As each segmented file was analyzed, a resultant graphic output (e.g. Figure 3.5) was created to verify the automatic range as well as overall analysis. Fundamental frequency estimation was performed combining three extraction routines to minimize artifacts: PRAAT, AudSwipe' (Camacho & Harris, 2008; Kopf et al., 2017), and SHRP (Sun, 2002). This f_0 extraction was used as the basis for the standard deviation of the f_0 measure obtained from speech samples. The standard deviation of f_0 is considered to provide a general picture of the dynamic range of the voice, where higher standard deviations are associated with more dynamic range and lower standard deviations of f_0 are associated with less dynamic, more monotone voice profiles. CPPS was estimated using techniques outlined by Maryn and Weenink (2015). PPE was calculated using techniques presented by Little et.al (2009) in a study of Parkinson's voice.

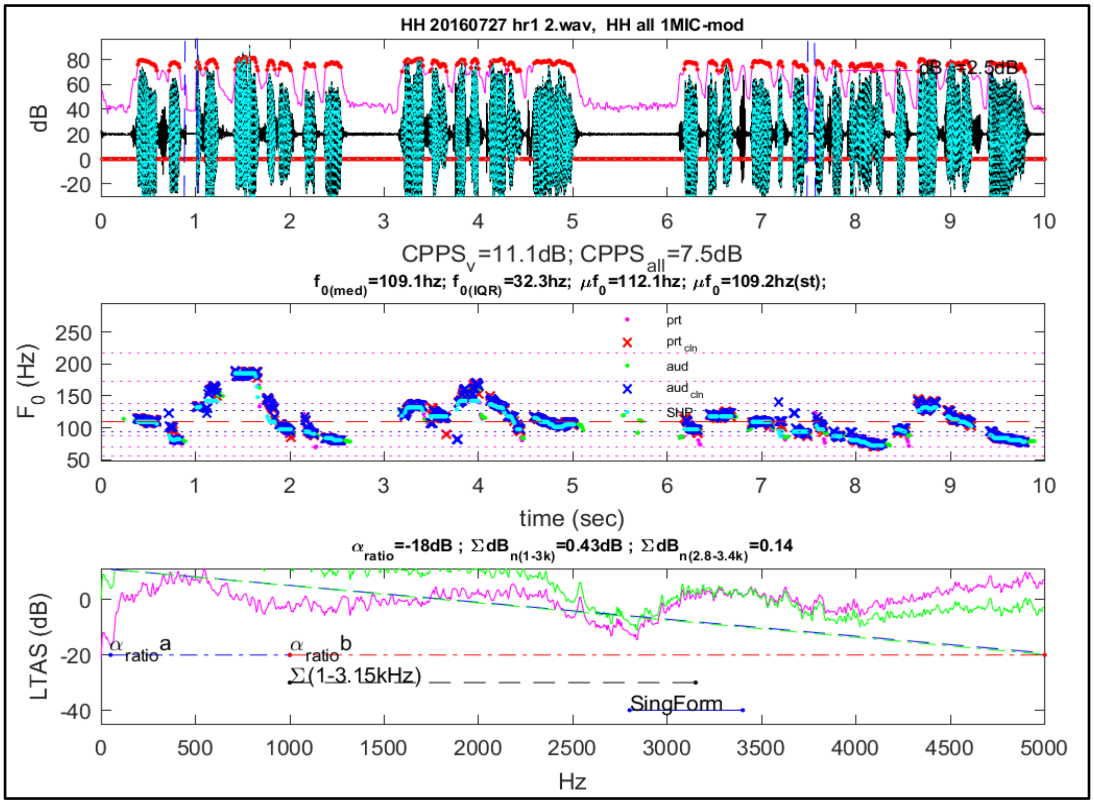

Figure 3.5. An example of the graphical result from the acoustic analysis of 10 seconds of connected speech. The upper graph indicates the temporal waveform; the middle graph shows the fundamental frequency contour, and the lower graph the spectrum of the speech.

Speech Fundamental Frequency (Mean and Standard Deviation):

Fundamental frequency analysis of sustained vowel productions and speech has been used to evaluate voice quality for many years including in individuals who have sustained a TBI (M. McHenry, 2009; Patel et al., 2013). The analysis of isolated vowel sounds has also been used to predict the presence of concussion (Falcone et al., 2013). This is a relatively rapid and reliable analysis to perform and can be used to perform perceptual analyses of pitch and voice quality. Though considerable variations make it difficult to compare between groups of individuals, speech f_0 analysis has been a common piece of voice analysis used to detect subtle changes in the voice and may indicate tonicity and stability control of the vocal folds (Horii, 1975). It may also be used to quantify diseases where tremor is noted as a biomarker of neurological disease (Arora et al., 2015; Tsanas et al., 2012). The Caterpillar Passage has been used to evaluate f_0 and its range in the dysarthric population (Patel et al., 2013). Additional research has indicated that changes in f_0 may be characteristic of individuals who have sustained a concussion (Falcone et al., 2013). These measures were applied to all tasks performed by participants in this study.

More importantly, recent research involving individuals with primary progressive aphasia (PPA) has discovered a decrease in f_0 range compared to healthy controls (Nevler, Ash, Irwin, Liberman, & Grossman, 2019). This decrease in f_0 was associated with an increase in left inferior frontal cortex atrophy and increased phosphorylated tau protein in cerebrospinal fluids. Frontal cortex damage and increased phosphorylated tau are both associated with several of the effects of CTE described in Chapter 2. Due to their use in previous literature examining degenerative, progressive, severe and mild brain injury, the analysis of f_0 and standard deviation of the f_0 in this dissertation is supported.

Mean f_0 and Standard Deviation of f_0 Hypothesized Outcome: It is anticipated that, consistent with previous research involving athletes with acute concussion and individuals with progressive brain injury, the average f_0 will not be significantly different between groups with a history of concussion and those with no history of concussion. In terms of the f_0 standard deviation, however, it is hypothesized that there will be significantly different decreased in those with a history of concussion compared to those with no history of concussion. Similar to those which occur in some aphasias, it is anticipated that those with a history of concussion will demonstrate a narrowed or decreased f_0 range compared to those with no history of concussion (Nevler et al., 2019).

***Smoothed Cepstral Peak Prominence (CPPs)*:** The CPPs measure has been shown to be sensitive to breathiness in voice signals (Peterson et al., 2013) and is not easily affected by signal noise which can be present in some audio recordings such as those gathered in this dissertation. As breathiness is associated with the voices of individuals following a more severe head injury (M. McHenry, 2009), it is anticipated that it will also be sensitive to the potential change in acoustic speech associated with individuals with a history of concussion

CPPs is a measure of the amplitude of fundamental and harmonic signal averaged, in the case of this dissertation, of the voice over time (Heman-Ackah et al., 2003; Hillenbrand, Cleveland, & Erickson, 1994). Specifically, this measure was calculated as the distance between inverted harmonic and frequency peaks. These were found by creating a regression line through the inverted spectral plane (Maryn & Weenink, 2015). When a more prominent peak is obtained, it is most commonly the result of a more harmonic (less noisy, breathy, or otherwise increased quality voice signal) to and periodic voice signal. This measure has been shown to be robust to many factors which often influence the quality of speech recordings (Eadie & Baylor, 2006; Heman-Ackah, Michael, & Goding, 2002; Maryn, Corthals, Van Cauwenberge, Roy, & De Bodt, 2010). These studies have been shown CPPs to be especially sensitive to breathiness, where breathier voices result in a decreased CPPs.

CPPs Hypothesized Outcome: It is hypothesized that participants with a history of concussion will demonstrate significantly decreased CPPs values compared to participants with no history of concussion. This, it is anticipated, may also be related to a perceptual decline in overall voice quality as rated by SLP listeners in this study.

Pitch Period Entropy (PPE): Various measures of entropy have been used in the classification and identification of individuals with Parkinson's Disease as well as other degenerative brain diseases (Arora et al., 2015; Little, McSharry, Hunter, Spielman, & Ramig, 2009; Tsanas, Little, McSharry, Spielman, & Ramig, 2012). As hypothesized above, it is anticipated that due to the variations likely present in the average pitch (the perceptual correlate of f_0) range there will be a difference in the pitch patterns associated with speech of individuals with a history of concussion compared to those with no history of concussion.

Specifically, PPE measures the impaired control of f_0 during sustained phonation based on the probability of a recurring pitch pattern taken from an individuals' phonated speech (Little et al., 2009). Traditionally, PPE has been used as a measure of the control individuals are able to maintain over a stationary pitch, often during a sustained phonation. This measure importantly takes into account the natural pitch differences in the voice (e.g. male vs female) as well as the natural, normal vibratory nature of the voice. Thus, using a logarithmic transformation, PPE is reported to be robust to naturally occurring voice characteristics which can be a challenge in general voice assessment. A PPE values near 0 is indicative of a healthy, stable and regular voice with natural vibratory characteristics, where values closer to 1 indicate a less healthy, more unstable and irregular vibratory nature and uncontrolled $f_{0.}$

<u>PPE Hypothesized Outcome:</u> It is anticipated that there will likely be less of a predictable periodic pattern in the f_0 variations of those with a history of concussion

compared to those with no history of concussion. Thus, it is hypothesized that those participants with a history of concussion will demonstrate higher PPE measures than those with no history of concussion.

Pilot Research in Concussed Voice Acoustics

Further acoustic speech analyses were performed on data gathered for this pilot study. Much of this previous work compares voice recordings pre and post-injury within and between subjects to identify changes in acoustic output measures (e.g., jitter, shimmer, f_0, etc.). Results from this pilot research indicated that there may, in fact, be significant differences in the voice (f_0, jitter, shimmer, and formant frequencies) following a concussion (Banks et al., 2017; Dettmann et al., 2018). Further, in ideal cases (no noise, high quality microphone, notable speech deficits), some simple rudimentary voice analyses may be used to predict concussion status, as measures of voice quality indicated significant differences before and after concussions were sustained. However, as these were field recordings, there several limitations inherent with this type of data collection including the methods of recording, consistent microphone distance to the sound source, microphone quality, consistency of instructions given by examiners, etc. Additionally, Poellabauer and his colleagues have recently described the difficulties of speech analysis of athletes following SRC, the analyses they applied to the voices of individuals following concussion are easily affected by background and environmental noise, baseline voice quality, etc. (Poellabauer et al., 2015). Measures applied in this dissertation, while still influenced by fundamental frequency, are very robust to signal noise and thus, may provide more insight into the acoustic speech differences between individuals with a history of concussion and individuals without a history of concussion.

Research to date has yet to report a comprehensive examination of the acoustic features and the perceptual characteristics of speech in individuals with a history of concussion. This would greatly assist in the development of a general analysis protocol of speech and voice of individuals with a history of concussion. This dissertation research provides a more complete analysis of the voice for those with a history of concussion compared to controls without a history of concussion.

Perceptual Measures

Using the speech recordings of participants in this study, each speech task was evaluated by trained SLP raters using the four perceptual parameters outlined in the previous chapter to quantify various speech and voice differences between groups. These perceptual measures included: Articulatory Precision, Rate, Rhythmic Consistency, and Voice Quality. Judgements were made on a 100 point scale with each end of the scale representing each end of severity (-50 = increased impairment compared to modulus provided in articulatory precision, rate, rhythmic consistency, or voice quality; +50 decreased impairment compared to modulus provided on each of the rating parameters). This was done to provide a comprehensive overall perspective regarding how the speech was perceived by trained SLPs during each task. All six licensed SLP raters were instructed on evaluation procedures and given detailed definitions for the perceptual measures below. They were also provided a modulus for comparison for each task. This modulus, they were told, demonstrated a “normal” articulatory precision, rhythmic consistency, rate, or voice quality, depending on the parameter being evaluated. Definitions and detailed descriptions of these measures are provided. Again, justifications for inclusion and hypothesized outcomes are also outlined.

Articulatory Precision and Rhythmic Consistency: Samlan and Weismer defined articulatory precision as “the accuracy with which the speaker produced the consonant and vowel targets.” They then defined rhythmic consistency as “the uniformity of the length of each segment and the time between segments” (Samlan & Weismer, 1995). Recent work subjectively rated the DDK speech of concussed individuals in terms of “accuracy” and “precision” (Peiffer-Lapid, 2016). However, Peiffer-Lapid’s work made no specific mention of what was being trained in order to rate these parameters. It may be that this lack of a uniform definition for these measures is what led to the findings of her experiment: increased speech accuracy following a concussion. The proposed research will use previously defined measures of articulatory precision and rhythmic consistency to rate the accuracy and precision of concussed speakers (Samlan & Weismer, 1995).

Articulatory Precision and Rhythmic Consistency Hypothesized Outcome: It is hypothesized that trained SLP raters will perceive less articulatory precision and rhythmic consistency during speech tasks produced by participants with a history of concussion compared to those with no history of concussion.

Rate: Due to the general objective evidence which suggests that speech rate decreases in individuals with acute concussion, the inclusion of a perceptual rate analysis is warranted. Additionally, further research is needed in this area as very little published research exists on this topic.

Previous research has found objective differences in speech rate between individuals with an acute SRC and those without (Dolan, 2013; Hewitt, 2015; Nevler et al., 2019; Peiffer-Lapid, 2016; Phan, 2016b). However, no study to date has described a formal subjective judgement of speech rate in this population with a sufficient number of raters. SLP's in this dissertation were provided a modulus to compare each recording in terms of rate, which has been shown to increase reliability between and within raters. It was anticipated that trained SLP raters with a consistent modulus for comparison, would note changes in rate in speech of those with a history of concussion compared to the speech of those without a history of concussion.

Rate Hypothesized Outcome: It is hypothesized that trained SLP raters will perceive a slower rate during speech tasks produced by participants with a history of concussion compared to those with no history of concussion.

Voice Quality: Previous research involving concussed individuals has found differences in basic rate and timing measures which may affect the perception of voice quality, including f_0 and unvoiced time during speech (Dolan, 2013; Hewitt, 2015; Nevler et al., 2019; Peiffer-Lapid, 2016; Phan, 2016). However, no study to date has described a formal subjective evaluation of voice quality in this population. SLP raters in this dissertation were instructed to consider voice quality as the overall aesthetic and general functionality of the voice. This instruction was patterned after instructions given in CAPE-V and GRBAS ratings detailed in the previous chapter (Karnell et al., 2007; Kempster et al., 2009; Stráník, Čmejla, & Vokřál, 2014).

Voice Quality Hypothesized Outcome: It is hypothesized that trained SLP raters will perceive a decrease in voice quality during speech tasks produced by participants with a history of concussion compared to those with no history of concussion.

Speech Stimuli and Speech Measures

A sample protocol used in the collection of data can be found in Appendix c. Additionally, Table 3.5 details each of the tasks and analyses that were performed on each participants' recording as well as the justification for the inclusion of each set of analyses.

Tasks	Timing Analysis (Primary Measure)	Acoustic Analysis	Perceptual Analysis
DDK-Alternating Motion Rates (puh; tuh; kuh)	Estimated average length per syllable (total time to produce 10 repetitions in seconds/ 10 repetitions) Average voicing time per syllable: total voicing time over the length of 10 repetitions/ 10 repetitions Average unvoiced time per syllable: total time to produce 10 repetitions in seconds– voicing time)	f_0 Standard Deviation f_0 Variance PPE CPPs	Auditory-perceptual Rating of: Articulatory Precision; Rate Rhythmic Consistency; Voice Quality
DDK – Sequential Motion Rate (puh-tuh-kuh)	*Same as 'DDK -Alternating Motion Rates'*	*Same as 'DDK -Alternating Motion Rates'*	*Same as "DDK-Alternating Motion Rate"*
DDK- Real Word (Pattycake, Buttercup)	*Same as 'DDK -Alternating Motion Rates'*	*Same as 'DDK -Alternating Motion Rates'*	*Same as "DDK-Alternating Motion Rate"*
Rainbow Passage – 1st Paragraph	Average length of single word (total time to read passage in seconds/ number of words in the passage) Voice length per word: (total voicing time over the length of 10 repetitions/ number of words in the passage) Total Pause Length per paragraph (total time to read passage in seconds– voicing time)	*Same as 'DDK -Alternating Motion Rates'*	*Same as "DDK-Alternating Motion Rate"*
Caterpillar Passage	*Same as 'Rainbow Passage'*	*Same as 'DDK -Alternating Motion Rates'*	*Same as "DDK-Alternating Motion Rate"*
Spontaneous Speech	*Same as 'Rainbow Passage'*	*Same as 'DDK -Alternating Motion Rates'*	*Same as "DDK-Alternating Motion Rate"*

Table 3.3. List of stimuli (TASKS) and timing, acoustic, and perceptual analyses that will be carried out on each task. The final column provides a small justification for the inclusion of each task; however, further detailed justification is provided below.

Statistical Analyses

Multi-level modeling was used to analyze data obtained in this dissertation as it is particularly suited to account for multiple sources of variability (Goldstein, 2011; Volpert-Esmond, Merkle, Levsen, Ito, & Bartholow, 2017). Statistical packages lme4 (Bates, Mächler, Bolker, & Walker, 2014), lmerTest (Kuznetsov, Brockhoff, & Christensen, 2016), and emmeans (Lenth, 2017) including Kenward-Roger degrees of freedom approximations, were used to perform analyses within R software version 3.5.1 (Team, 2013). Final analysis included 58 participants (29 with a history of concussion, 29 with no history of concussion). All analyses carried out in this study used an $\alpha = 0.05$ to indicate significance.

Separate z-scores were computed for males and females (as reported by each participant) on each speech timing analyses. Next, speech tasks within each level of task complexity were collapsed (e.g. z-scores for *puh, tuh,* and *kuh* productions were collapsed across task complexity into one composite: AMR). The z-scores were also collapsed across timing analysis methods (i.e. all objective timing measures of estimated time per syllable, voiced and unvoiced time per syllable were averaged into one composite measure: objective timing; all subjective timing measures of articulatory precision, rate, and rhythmic consistency were averaged into a single composite measure: subjective timing). Thus, the first model analyzed speech task complexity, and timing analysis methods using a 2 (Concussion Status: 0 or 1) x 3 (Task Complexity: AMR, SMR, Connected speech) x 2 (Analysis Method: Objective Timing, Subjective Timing) univariate multi-level model controlling for the random variance associated with each participant.

Separate z-scores were computed for males and females (as reported by each participant) on each acoustic voice quality analyses. Next, z-scores for all speech tasks were collapsed within each level of task complexity. Thus, the second model analyzed speech task complexity, and acoustic voice quality analysis methods using a 2 (Concussion Status: 0, 1) x 3 (Task Complexity: AMR, SMR, Connected speech) x 2 (Analysis Method: Objective Acoustic, Subjective Acoustic) univariate multi-level model controlling for the random variance associated with participants.

CHAPTER 4: Results

Demographics

Nearly 200 individuals were filtered during screening after having not met inclusion criteria (or having met exclusion criteria) via the online inclusion/exclusion questionnaire used to enroll participants in this study. Thirty SRC participants were recruited (16 females, 14 males); however, after data collection one participant (male) was removed due to inconsistencies in their responses and thus, he did not meet inclusion criteria. A table of general demographics is provided in Appendix D. Participants with no history of concussion were matched to participants with a history of concussion based on height, weight, and age. No statistically significant between group differences were observed in these control factors (Table 4.1). Additionally, there were 30 matched controls who consented to participate in this research. Full demographic details are available in table 4.2.

	No History of Concussion	Concussion History	*P*
Height (in.)	68.05	67.3	0.2
Weight (lbs.)	155.8	153.9	0.1
Age (YOB)	1997.5	1997.7	0.6

Table 4.1. Descriptive statistics for participant demographics used as control variables.

Analyses were run using concussion status as the independent variable (0 = never previously concussed; 1 = history of 1+ concussion) in order to determine if previous concussions influenced timing measures and acoustic measures listed in Table 3.3.

Descriptive Analysis

Presented in this section are the descriptive statistics and associated figures related to the raw data collected from participants in this study. First, tables 4.2 and 4.3 provide descriptive statistics by sex and concussion status the raw values obtained for objective and subjective timing analysis respectively. All objective timing analysis collected are detailed in terms of time per syllable across increasing complex speech tasks. Thus, all mean values in table 4.3 indicate the time in seconds each measure was observed. Figure 4.1 illustrates the changes in the outcomes of these timing analysis methods as a function of task complexity. Generally speaking, the figure shows that measured timing values for those with no history of concussion were lower (faster or less time take to produce each syllable) than for those with a history of concussion. Figure 4.2 contains means for the raw values of perceived speech timing measures evaluated by trained SLP raters. It can be seen generally that, across tasks, subjective evaluations of timing during all 3 timing variables indicated a perceived slow down or lengthening of time per syllable for individuals with a history of concussion compared to those with no history of concussion. Statistical analysis below will shed more light on between group differences and objective and subjective timing measures.

Mean values in table 4.4, indicate average SLP (subjective) timing ratings for each evaluation parameter across tasks of increasing complexity. Figure 4.3 provides a visualization of the raw subjective data collected from SLP voice quality ratings. This figure provides visualizations of the differences between those with a history of concussion and those with no history of concussion as detailed by the acoustic voice methods outlined in the previous chapter. While statistically significant differences were not found between groups on these objective measures or the subjective voice quality measures (detailed in table 4.4 and figure 4.4), the visualizations provided in figures 4.3 and 4.4 give an indication of the differences in raw values recorded for these acoustic analysis methods.

		Female						Male					
		No History of Concussion			History of concussion			No History of Concussion			History of Concussion		
Task Complexity	Objective Measures	Mean	N	Std. Deviation	Mean	N	Std. Deviation	Mean	N	Std. Deviation	Mean	N	Std. Deviation
AMR	Time Per Syllable	0.16	16	0.04	0.18	16	0.05	0.14	13	0.02	0.17	13	0.04
	Voicing Time	0.08	16	0.02	0.08	16	0.03	0.07	13	0.01	0.08	13	0.03
	Unvoiced Time	0.1	16	0.03	0.12	16	0.03	0.08	13	0.01	0.1	13	0.02
SMR	Time Per Syllable	0.16	16	0.03	0.18	16	0.03	0.15	13	0.02	0.17	13	0.02
	Voicing Time	0.07	16	0.02	0.07	16	0.01	0.06	13	0.01	0.07	13	0.01
	Unvoiced Time	0.1	16	0.02	0.12	16	0.02	0.09	13	0.02	0.1	13	0.02
Connected Speech	Time Per Syllable	0.23	16	0.03	0.26	16	0.03	0.24	13	0.03	0.24	13	0.03
	Voicing Time	0.12	16	0.02	0.13	16	0.02	0.13	13	0.01	0.13	13	0.02
	Unvoiced Time	0.11	16	0.02	0.13	16	0.03	0.11	13	0.02	0.11	13	0.02

Table 4.2. Descriptive statistics of raw objective timing data. Mean values are in seconds. N is the number of participants' data analyzed.

		No History of Concussion			History of concussion			No History of Concussion			History of Concussion		
Task Complexity	Subjective Analyses	Mean	N	Std. Deviation	Mean	N	Std. Deviation	Mean	N	Std. Deviation	Mean	N	Std. Deviation
AMR	Articulatory Precision	-2.19	16	16.1	-6.94	16	10.86	2.77	13	22.9	-0.85	13	18.09
	AMR Rate	2.18	16	14.91	-5.26	16	14.56	7.82	13	9.17	-0.92	13	11.15
	Rhythmic Consistency	-1.53	16	13.67	-3.64	16	11.69	7.44	13	17.72	1.05	13	14.25
SMR	Articulatory Precision	-3.81	16	16.83	-3	16	15.25	1.08	13	23.46	2.85	13	15.14
	AMR Rate	-3.58	16	14.96	-8.5	16	10.14	4.34	13	14.02	-6.13	13	9.88
	Rhythmic Consistency	-1.24	16	13.66	-6.55	16	12.23	-2.66	13	18.04	-2.24	13	13.34
Connected Speech	Articulatory Precision	5.31	16	17.85	5	16	14.43	16.92	13	24.38	14.77	13	16.63
	AMR Rate	2.17	16	11.72	0.51	16	8.02	-3.04	13	10	-5.32	13	8.73
	Rhythmic Consistency	2.29	16	9.97	2.73	16	9.51	-1.07	13	12.32	-3.61	13	10.68

Table 4.3. Descriptive statistics of raw subjective timing data. Mean values represent average SLP ratings on a 100-point scale.

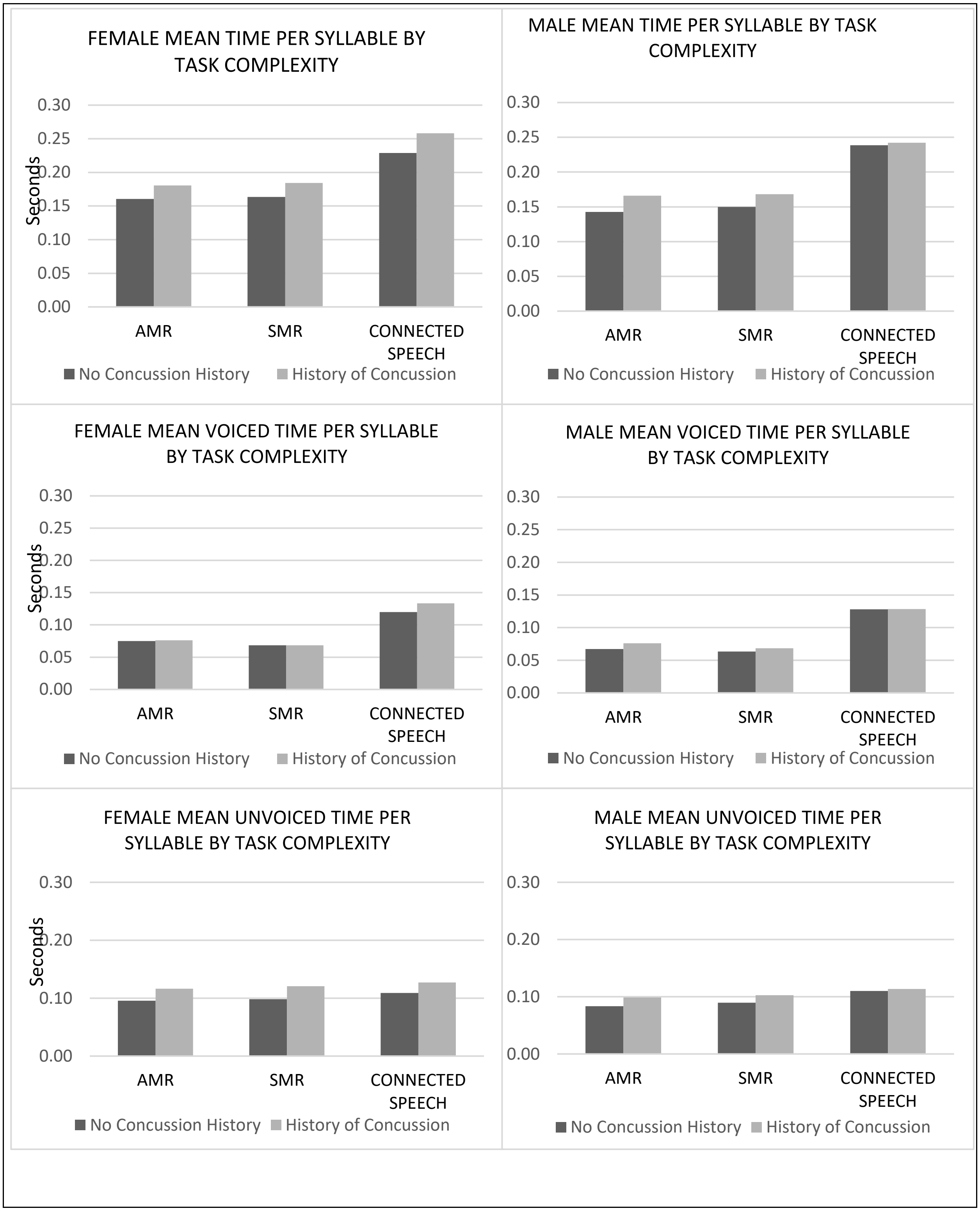

Figure 4.1. Visualizations of mean raw values for objective timing analysis methods of both male and female participants.

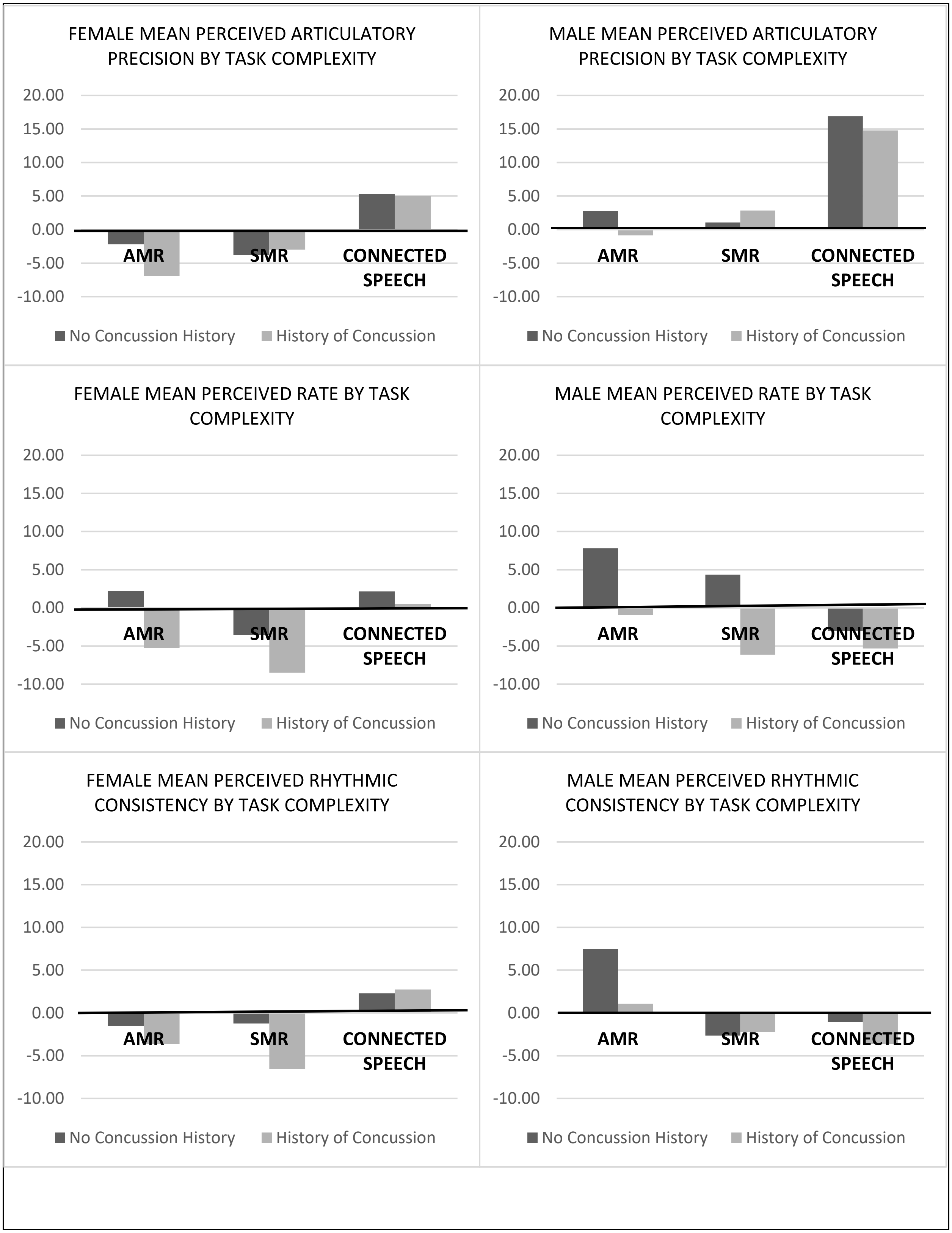

Figure 4.2. Visualizations of mean raw values for subjective timing analysis methods of both male and female participants. The bold line at the “0” value indicates the reference value of

the modulus provided to each rater for each of the evaluated timing parameters (articulatory precision, rate, and rhythmic consistency).

		Female						Male					
		No History of Concussion			History of concussion			No History of Concussion			History of Concussion		
Task Complexity	Objective Measures	Mean	N	Std. Deviation	Mean	N	Std. Deviation	Mean	N	Std. Deviation	Mean	N	Std. Deviation
AMR	f0	218.72	16	20.68	209.71	16	18.57	127.42	13	13.4	116.79	13	24.1
	f0 St. Dev.	9.33	16	2.83	10.17	16	2.71	6.72	13	1.64	10.09	13	4.96
	PPE	0.65	16	0.07	0.67	16	0.03	0.66	13	0.04	0.63	13	0.05
	CPPs	9.18	16	1.34	8.59	16	1.32	8.58	13	0.83	7.96	13	1.26
SMR	f0	206.68	16	21.47	199.66	16	17.84	115.62	13	12.62	107.1	13	20.3
	f0 St. Dev.	12.17	16	2.98	13.8	16	5.2	11.26	13	3.55	12.04	13	4.1
	PPE	0.69	16	0.05	0.71	16	0.04	0.69	13	0.05	0.67	13	0.06
	CPPs	8.57	16	1.23	8.24	16	1.24	7.59	13	0.97	7.32	13	1.16
Connected Speech	f0	189.86	16	21.52	188.32	16	15.99	108.78	13	10.56	102.31	13	16.77
	f0 St. Dev.	29.75	16	10.93	31.32	16	9.57	17.35	13	4.04	20.91	13	7.35
	PPE	0.66	16	0.04	0.67	16	0.04	0.64	13	0.06	0.63	13	0.07
	CPPs	9.95	16	0.81	9.74	16	1.03	9.28	13	0.57	8.56	13	1.25

Table 4.4. Descriptive statistics of raw subjective acoustic data. N is the number of participants' data analyzed.

		Female						Male					
		No History of Concussion			History of concussion			No History of Concussion			History of Concussion		
Task Complexity	Subjective Measures	Mean	N	Std. Deviation	Mean	N	Std. Deviation	Mean	N	Std. Deviation	Mean	N	Std. Deviation
AMR	Voice Quality	-6.38	16	11.89	-3.93	16	13.72	-1.71	13	11.79	-8.52	13	14.16
SMR	Voice Quality	-6.09	16	13.2	-4.35	16	15.15	5.03	13	9.71	-4.65	12	14.18
Connected Speech	Voice Quality	-4.55	16	17.76	0	16	15.75	5	13	17.49	0.47	13	19.06

Table 4.5. Descriptive statistics of raw perceived acoustic voice quality data Mean values represent average SLP ratings on a 100pt scale.

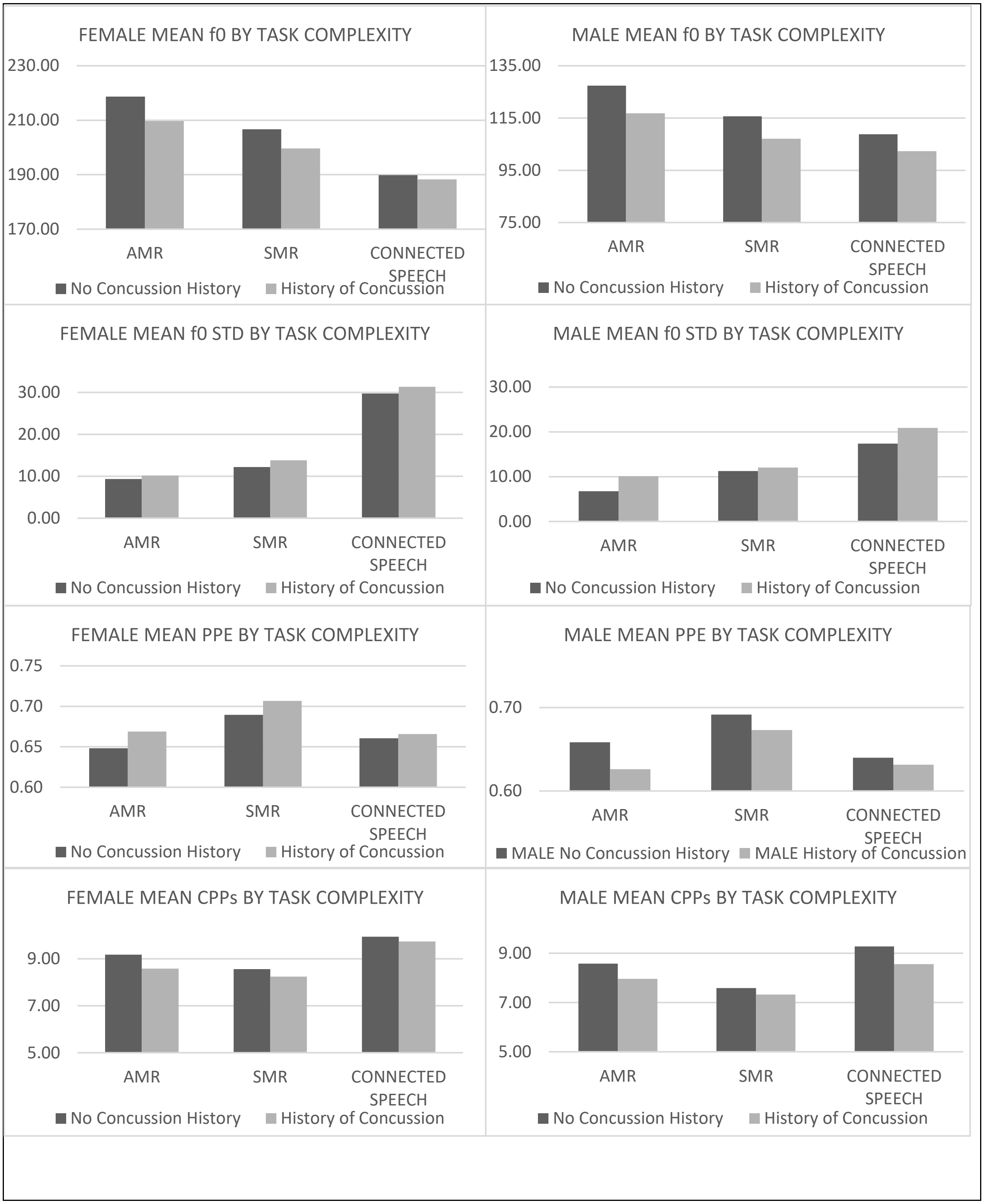

Figure 4.3. Visualizations of mean raw values for objective acoustic voice analysis methods of both male and female participants. Mean f0 and f0 standard deviations were measured hertz, PPE values in percentages (1.0 = 100%), and CPPs values in

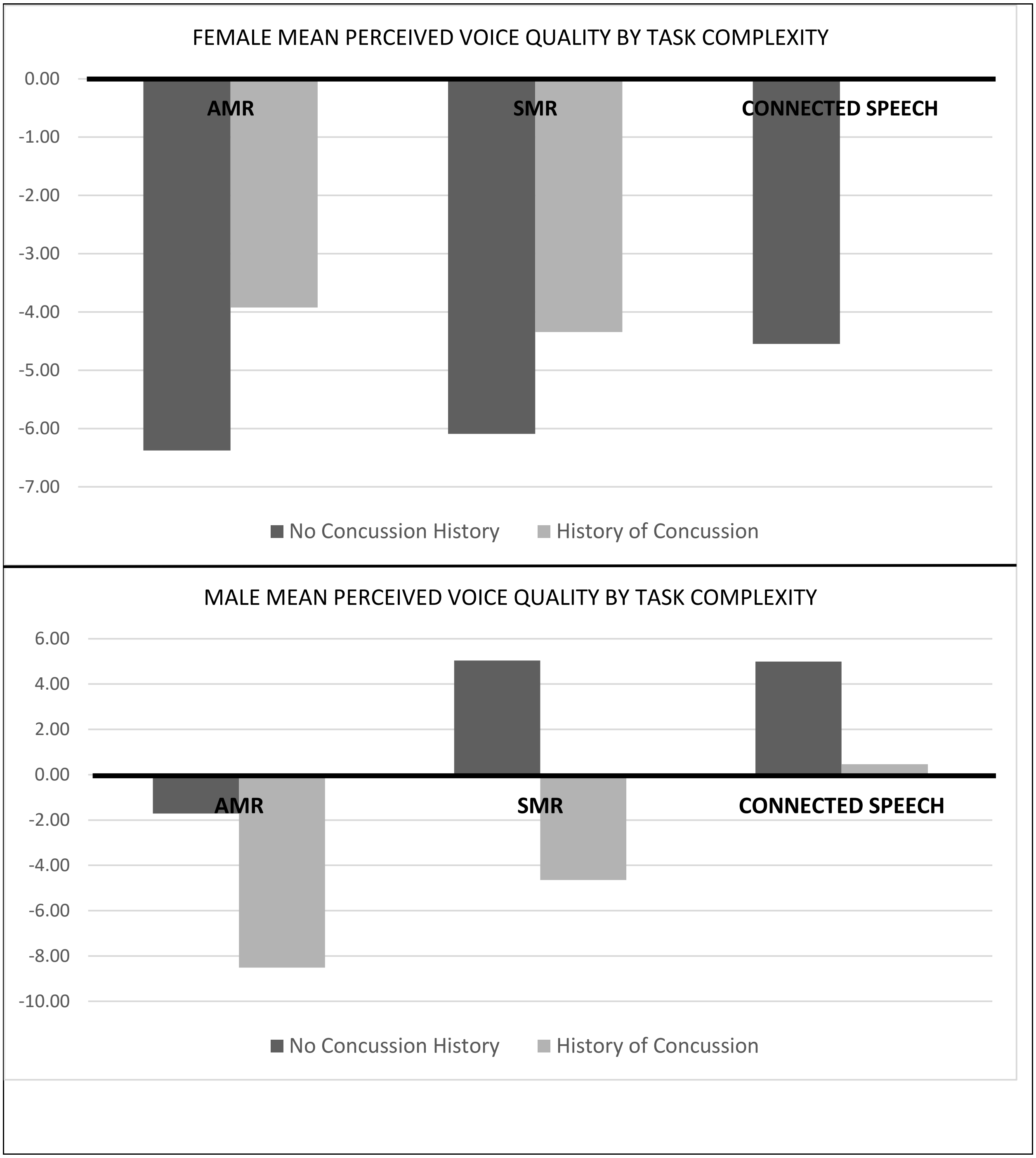

Figure 4.4. Visualizations of mean raw values for subjective acoustic voice quality analysis methods of both male and female participants. The bold line at the “0” value indicates the reference value of the modulus provided to each rater for each of the evaluated voice quality measure.

Timing Analysis

There was no main effect of concussion status (F(1, 56) = 2.7, p = 0.1, f^2 = 0.11 [95% CI: 0.00 to 0.30]), task complexity, (F(2, 280) = 0.0, p = 1, f^2 = 0.00 [95% CI: 0.00 to 0.00]), or timing analysis method (F(1, 280) = 0.0, p = 1, f^2 = 0.00 [95% CI: 0.00 to 0.00]).

Task complexity and timing analysis methods used were also investigated for their potential interaction on the effects of concussion status. There was no interaction of concussion status x task complexity (F(2, 280) = 0.2, p = 0.8, f^2 = 0.02 [95% CI: 0.00 to 0.08]). There was however, a significant interaction of concussion status x timing analysis method (F(1, 280) = 20.7, p < 0.001, f^2 = 0.83 [95% CI: 0.39 to 1.69]. Post-hoc decomposition of the concussion status x timing analysis method interaction was conducted by examining the effect of timing analysis method within each group of concussion status. Post-hoc decomposition of the concussion status x timing analysis method interaction was conducted by examining the effect of concussion status within

	Concussion History (n= 29)		No Concussion History (n= 29)	
	Method of Analysis			
Task Complexity	Objective	Subjective	Objective	Subjective
Timing Analysis				
AMR	0.26 ±1.06	-0.20 ±0.80	-0.26 ±0.63	0.20 ±0.71
SMR	0.30 ±0.82	-0.12 ±0.69	-0.30 ±0.70	0.12 ±0.79
Connected Speech	0.23 ±0.78	-0.06 ±0.72	-0.23 ±0.76	0.06 ±0.93
Acoustic Analysis				
AMR	-0.07 ±0.48	-0.06 ±1.07	0.07 ± 0.53	0.06 ±0.92
SMR	-0.04 ±0.56	0.00 ±1.08	0.04 ±0.41	-0.00 ±0.94
Connected Speech	-0.04 ±0.64	0.02 ±0.99	0.04 ±0.56	-0.02 ±1.01

Table 4.6. Mean estimates for computed z-scores for the collapsed task complexity scores across objective and subjective analyses (± SD).

each timing analysis method.

For the objective timing measures (estimated time per syllable, average voiced time per syllable, and average unvoiced time per syllable), the difference between participants with no history of concussion (-0.3 +/- 0.7) and those with a history of concussion (0.3 +/- 0.9) was statistically significant; ($t(187) = 4.4$, $p < 0.001$, $d_s = 1.15$ [95% CI: 0.62 to 1.68]). For the subjective timing measures (articulatory precision, rate, and rhythmic consistency), the difference between no history of concussion (0.1 +/- 0.8) and history of concussion (-0.1 +/- 0.7) was statistically significant; $t(187) = 2.1$, $p = 0.041$, $d_s = 0.54$ [95% CI: 0.02 to 1.06]. Finally, no significant interactions of task complexity x acoustic analysis method ($F(2, 280) = 0.0$, $p = 1$, $f^2 = 0.00$ [95% CI: 0.00 to 0.00]) or concussion status x task complexity x acoustic analysis method ($F(2, 280) = 0.4$, $p = 0.7$, $f^2 = 0.03$ [95% CI: 0.00 to 0.12]) were revealed. Descriptive statistics for the objective and subjective raw timing data associated with these analyses are provided in tables 4.3 and 4.4, respectively.

Acoustic Analysis

There was no main effect of concussion status, F(1, 58) = 0.2, p = 0.7, f^2 = 0.13 [95% CI: 0.00 to 0.35]), task complexity(F(2, 257) = 0.0, p = 1, f^2 = 0.00 [95% CI: 0.00 to 0.00]), or acoustic analysis method (F(1, 257) = 0.0, p = 1, f^2 = 0.00 [95% CI: 0.00 to 0.00]). Additionally, there was no interaction of concussion status x task complexity (F(2, 257) = 0.2, p = 0.8, f^2 = 0.30 [95% CI: 0.06 to 0.69]) or concussion status x acoustic analysis method (F(1, 257) = 0.3, p = 0.6, f^2 = 0.16 [95% CI: 0.00 to 0.41]). Finally, there was no interaction of task complexity x acoustic analysis method (F(2, 257) = 0.0, p = 1, f^2 = 0.00 [95% CI: 0.00 to 0.00]) or concussion status x task complexity x acoustic analysis method (F(2, 257) = 0.1, p = 0.9, f^2 = 0.07 [95% CI: 0.00 to 0.21]). Descriptive statistics for the objective and subjective raw acoustic voice quality data associated with these analyses are provided in tables 4.5 and 4.6 respectively

Perceptual Analysis

Intra and inter-rater reliability statistics were calculated and reported below. Intra-rater reliability scores were excellent (Intraclass correlations all .78 or above) for each perceptual measure: articulatory precision, rate, rhythmic consistency, and vocal quality (Table 4.7).

Perceptual Rating	Intraclass Correlation	95 % CI Lower	95% CI Upper	Value	df	Sig
Articulatory Precision	.957	.926	.976	23.445	80	.000
Rate	.827	.693	.902	5.774	80	.000
Rhythmic Consistency	.784	.618	.878	4.637	80	.000
Voice Quality	.920	.857	.956	12.528	80	.000

Table 4.7. Intra-rater reliability across perceptually rated factors.

However, the inter-rater reliability was poor with only perceptual judgements of rate being near to moderate reliability (Table 4.8). Raters were asked to perform judgements on a 100-point scale with measures less than “0” indicating a decrease in the perceived functional performance compared to the modulus provided and measures greater than “0” indicating increased perceived functional performance compared to the modulus provided.

Perceptual Rating	Intraclass Correlation	95 % CI Lower	95 % CI Upper	Value	df	Sig
Articulatory Precision	-.219	-.911	.223	.821	80	.806
Rate	.337	-.043	.579	1.509	80	.038
Rhythmic Consistency	.045	-.485	.386	1.047	80	.419
Voice Quality	.291	-.103	.544	1.410	80	.063

Table 4.8. Inter-rater reliability across perceptually rated factors.

CHAPTER 5: Discussion & Conclusions

Discussion

Results of previously conducted research by Dolan, Hewitt, Peiffer-Lapid, and Phan indicate that concussion may affect various aspects of the production rate of DDK speech tasks. The current research set out to improve on these previous studies by having better control for population relevant characteristics in order to determine if concussion history has an effect on both speech timing and acoustics. This research also examined the impact of speech task complexity and the type of timing and acoustic analysis applied on the differences between speech of those with a history of concussion and those with no history of concussion. This work aimed to replicate the procedures of the previously mentioned studies while expanding the protocols to include the analysis of real-word DDK repetitions, continuous speech during reading tasks and spontaneous speech productions. This study also attempted to incorporate the analysis of various acoustic parameters of the voice of individuals with and without a history of concussion. Finally, this work is the first of its kind to include perceptual analyses by a consequential number of raters. Contrary to previous work, raters in this research were also trained on the same protocol and provided with samples of each rated parameter to ensure consistency and clarity in rating procedures. Results of the current research both confirm significantly slower rates on real-word and non-word DDK speech productions and some continuous speech productions, as well as establishes a reasonable justification for further research into the timing, acoustic and perceptual analysis of speech in the concussed population.

Timing Variables

In response to question one, it was hypothesized that there would be a significant speech timing difference between those with a history of concussion and those with no history of concussion. While there were however no significant differences between groups on the timing measures applied in this research, there was a significant interaction of concussion status and the timing analysis method applied. Specifically, while both subject and objective measures of timing were each significantly different between groups of concussion status, the effect size for objective measures (d= 1.15) was larger than for subjective measures (d= .54).

Therefore, this research has determined that significant speech timing differences between groups of previously concussed and never concussed populations can be identified with the application of both objective and subjective metrics detailed in this study. Results presented in this research cannot confirm structural damage to areas and networks of the brain responsible for motor speech production and coordination. However, concussion is the result of microstructural alterations in the brain's white matter that are only observable on advanced neuroimaging (Wu et al., 2017). As the white matter facilitates communication across the brain's vast network architecture, the microstructural damage impacts the function of the networked grey matter (Arfanakis et al., 2002; Browne, Chen, Meaney, & Smith, 2011). Speech production is an extremely complex neurological process that involves the coordination of a neural network of grey matter regions to conceptualize, plan and execute the desired output via several pairs of muscles. Due to the diffuse nature of concussion, the functional networks that support speech production may be altered thus potentially being at least in part, responsible for the decrease in speech rate noted in this and other research. This theory is consistent with the results of several previous experiments, which have examined general motor function in the concussed and other brain injured populations.

While no published research has examined the objective articulatory muscle function of individuals following a concussion, several have looked at general motor function of the periphery such as the hands and legs (Dolan, 2013; Hewitt, 2015; Kuruvilla et al., 2012; Peiffer-Lapid, 2016; Phan, 2016b; Sellars, Carding, Deary, MacKenzie, & Wilson, 2002; Y.-T. Wang et al., 2005). Research regarding general motor function following a concussion has demonstrated that significant differences in both the timing and strength of the muscle contractions occurs following a concussion (De Beaumont, Lassonde, Leclerc, & Théoret, 2007; Miller et al., 2014; Tallus, Lioumis, Hämäläinen, Kähkönen, & Tenovuo, 2011; Dolan, 2013; Miller et al., 2014). These studies have found that peripheral motor movements are negatively affected by concussion. They have also begun to build evidence of a deterioration/disruption of the pathway from the cortex to the spine and the extremities after injury or multiple injuries, potentially existing long after the initial injury. This disruption then, may extend to muscles of the face and speech articulators, causing a delay or timing effect, thus producing longer, drawn-out DDK repetitions and general speech.

Importantly, motor limb, speech articulation movements and voice production are believed to be controlled by adjacent (and possibly overlapping) anatomical locations of the cortex. This may contribute to coordinated functional declination of these systems following a concussion or multiple concussions (Brown, Ngan, & Liotti, 2008; Simonyan, 2014; Simonyan & Horwitz, 2011). This relationship is demonstrated in research which suggests that after severe injury, neural reorganization of motor areas for the hands and fingers may occur to incorporate function of the face (and vice versa) (Cramer & Crafton, 2006). Research has also indicated that after severe injury to these cortical areas, motor cortex function can be affected long after acute symptoms have subsided (De Beaumont et al., 2007). Again, while participants in this study were recorded up to two years following their last concussion, results of this study indicate that they may still be experiencing a disruption in the neural connections responsible for speech production and speech timing in particular.

Interestingly, 66% (19/29) of participants in this study who reported having one diagnosed concussion indicated that they suspected they had at least one other concussion that was not diagnosed. Therefore, future research should attempt to control for both the number of diagnosed concussions as well as those potential concussions where were not reported or diagnosed in participants.

Future research involving the speech and voice of individuals with a history of concussion should examine the number of errors produced during tasks to determine if this may have had a significant effect on speech timing and acoustic analyses. As errors produced during tasks in this research were not counted toward the overall count of 10 needed for this analysis, those errors produced did affect (increase) both the average times per production and potentially the average total unvoiced times. While errors produced were not controlled for in this research, they may have had an effect on outcomes obtained and should be considered a limitation to this work. Objective measures of timing should also be investigated deeper in order to understand which specific AMR, SMR, and/or continuous speech tasks provided the largest effect sizes.

This would be useful in a clinical application to narrow down the speech tasks which may be most effective at identifying differences between groups.

Important to note is that it appears that trained SLP evaluators were able to attend to timing differences between those with a history of concussion and those with no history of concussion. Further, as mentioned above regarding the number of errors, SLP ratings were also consistent with the timing analysis of the effect of the number of concussions where they rated participants with a single concussion history as being significantly slower than those with a history of more than one concussion. It may have been that SLP raters were attending to the number of errors produced by participants and thus rated them as having a slower rate during SMR productions. This explanation, however, does not account for the significantly slower results perceived during AMR productions of *puh* and *kuh*. Subjective analysis of AMRs indicated that there were not enough errors produced during these tasks to perform any meaningful analysis. It is reasonable to assume that these participants were, in fact, producing significantly slower DDK productions across the tasks. Results of this analysis indicate that trained evaluators of speech may be able to identify individuals following concussion based on comparison of speech rate on various DDK tasks.

Acoustic Metrics

The acoustic voice analysis results found between those with a history of concussion and those without a concussion history, should be approached with caution. Generally speaking, acoustic analysis of voice and speech are often quite variable. Not surprisingly, results of the acoustic analysis of the voices of participants in this study were also extremely variable between subjects. Additionally, as stated in the results section, some recordings were unable to be included in analysis as they included too much fry to distinguish a reliable fundamental frequency estimate. Also, important to note is that while participants in this study were matched on several factors to reduce variability generally, they were not matched on any measurements directly related to voice.

For example, while voice physiology does have some correlation with adult body height, voice differences due to concussion (e.g. vocal pitch) may not be larger than variations of average pitch between people that are the same height and weight. This naturally occurring variability introduced into the data may then have canceled out the potentially significant effects of concussion on measures surrounding fundamental frequency Additionally, PPE and CPPs analyses rely heavily on the voicing contained in a sample. As was established above, estimated average unvoiced times (times without voicing) in the samples recorded from participants were significantly longer for individuals with a history of concussion, directly indicating a decrease in the overall voicing in each sample. This may have negatively impacted the results of these measures. It may be possible to ameliorate some of these effects by attempting to control participants based on the rough average fundamental frequency of their voice. This would provide a more meaningful comparison of acoustic voice measures between groups.

With these acoustic measures qualified, explanation of the acoustic analysis results obtained may be more readily understood. As indicated above, no main effects or interaction effects were observed in the acoustic analysis of voice in this research. This was especially compelling given the pilot research discussed chapter 3 which indicated that, for those within 72 hours of having sustained an SRC, significant differences in several acoustic voice measures were observed. With this pilot data in mind, it may be possible that cortical and white matter regions of the brain responsible for voice production may be more sensitive to the acute effects of concussion, such as the metabolic effects discussed in detail in chapter 2. It may also have been due to the relatively small number of participants in this study with a history of concussion who were within a year of sustaining their last concussion. Only five of the 29 participants with a concussion history sustained their last concussion in the last year. Interestingly, all of those who sustained their concussion in the past year sustained it in the last 5 months (3 of them within 2 months of being recorded; Figure 15.1).

It is also reasonable to believe that cortical and subcortical pathways responsible for maintaining appropriate motor speech rate may be more susceptible to the functional effects associated with concussion, much like it is in some degenerative brain diseases (Claassen et al., 2016; Nevler et al., 2019). Thus, measurable differences in speech timing may manifest themselves earlier than those differences in voice production.

Another potential reason that no significant differences between those with a history of concussion and those with no history of concussion on the acoustic voice analyses were observed is due to the tasks used in this study. Generally, DDK's possess several unvoiced plosives, particularly *p, t,* and *k* sounds. These three sounds in particular contain high frequency noise which may have significantly affected f_0 analyses of these tasks. This may have made it difficult to find any significance in the comparison of groups with acoustic voice analyses. It may also be responsible for the lack of significance seen in many of the other acoustic metrics. Future research will isolate voicing across DDK and connected speech tasks to limit the variability in the analyzed samples.

Subjective Analysis

This dissertation sought to build on previous limited experiments regarding the perception of speech articulatory precision, rate, rhythmic consistency, and voice quality of individuals with a history of concussion compared to controls. Contrary to previously conducted research by Peiffer-Lapid which only used two SLP raters, judgments from 6 trained SLP evaluators indicated significantly lower rates during SMR speech tasks. Specifically, SLP's in this study indicated SMR productions (real and non-word) of individuals with a history of concussion to be significantly slower than their never-concussed controls during puhtuhkuh and buttercup productions. This was not surprising even with the lack of inter-rater reliability mainly because most raters judged the speech timing and acoustics of those with a history of concussion to be slower generally, there was simply a healthy deal of variability in relation to how both those with a history of concussion and those with no history of concussion were evaluated in relation to the modulus provided. Future, research will provide more standardized and clear moduli in an attempt to increase the reliability between speech and voice raters.

Differences between perceptual analysis results in this research and those provided in the Peiffer-Lapid study are due to the insufficient number of raters, lack of an established protocol, and the 3-point rating system adopted in the latter. The current research employed a Likert-type scale including a zero (same as modulus) rating and 50 points above and below the modulus where raters could indicate more/less accuracy, faster/slower rate, more/less rhythmic consistency, and higher/lower voice quality. Further, the training given to each of the SLP evaluators in this study was consistent and detailed and thus, ensured evaluations between SLP's were consistent.

Clinical Implications

An important benefit of this dissertation was the clinically relevant data that was collected and may assist to increase the involvement of speech-language pathologists in the assessment and identification of individuals following concussion. It may also help to identify those at risk of further, long-term damage by identifying individuals who may demonstrate functional damage to cortical areas of the brain as a result of concussion. Most importantly, this research provides additional objective and subjective means which may be added to current assessment protocols used by SLP's in the concussed population. Similar to what has been done in previous work involving DDK tasks, future work in this area will seek to establish thresholds for timing variables where those who score under an expected threshold should be considered for further neurological testing (Icht & Ben-David, 2014).

Given the results of this research, it is recommended that single and multisyllable word and non-word DDK productions be the focus of future research and potentially clinical investigation. As these multisyllabic words demonstrated the most significant between group differences and single syllable DDK's demonstrated the most predictive differences between groups, it is suggested that future protocols include these tasks as a means of potentially identifying individuals with acute or persistent concussion and those with a history of concussion. Results of this research may lead to the development of cut-off values for DDK productions for individuals with a history of concussion. This may be a potentially useful means to screen athletes following a suspected concussion. Additionally, many of the objective measures which were used in this research may be applied in a real time, mobile fashion making them relatively simple to perform in sport or non-medical setting.

A recent review of the current literature examining the long-term effects of multiple concussions on various modalities stated:

> *"The greatest limitations of long-term effects of concussion history on motor performance concern the confounding factors associated with normal aging and differential diagnoses. […] Beyond the TMS literature (De Beaumont et al., 2007b, De Beaumont et al., 2009) on the long-term effects of concussions, there are very few investigations powered to assess the effects of previous number of concussions, leaving another large gap in the literature." (Martini & Broglio, 2018)*

The current research attempts to begin to fill the gaps in our knowledge as they relate to the clinically relevant, long-term effects of concussion on speech production. This study is also an answer to the call by Harmon et al. (2019) to further develop research regarding technologies for speech pattern analysis for the concussion population. Further, speech differences are currently associated with acute concussion symptoms, however, specific details regarding what to look for in this population is unclear. This dissertation proposes to fill the gaps in our understanding of speech and voice differences between concussed athletes and those who are not concussed.

Limitations

This research is not without limitations. Included in its limitations are the patient reported nature surrounding concussion events, timing, number, and general health history. First and foremost, relying on patient report for the number of previously diagnosed concussions is the greatest limitation and the one with the most potential harm to results in this study. However, because access to participants' medical histories was not part of the data collection, it became necessary to rely on patient reports of their injury. Especially with head injury, it can be difficult for a person to recall specific details surround the circumstances of the injury. The exact circumstance of each injury was not the focus of this research, but rather the general nature (sports related) and number (diagnosed by an MD or AT). Therefore, the effects of this limitation were potentially mitigated.

Not controlled for in this study was the length of time in which participants were involved in sports related to their reported concussions. It may be that those who reported a history of one concussion were involved in sports over a longer period of time than those who reported two previous concussions, exposed to more concussive and sub-concussive hits and thus, more likely to experience the detrimental effects of such exposures (McHenry, 2009; McHenry, 1999; McKee et al., 2009; Montenigro et al., 2017; Talavage et al., 2010).

Additionally, an important limitation in this research is the need for further research regarding the objective analysis of speech muscle activation, timing, and coordination. Future research should address these limitations to understand if articulatory muscle activation metrics correspond with the objective metrics of timing reported in this and other research. Such future work should include those in the acute stage of concussion as well as those further removed from their last injury. Results of this research are limited in their application to the acute concussion population as they may report differences unlike those that presented in this research.

With regards to the perceptual analysis performed in this research, several more in-depth subjective analyses should be the focus of future research. For example, participants who were rated as being the least articulatorily precise, the slowest, the least rhythmically consistent, worst in vocal quality, should be examined to determine what perceptual features were most salient for raters and thus, led to their individual judgements. This would be important to, among other things, understand what led to significantly different judgements in rate for the population of participants with a history of concussion.

As was mentioned in a previous chapter, some of the repetition of participants in this study were unable to be included in analysis due to increased vocal fry. Future work in this area may benefit from establishing a minimum phonation loudness threshold in order to avoid unusable data due to vocal fry. Finally, this research did not include individuals with acute concussion participants in the acute stage of concussion. Ideally, this research would have had an equal number of acutely concussed, previously concussed, and never concussed participants. However, due to the nature and unpredictability of such injuries, obtaining a balanced and an appropriate number of acutely concussed participants will be left to future multi-year or multi-site research.

Conclusions

Results of this dissertation indicate objectively measurable timing, acoustic and perceptual speech differences between those with a history of concussion and those who have never been diagnosed with an SRC during DDK and connected speech tasks. Specifically, the estimated average time per syllable and word productions and the average amount of unvoiced time were significantly higher for those with a history of concussion. Acoustically, during many speech tasks, there was a significantly greater fluctuation in the fundamental frequency of speech. Also important was the significantly different rates perceived during subjective ratings by SLP’s. While participants with no concussion history were consistently perceived as having higher articulatory precision, rhythmic consistency, and voice quality than those with a history of concussion, only rate was perceived to be significantly higher.

Future research will establish cutoff values for timing, acoustic and perceptual measures of DDK productions in order to better predict concussion status. Future work in this area will also perform speech and voice analysis across age groups controlling more closely for previous medical history particularly age at start of sports play, age at first injury and severity of injury. Interestingly, objective analysis of motor muscle movements of speech articulators (jaw, tongue, cheeks, etc.) has not yet been performed using individuals with a concussion despite preliminary evidence to suggest that motor speech function may be affected in athletes following concussion. Objective motor speech muscle function should be made a central part of future research given the evidence presented in this study.

APPENDICIES

APPENDIX A: THE RAINBOW PASSAGE

When the sunlight strikes raindrops in the air, they act as a prism and form a rainbow. The rainbow is a division of white light into many beautiful colors. These take the shape of a long round arch, with its path high above, and two ends apparently beyond the horizon. According to legend, there is a post of gold at one end of the rainbow. When a man looks for something beyond his reach, his friends say he is looking for the pot of gold at the end of the tunnel.

APPENDIX B: THE CATERPILLAR PASSAGE

"Do you like amusement parks? Well, I sure do. To amuse myself, I went twice last spring. My most MEMORABLE moment was riding on the Caterpillar, which is a gigantic roller coaster high above the ground. When I saw how high the Caterpillar rose into the bright blue sky I knew it was for me. After waiting in line for thirty minutes, I made it to the front where the man measured my height to see if I was tall enough. I gave the man my coins, asked for change, and jumped on the cart. Tick, tick, tick, the Caterpillar climbed slowly up the tracks. It went SO high I could see the parking lot. Boy was I SCARED! I thought to myself, "There's no turning back now." People were so scared they screamed as we swiftly zoomed fast, fast, and faster along the tracks. As quickly as it started, the Caterpillar came to a stop. Unfortunately, it was time to pack the car and drive home. That night I dreamt of the wild ride on the Caterpillar. Taking a trip to the amusement park and riding on the Caterpillar was my MOST memorable moment ever!"

APPENDIX C. RESEARCH PROTOCOL

Version 1 - Concussion Data Collection Instructions

SUBJECT NUMBER_______________ DATE:_______________________

“Hello and welcome to our study. Thank you for your participation. Do you have any questions before we begin?”

“Please state your Subject Number… todays date and the time.”

□ **Click The Button In Labchart To Mark The Start Of This Task: Ah’s**
Say “ah” for 5 seconds. Repeat three times.

□ **Click The Button In Labchart To Mark The Start Of This Task: DDDKs**
“Please repeat ‘puhpuhpuh’ as quickly and steadily as possible until I raise my hand… like this:...”
“Please repeat ‘tuhtuhtuh’ as quickly and steadily as possible until I raise my hand … like this:…”
“Please repeat ‘kuhkuhkuh’ as quickly and steadily as possible until I raise my hand… like this:…”
“Please repeat ‘puhtuhkuh’ as quickly and steadily as possible until I raise my hand … like this:…”
“Please repeat ‘Pattycake’ as quickly and steadily as possible until I raise my hand … like this:…”
“Please repeat ‘Buttercup’ as quickly and steadily as possible until I raise my hand … like this:…”

□ **Click The Button In Labchart To Mark The Start Of This Task: Rainbow Passage**
“For this next task I am going to ask you to read a passage in a comfortable voice. Begin when you are ready.” Present the Rainbow Passage (Timing and acoustic measures; Perceptual: voice quality, speech rate, articulatory precision, number of pauses)

□ **Click The Button In Labchart To Mark The Start Of This Task: Caterpillar Passage**
“For this next task I am going to ask you to read a passage in a comfortable voice. Begin when you are ready.” Present the Caterpillar Passage. Timing and acoustic measures; **Perceptual**: voice quality, speech rate, articulatory precision, number of pauses)

□ **Click The Button In Labchart To Mark The Start Of This Task: Spontaneous Speech**
“For this next task I am going to ask you to please describe for one minute, what your bedroom looks like.” (Timing and acoustic measures; **Perceptual**: voice quality, speech rate, articulatory precision, number of pauses)

APPENDIX D. FULL DESCRIPTIVE STATISTICS

Sex and ID	Birth Year	Height In.	Weight Lbs.	Gender	Last Concussion	Diagnosed Concussion	Suspected Undiagnosed
F16	1999	69	155	Femal	Jan-17	4	1
M13	1996	72	165	Male	May-18	4	1
F15	1999	63	128	Femal	Jun-18	3	2
M05	1997	70	180	Male	Jul-17	3	5+
M09	1997	72	182	Male	Aug-17	3	3
F02	1997	65	128	Femal	Jan-17	2	0
F03	1999	65	124	Femal	Aug-17	2	0
F05	1998	66	113	Femal	Mar-17	2	0
F11	1996	69	175	Femal	Jul-18	2	1
F17	1998	66	137	Femal	Apr-17	2	0
M01	1997	67	155	Male	Sep-18	2	1
M04	1998	72	177	Male	Jun-17	2	2
F04	1999	61	115	Femal	2016	1	1
F06	1997	70	140	Femal	2017	1	2
F07	2000	64	178	Femal	Mar-19	1	0
F08	1998	69	198	Femal	Sep-18	1	0
F09	1999	61	125	Femal	Jul-17	1	1
F10	1999	64	133	Femal	Sep-17	1	1
F12	1998	65	116	Femal	Dec-16	1	0
F13	1998	61	120	Femal	Sep-18	1	0
F14	1997	62	150	Femal	Jan-19	1	0
M02	1999	68	137	Male	Jul-18	1	2
M03	1997	69	175	Male	Sep-17	1	1
M06	1998	71	160	Male	Feb-18	1	2
M07	1997	71	165	Male	Aug-17	1	2
M08	1996	68	155	Male	Mar-17	1	2
M10	1998	77	246	Male	Jul-17	1	2
M11	1996	69	205	Male	Nov-18	1	0
M12	1997	70	175	Male	Sep-17	1	2
F01	1996	67	128	Femal	-	-	-
F02	1999	64	125	Femal	-	-	-
F03	1999	65	116	Femal	-	-	-
F04	1998	64	125	Femal	-	-	-
F05	1998	68	140	Femal	-	-	-
F06	1997	69	253	Femal	-	-	-
F07	1998	73	195	Femal	-	-	-
F08	1998	61	119	Femal	-	-	-
F09	1999	64	133	Femal	-	-	-
F10	1997	68	165	Femal	-	-	-
F11	1997	67	115	Femal	-	-	-
F12	1999	64	112	Femal	-	-	-
F13	1996	57	165	Femal	-	-	-
F14	1999	64	125	Femal	-	-	-
F15	1997	66	140	Femal	-	-	-
F16	1999	68	135	Femal	-	-	-
F17	1998	62	105	Femal	-	-	
M01	1997	68	170	Male	-	-	-
M02	1999	68	128	Male	-	-	-
M03	1996	68	175	Male	-	-	-
M04	1997	73	175	Male	-	-	-
M05	1997	70	180	Male	-	-	-
M06	1997	71	155	Male	-	-	-
M07	1997	74	160	Male	-	-	-
M08	1996	70	145	Male	-	-	-
M09	1997	73	185	Male	-	-	-
M10	1998	76	218	Male	-	-	-
M11	1997	69	200	Male	-	-	-
M12	1998	71	172	Male	-	-	-
M13	1996	74	165	Male	-	-	-

Participant demographics.

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