LINGUAL SPEECH MOTOR CONTROL ASSESSED BY A NOVEL VISUOMOTOR TRACKING PARADIGM

by

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To my mother and father.

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"You are not a drop in the ocean; you are the entire ocean in a drop." - Rumi

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Like other types of human motor control, speech production is thought to be accomplished through the process of receiving sensory feedback and continually refining predictive feedforward models to achieve the desired articulatory movement. Visuomotor tracking (VMT) has been an influential paradigm used to test this motor control theory. VMT tasks examine articulatory movement by requiring participants to follow external signals visually presented on a screen. By varying the predictability of the signal, information about processes involved in speech motor planning and execution can be gained. Previous studies of healthy adults have suggested that when tracking predictable frequencies, an internal model of the target movement is formed to guide accurate movement. When the signal is unpredictable, no model can be formed, and feedback information is used to detect errors and aid in tracking. Research from this line of work has also suggested that the underlying basis of apraxia of speech, a speech motor disorder, is due to a deficit in feedforward processing.

Speech VMT studies have focused on the lips and jaw (external articulators); therefore, little is known about the tracking capabilities of the tongue, the primary articulator for speech. Although it could be the case that tongue motor control uniformly resembles that of other articulators, its biomechanically unique properties (i.e., a muscular hydrostat) and braced position during speech suggest it may not share the same motor control properties. In the present study, tongue motor control was assessed using a novel VMT paradigm based on an electromagnetic articulography system (Opti-Speech). In a first experiment, ten healthy young adults (mean age = 28.8 years) used their tongue tip to track a virtual intra-oral moving target that varied in conditions of predictability, frequency (0.4, 0.6, 0.8 Hz), and direction (vertical, horizontal, lateral). These conditions tested feedforward/feedback control, speed-accuracy tradeoff, and speech-like versus non-speech-like properties, respectively. In a second experiment, another group of ten healthy young adults (mean age = 21.0 years) participated in a similar tracking experiment assessing whether synchronous tongue-jaw patterns extend to cases of the tongue moving in isolation. In both experiments, tracking accuracy was measured by computing correlation coefficients, amplitude ratios, and phase differences. Experiment 1 demonstrated significantly higher accuracy in the predictable condition than the unpredictable condition, providing support for the notion of an internal model guiding expected movement. In addition, a speed-accuracy tradeoff was found, with significantly higher accuracy for the slowest frequency (0.4 Hz) compared with the fastest (0.8 Hz). Amplitude ratio data revealed significantly higher accuracy in the lateral direction when compared to the vertical direction, suggesting a difference in control of movement for speech-like (vertical) versus non-speech-like (lateral) directions.

Results from Experiment 2 corroborated that basic motor control principles noted in Experiment 1 are also found for movement of the tongue alone. Taken together, the findings suggest that tongue motor control shares similar properties with the limbs and previously studied speech articulators. Results serve as a basis for expanded investigations into visual feedback and feedforward deficit theories.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

This research is concerned with understanding the properties of motor control responsible for speech by healthy talkers. Current evidence supports that the movement of the lips and jaw is likely guided by the same motor control mechanisms as the limbs (e.g., Ballard et al., 2003; Folkins et al., 1995; Robin et al., 1997). Using visuomotor tracking (VMT), a technique that permits study of feedforward and feedback processing, studies have suggested that movement of these articulators is guided by an "internal model" (learned representation of intended movement). In addition, online sensory feedback provides information to refine the model (Ballard & Robin, 2007; Clark & Robin, 1998; Hageman et al., 1994; Moon et al., 1993; Robin et al., 2008). While findings have been informative for understanding speech produced by healthy and speech-impaired talkers, it is not known if these results can be generalized to the tongue, the primary articulator of speech (Hiiemae & Palmer, 2003; Iskarous, 2003; Yano et al., 2015).

Although some researchers have assumed that motor control principles for the lips and jaw extend to all speech articulators, this has not been established with certainty for the tongue. The tongue is enclosed in the mouth; therefore, collection of accurate experimental data about its movements has been more difficult to obtain than for the external articulators (Levin, Torcaso, & Stone, 2006). A complex organ, the tongue has a unique curved shape (Abd-El-Malek, 1938; Steiner & Ouni, 2011), and is classified as part of a unique class of structures known as "muscular hydrostats" (Smith & Kier, 1989). Muscular hydrostats, like the trunks of elephants and tentacles of octopuses, lack a rigid external or internal skeleton and are constrained to a constant volume due to the incompressibility of the muscles (Smith & Kier,1985). Movement of the tongue during speech involves control of complex interweaving and contractile extrinsic and intrinsic muscles (Mu & Sanders, 2010). The tongue's unique characteristics and a virtually infinite number of mechanical degrees of freedom suggest its underlying control mechanisms to differ from limb control. Like the arm of an octopus, the tongue's hydrostatic properties increase its maneuverability, but may also impose a large load on the motor control system (Zullo et al., 2019), qualitatively making its motor control potentially different from other speech articulators or the limbs.

Speech articulators (e.g., lips, jaw, tongue) each have complex and variable physical characteristics (Perrier, Payan, & Nazari, 2011). For instance, muscles of the jaw can be separated into joint-related muscles, and sphincteric muscles describe the orbicularis oris muscle of the lips (Kent 2004). Whereas the jaw properties resemble a damped mass spring (Saltzman & Munhall, 1989) and lips can be described in terms of constrictor mechanics, (Gick et al., 2011), the tongue possesses unique biomechanical properties, and complex innervation due to its involvement in chewing, speaking, breathing, and taste (Bordoni, 2018). Therefore, examining tongue motor control is important not only for broadening our understanding of the speech articulatory system, but also concerning whether motor control generalizes across speech articulators and limbs.

The present study used a novel tongue VMT paradigm in order to empirically examine motor control properties of the tongue. The VMT paradigm allows for quantitative assessment of human kinematics by comparing the movement of an articulator against a controlled target. The approach taken was to investigate the volitional tongue motor behavior of healthy adults during a series of tongue tracking tasks in which virtual intraoral targets were followed at different levels of predictability, frequencies, and directions (Experiment 1).

Speech production typically involves tongue and jaw movement in synergy; however, by removing contributions from the jaw, a more specific assessment of tongue motor control can be gained. Thus, in a second experiment, the jaw was stabilized and tongue movement in isolation was assessed at different levels of predictability and frequencies.

Findings gained from the present study may have potential clinical implications. For example, research on limb movement has provided evidence for the different effects that some practice variables have on motor learning during acquisition of a skill, in comparison to retention and transfer (e.g., Leving et al., 2016). The separate effects and the interplay of these practice variables, known as *principles of motor control (learning)*, have been described as “a set of processes associated with practice or experience leading to relatively permanent changes in capacity of skilled movement” (Schmidt & Lee, 2011, p. 327). Principles such as structure of practice amount and practice distribution, have been shown to enhance physical therapy treatment of neurologically impaired motor systems (e.g., Muratori et al., 2013; Rendos et al., 2020). Because speech is a skilled motor movement, there is potential for the principles of motor learning to be effectively used in speech therapy if speech production is governed by the same motor control mechanisms as that of limb motor movement. Although evidence has suggested that nonspeech motor control properties can be applied to speech motor (Ballard et al., 2009) more data are needed (Kent, 2015; Maas et al., 2008). Evidence concerning motor control for speech and nonspeech processes, such as obtained in the present study of the tongue, may be valuable for addressing this controversy.

A long-term aim of this study is to extend findings from healthy tongue motor control to understanding motor control properties responsible for speech errors produced by adults with acquired apraxia of speech (AOS), a motor speech disorder thought to result from a breakdown in the planning and/or programming of speech articulators (Deger & Ziegler, 2002; Duffy, 2013; Maas, Mailend, Guenther, 2015; Maas et al., 2008; McNeil, Robin & Schmidt, 2008; Van der Merwe, 2008). Recent accounts of the speech errors made by individuals with AOS have attributed difficulty with feedforward processing as a potential source of the motor planning and/or programming difficulties of these individuals (Jacks, 2008; Robin et al., 2008; Terband, Rodd, & Maas, 2019). However, these conclusions have been drawn using data from the lips and jaw in VMT research. The nature of the disorder has not yet been studied with respect to the tongue.

It is important to determine if tongue motor control is like that of the lips and jaw because if it is the case that all speech articulators share similar control properties, then theories regarding the feedforward deficit for individuals having AOS can be asserted with greater certainty and generalization. In addition, visual feedback-based methods for treatment can be better understood and applied.

In summary, the present research addresses knowledge gaps for volitional tongue movement. Questions focus on whether the speech motor control properties based on the lips and jaw also extend to the tongue, including the extent to which speech motor control shares properties with non-speech oral motor and limb motor control.

1.1 Models of Tongue Motor Control: Feedforward and Feedback Systems

Our understanding of articulatory movement during tracking tasks can be grounded in motor control theory, widely used to describe control mechanisms across various fields of study, such as biology, cognitive science (e.g., "cybernetics"), and rehabilitation medicine. Proposed models of motor control theory share similar framework that have been used for describing control in robotic systems and in humans (Parrell et al., 2019), where an executive control center generates instructions for movement. In people, this central controller is the central nervous system that initiates actions for the effectors, such as muscles of the limbs (Latash et al., 2010).

Two systems, *feedforward* and *feedback* control, have been used in accounting for observed movement behavior (Seidler, Noll, & Thiers, 2004). These two systems provide general descriptions of how the central and peripheral nervous systems generate and control movement. Different terminology has been used to describe the control systems, such as an *open-loop* control system, a *closed-loop controller*, *model predictive* control, and the *Smith predictor* control system (Parrell et al., 2019). Feedforward and feedback control are important components of recent speech production models, including the Directions Into Velocities of Articulators (DIVA) model (Guenther, 1994, 2016) and the Task Dynamics (TD) (Saltzman and Munhall, 1989).

Figure 1.1. displays a schematic of the two motor control subsystems in a hybrid feedforward/feedback model (Maill & Wolpert, 1996; Saltzman & Munhall, 1989; Smith, 1959; Tourville & Guenther, 2011). This model is supported by evidence obtained from (VMT) studies of the lips/jaw (Ballard & Robin, 2007; Moon et al., 1993). The feedforward control system is responsible for learning and encoding movement information for the articulators and

the larynx as stored motor programs. The mechanism creates articulatory parameters and activates pre-planned articulator movement from an internal model. When a movement command is activated, simultaneously, an *efference copy* of that action is created by the predictor (Figure 1.1). The efference copy is a prediction of expected sensory feedback (Wolpert and Kawato, 1998). The predictor generates the efference copy of movement as an internal estimation and feedback check for movement, accounting for delays in the feedback loop (Flanagan et al., 2003, Wolpert & Miall, 1996).

As movement takes place, the actual sensory consequences are compared to intended actions using the feedback control system, which provides online motor commands. The difference between the predicted movement goal and feedback information is used to correct motor commands and modify ongoing movement.

The feedback control system is also responsible for generating compensatory motor commands during unexpected external perturbations to the articulatory system (Wagner & Smith, 2008). For example, when a pipe is held between the teeth during production of speech, feedback information is compared against the internal predicted expectation of the movement outcome. A mismatch of between the efference copy and the feedback information signals an error to be generated. This information is sent back to the internal model of movement, where feedforward motor programs are updated and adapted for prevention of future errors (Lindblom, Lubker, & Gay, 1979).

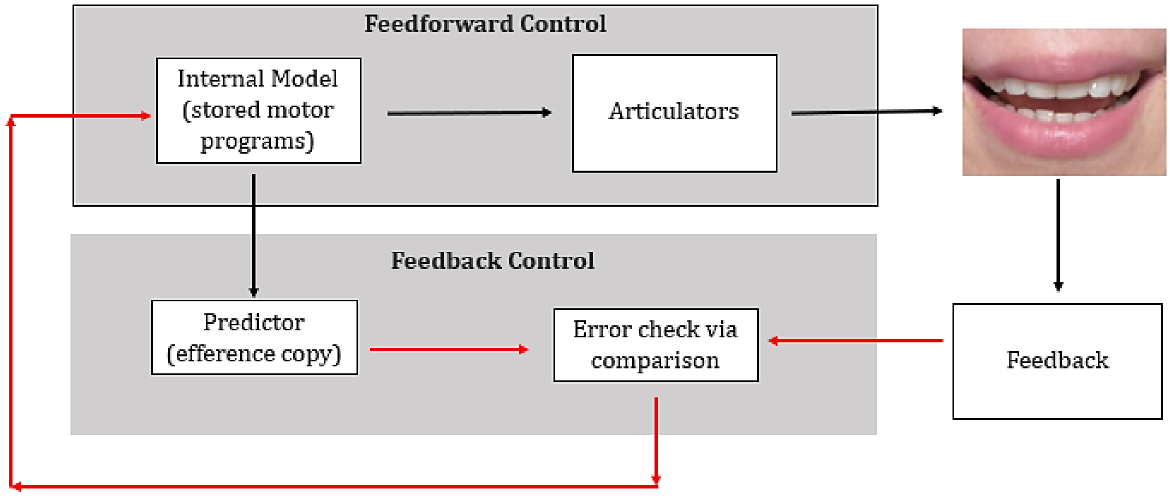

Figure 1.1. Schematic of feedforward and feedback systems.

Information about feedforward/feedback processing can be obtained by using the VMT paradigm. During a VMT task, participants use an articulator (e.g., lip or jaw) to track a moving target viewed on a screen. When tracking a target moving in a predictable pattern, sensorimotor and visual information are received from the feedback system, used to create the appropriate articulatory parameters of tracking movement. Information is stored as internal models (motor programs) and utilized to make predictions for continued movement and accurate tracking of the target.

Continually tracking a sinusoidal signal at one frequency (e.g., 0.6 Hz), in theory, allows for an internal model of the target motion to be formed (learned) because the target's movement is predictable (Robin et al, 2008). The internal model of the movement is continually updated and stabilized with visual feedback information during tracking. During tracking of a predictable signal, healthy talkers are generally in synch with the target signal. Data from previous speech VMT studies have suggested that when healthy individuals track predictable signals (versus unpredictable signals), internal models of the movements are created (Ballard et al., 2001, Ballard & Robin, 2007; Hageman et al., 1994, McClean, Beukelman, & Yorkston, 1987; Moon et al., 1993). Accurate production of a predictable movement has been demonstrated even with removal of the target signal (Ballard & Robin, 2007), suggesting an internal model guides movement.

When participants track unpredictable frequency modulated (random) signals, however, their accuracy is less accurate than when tracking predictable signals (Ballard & Robin, 2007; Moon et al., 1993). Following unpredictable frequencies places participants in a genuine tracking task, where they are not able to predict the position of the target, due to the varying nature of the target. With no specific pattern to learn, the individual cannot establish an internal model to guide feedforward commands. Consequently, online feedback information received from the visual input is used to continuously monitor the changing movement pattern. Thus, there is greater reliance on the visual feedback to monitor tracking accuracy, and articulator movement is more intermittent (Robin et al., 2008).

Following McClean et al.'s (1987) preliminary study assessing tracking of a predictable frequency (0.6 Hz), Moon et al. (1993) presented the first VMT study testing feedforward and feedback control processes. Their aim was to test if speech structures exhibited the same predictive (feedforward) and response (feedback) modes reported for nonspeech structures by previous researchers (e.g., Noble, Fitts, & Warren, 1955; Flowers, 1978). This was done by having healthy participants track both predictable (sinusoidal) and unpredictable target signals using their lower lip, jaw, or by modulating their voice pitch. The researchers tested three predictable oscillating patterns of 0.3, 0.6, and 0.9 Hz, and an unpredictable complex signal. The unpredictable signal was made of ten equal amplitude frequencies, ranging from 0.1 to 1.0 Hz, and in steps of 0.1 Hz. The study results were similar in many respects to those obtained from previous nonspeech (and speech) tracking. That is, predictable targets were tracked more accurately than unpredictable ones, suggesting the development of an "internal model" from which movements are controlled. Development of an internal model involves motor learning, which entails more than motor processes. Other variables must be considered in the acquisition of a skill. One such variable is augmented feedback, which enhances intrinsic feedback gained by an individual's sensory system. One form of augmented feedback, known as knowledge of performance, is related to information about specific movement component characteristics (Sharma et al., 2016). The VMT paradigm provides knowledge of performance in the form of visual feedback, which has been shown to have positive effects on learning (Buchanan & Wang, 2012; Katz & Mehta, 2015).

In summary, information about feedforward/feedback processing can be gained by varying the predictability of the target signal (either predictable or unpredictable) in a VMT task. Findings from both limb and speech articulators have shown that tracking a target moving in a predictable pattern allows for an internal model to be formed, which aids in guiding movement through feedforward processing. In contrast, with tracking an unpredictable (random) target movement, the varying pattern of the target prevents the creation of an internal model. Consequently, there is greater reliance on external (augmented) feedback to monitor movement errors caused by tracking in less predictable circumstances.

With the goal of confirming whether the motor control properties inferred for the lip and jaw would generalize to the tongue, tracking in the present study used predictable and unpredictable (frequency modulated, or FM) conditions to test predictions regarding feedforward/feedback control systems in tongue motor control. Questions and predictions regarding these variables are presented in section 1.7.

1.2 Speed-Accuracy Tradeoff Properties in Tongue Movement

A second goal of the present study was to examine if tongue motor control complies with a widely agreed upon principle of motor control, the speed-accuracy tradeoff effect. The tradeoff between speed and accuracy of movement can be described using Fitts' Law (1954). This law expresses the relation between the task-specific property of accuracy and movement speed as linear, predicting that the time required to rapidly reach a target area is a function of the distance to the target divided by the size of the target. Simply put, when speed becomes excessive, accuracy diminishes. Extending our understanding of tongue motor control with respect to Fitts' law provides insight into the potential relationship between speech and other areas of human motor control, and may help build improved models of speech production.

Moon et al.'s (1993) study was the first VMT research describing speed-accuracy tradeoff features in the movement of the lips/jaw, as well as larynx (with modulation of the fundamental frequency of sustained phonation). Increasing oscillating target frequency led to a decrease in tracking accuracy when the target moved at predictable frequencies. This finding was further supported by findings from healthy control participants in subsequent VMT studies (Hageman et al., 1994; Clark & Robin, 1998; Ballard & Robin, 2007; Robin et al., 2008), suggesting that the lip and jaw exhibit speed-accuracy tradeoff motor control properties like the limbs.

Recent studies have examined whether tongue movement is governed by speed-accuracy tradeoff. Kuberski and Gafos (2019) used a speech elicitation paradigm and electromagnetic articulography (EMA) to gather tongue movement data while participants produced repeated sequences of /ta/ and /ka/ to metronome rates that ranged from very slow to extremely fast. The authors found that the linearity of the relation between time and index of difficulty appears with fast tongue movements of repetitive speech. However, for slower movements, the relation expressed by the law appeared to break down. The authors concluded that like limb motor control (e.g., Huys et al., 2008), the underlying control strategies for the tongue movement may change as the rate of movement varies.

Control Strategies for Slow and Fast Movements

In an X-ray microbeam study using a magnitude production task to examine movement of the lower lip and tongue tip movement during production of stop consonants at rates ranging from very fast to very slow, Adams, Weismer, and Kent (1993) gained similar findings as Kuberski and Gafos (2019). The investigators found that as speaking rates become slower, the number of velocity peaks per gesture increase. Jaw movement, influenced by speaking rate, has been shown to exhibit similar outcomes (Wieneke, Janssen, & Belderbos, 1987). The multiple velocity peaks found for slower rates have been attributed to changes in underlying motor control strategies, where multiple sub-movements comprise the slower movements, and the movements are controlled through feedback mechanisms (Adams, Weismer, & Kent, 1993).

Slow hand movements have also exhibited multiple velocity peaks (Milner, 1992; Milner & Ijaz, 1990; van der Wel, Sternad, & Rosenbaum, 2010). When physical actions are performed at various slower rates, such as transitioning from running to walking, the movements are not simply slowed down, but rather categorical changes are made (van der Wel et al., 2010). The multiple peaks observed for slow limb movements are also suggested to reflect the motor control strategy where multiple sub-movements are produced for achieving accurate increases in movement duration at slow movement speeds (Burdet & Milner, 1998). Thus, control of movements at slow rates is similar for speech articulators and the limbs.

At fast speaking rates, the control strategy for speech gestures have been proposed to involve the use of preprogrammed unitary gestures (Adams, Weismer, & Kent, 1993). Similarly, fast movements of the limbs are proposed to use preprogrammed motor commands and predictions using an efference copy guide to movement (Desmurget & Grafton, 2003). Unlike slower movements, they are not modified through visual or proprioceptive feedback. It can be expected then, that while visual feedback is provided during the VMT task, preprogrammed internal predictions may guide faster movements in place of using feedback to make movement adjustments.

As will be described in more detail in the methodology section (2.1.5), the predictable frequencies in the present experiment (0.4, 0.6, 0.8 Hz) were selected to represent a comfortable rate, reflecting a unitary gesture (i.e., single velocity peak) control strategy. These frequencies were based on a series of pilot tests, beginning first with assessment of established frequencies in previous lip and jaw tracking studies (0.3, 0.6, 0.9 Hz), said to be representative of articulatory movement during speech (Moon et al., 1993).

Discrete versus Continuous Movements

Although the Kuberski and Gafos (2019) study showed that a speed-accuracy tradeoff occurs with fast tongue movements of repetitive speech, a potential limitation is that these findings were shown for discrete-like movements of the tongue. Differences have been noted in motor control of discrete versus continuous limbs movements (Huys et al., 2008), therefore, it is important to determine whether continuous movement of the tongue, like that required in a tracking task, also reflects this property. Continuous movements, such as walking, do not have definite endpoints, and are rhythmic in nature (Wiegel, Kurz, & Leukel, 2020), like the sinusoidal pattern of the moving target in the VMT task. These types of movements are said to be controlled by limit cycle behavior (Wei et al., 2003). Discrete movements, such as finger flexion or production of /ta/, are defined as gestures that have a distinct beginning and end, and have no activity occurring before or after the movement (Hogan & Sternad, 2007; Huys et al., 2008). These types of movement are proposed to be governed by fix-point attractors (see Strogatz, 1994 for more on these concepts). Thus, another aim of the present study was to confirm if speed-accuracy tradeoff features for tongue are reflected in continuous movement.

1.3 Speech and Nonspeech Lingual Movement

A third topic examined in this study was whether tongue motor control differs according to movement direction and, by extension, by speech versus non-speech function. This is a fundamental question in the field of speech science, and controversy surrounds which motor principles are specific to speech motor control and which overlap with non-speech motor control (Moore, 1993; Moore & Ruark, 1996; Moore, Smith, & Ringel, 1988; Nelson, Perkell, & Westbury, 1984).

Proponents of the dissociation between speech and nonspeech motor function emphasize that motor functions such as swallowing are different from volitional activities such as speaking (e.g., Ziegler, 2003). Speech is hypothesized to be part of an entirely separate motor system with distinct underlying neurological pathways and differs from other voluntary motor actions, specifically oral nonspeech motor actions (Ziegler, 2012). Movements of the speech articulators (tongue, lips, etc.) are controlled in different ways, depending on the purpose of their motor activity, and speech is considered part of a set of sensory-motor functions specialized for communication. While speech motor control utilizes an internal model to match the relation of the vocal shapes to their acoustic goals (Perkell et al., 1997; Ziegler, 2003), voluntary nonspeech tasks (such as VMT) assess an internal model that is related to proprioceptive or visual-spatial targets. Furthermore, the syllable movement rates used during speech are reported as values between 5 and 8 Hz (Poeppel & Assaneo, 2020), which are much faster than the frequencies typically used in VMT. Therefore, although there may be an overlap between the muscles used in nonspeech oral motor tasks and speech, they are considered constituents of separate systems at higher levels and cannot be compared.

In contrast, other researchers have proposed that the speech motor system is not uniquely separate, but that it is part of a more general motor system (e.g., Ballard et al., 2003). These authors suggest that some nonspeech motor tasks, but not all, have shared neural and behavioral motor control properties with speech and volitional nonspeech tasks. According to this view, the underpinnings of motor control are comprised of a highly flexible network that can accommodate a specific initial condition; thus, some volitional motor actions that are nonspeech have overlapping motor control characteristics in common with speech. When the motor system is learning, it generalizes previously internalized movements to new skills, enabling transfer to occur from tasks that have shared motor control properties. Thus, a better understanding of the whole system and the complex behaviors of speech can be gained by examining the different system levels (Ballard et al., 2003).

Ballard et al. (2003) further state that although laboratory studies are often a reproduction and approximation of typical everyday behaviors, the VMT task provides increased control of visual ability in terms of accuracy and age of participants. This permits close examination and interpretation of data collected for the preferred area of motor control. Furthermore, the need for continual adaptation in visual-motor tracking does not seem to pose difficulty for healthy speakers and other sensory stimulus may correspond to similar motor control functions.

Another way the VMT paradigm can potentially be useful to the discussion of speech and non-speech motor control is by examining the directionality of tongue movement during tracking tasks. Traditional phonetic descriptions classify speech sounds in terms of high-low (vertical) and front-back (horizontal) positions of the tongue in the vocal tract (Ladefoged, 1975), and flesh-point tongue movements measurement techniques such as X-ray micro-beam and electromagnetic articulography (EMA) usually record in these directions (Payan & Perrier, 1997). That is, kinematic studies of speech production are mainly conducted in the midsagittal plane (e.g., Kim & Max, 2014). Tongue movement in the midsagittal plane is considered more speech-like (Matsuo & Palmer, 2010) than movement in the lateral direction, which is typically non-speech like. VMT studies have not yet compared the difference between directions of tongue movement. One lingual VMT study (Sussman,1970), required participants to track in the lateral (side to side) direction, which is suggested to aid in chewing (Adams et al., 2020) and less for production of speech, and the study did not examine the effects of directionality. Thus, the present study required participants to track in three distinct directions of vertical, horizontal, and lateral as tracking in these directions may have differential value for predicting the difference between speech and non-speech movement performance (McClean et al., 1987).

1.4 Tongue/Jaw Synergy versus Tongue Movement in Isolation

Examining whether patterns of typical tongue/jaw synchronous movement extend to the case of the tongue moving in isolation is another related question explored in the current research. Even with its hydrostatic qualities, the movement and shape changes of the tongue occur in a space with dimensions determined by the movements of the jaw and hyoid (Hiiemae & Palmer, 2003). Although the tongue and jaw have a kinematic connection that may be due to the mechanical linkage of these structures (Matsuo & Palmer, 2010), the dynamic interaction of the two structures should also be considered and the jaw should not only be considered as a moving frame of reference (Sanguineti et al., 1996). However, by removing contributions from the jaw, it will be possible to examine control properties for the moving tongue alone.

In speech perturbation studies, bite blocks can be used to identify articulatory motor control functions (e.g., Jacks, 2008; Golfinopoulos et al., 2011). Bite blocks are small obstructions placed between a participant's back molars to create a gap between the upper and lower teeth, effectively stabilizing the jaw. By preventing jaw movement, bite blocks can allow for measurement of independent measurement of tongue kinematic performance and compensatory responses.

The speech production system is remarkably flexible and adaptive. Despite perturbations to the articulatory system, perceptually accurate speech can be produced. For example, when the jaw is artificially held in a fixed position due to a bite block, the upper lip is shown to compensate (e.g., Abbs et al., 1984). Similar responses are reported where tongue body gestures have been shown to compensate to achieve the same acoustic vowel target when the mandible has been held in a fixed position (Gay, Lindblom, & Lubker, 1981). Further, in healthy talkers, no change is noted in tongue movement durations in response to bite blocks (Solomon & Munson, 2004), as speakers achieve full acoustic compensation (Kelso & Tuller, 1983; Sussman, Fruchter & Cable, 1995).

When the nervous system receives sensory feedback that a perturbation is preventing the normal production of the desired movement goal, an internal predictive error signal (i.e., an efferent copy of the sensory consequences) is generated, allowing the system to make appropriate motor responses. These internal predictions are continually compared against feedback errors received from the periphery, and speech motor output is adjusted accordingly (Houde & Jordan, 1998; Lindblom, Lubker, & Gay, 1979).

In the present study, bite blocks were used to determine how jaw fixation can affect tongue motor control during tracking. With the natural condition of movement being the tongue and jaw moving in synergy, the aim was to examine if the tongue's motor control properties would differ when the contribution from the jaw was removed. Tracking accuracy of the tongue was compared in jaw-stabilized and jaw-free conditions to test whether the motor control properties examined in Experiment 1 (feedforward/feedback systems, speed/accuracy trade-off) would be found for the tongue alone.

1.5 Visuomotor Tracking (VMT) Paradigm Studies of Limb and Speech Effectors

The origins of VMT reside in limb motor control studies. VMT allows for the study of neural processes and computations underlying motor control mechanisms that enable humans to perform every day skilled action, like walking and writing (Kobori & Haggard, 2007; Poulton, 1974). VMT tasks assessing limb motor control generally involve participants holding a joystick (or steering wheel) to track a moving target presented on a computer screen. Much of the online motor control for everyday voluntary actions is guided by input from vision (Franklin & Wolpert, 2008; Saunders & Knill, 2004). Thus, performance measures obtained from visual tracking of targets (i.e., VMT) are useful for gaining insight into feedback or feedforward motor control processes.

Researchers in the speech domain have adapted the VMT paradigm to better understand healthy and disordered speech motor control (Ballard & Robin, 2007; Ballard, Robin, Folkins, 2003; Robin et al, 2008; Hageman et al., 1994; Mclean et al., 1987; Moon et al., 1993). Speech VMT studies have used a strain-gauge transducer system for tracking tasks. This early-stage device has been used to record the movement of the jaw and lips as participants (silently) track a moving target on a screen.

In a typical VMT task, participants observe a screen displaying two cursors. One cursor represents the participant's articulator movement and the other a moving target. The task essentially requires the participant to keep the articulator cursor superimposed on the moving target. In previous studies, signals from the articulator of interest were represented as a dot centered on the screen. As the target signal moved up and down on the screen, the participants were instructed to track it (using their lips or jaw) by keeping the dot representing their articulator on the moving target throughout the task (Abbs & Gilbert, 1973; Barlow, Cole, & Abbs, 1983; Muller & Abbs, 1979; Sussman & Smith, 1970a, 1970b).

The present study employed a similar design where participants were tasked with matching their tongue tip cursor to an oscillating target. Because oscillating signals are predictable, tracking accuracy can be quantified by measuring the difference between the participant's tracking movement and the target waveform. By measuring the difference between the moving target and the participant's movement, accuracy can be quantified. Perfect pursuit tracking is the movement of the two cursors in unison.

McClean, Beukelman, and Yorkston (1987) were the first to advocate the use of visuomotor tracking of sinusoidal targets in assessing dynamic position control of articulators. Participants used their lower lip, jaw, laryngeal, and respiration system to track sinusoidal movements of targets moving at a (predictable) speed of 0.6 Hz. Lip and jaw tracking was conducted using a head-mounted strain-gauge system. Laryngeal system control was evaluated by voice fundamental frequency modulation, while control of the respiratory system was indirectly measured by assessment of transduced air-pressure changes to face masks worn by participants. The results indicated that VMT of sinusoidal targets can serve as a viable approach to assess the motor integrity of articulatory systems used in speech production.

Naturally, speech movements do not follow perfectly sinusoidal (oscillating) patterns, like those required in VMT. However, tracking of them might be advantageous in that the alternation of opening and closing movements have their peak velocity in the middle of the gesture, comparable to patterns observed for speech movement (Gracco & Abbs, 1986). This is claimed to be an important benefit of the VMT task in that non-speech movements can be used to examine speech motor control without the possible confounds of linguistic processing such phonology, syntax, semantics, and pragmatics (Robin et al., 2008; although cf. Ziegler, 2003).

As mentioned in section 1.2, the VMT task is also a useful way to examine movement in continuous motion. This is an important advantage over the static fine force or position control tasks of the past. For example, in the test of static fine force control, participants match the presented target force level by compressing the force transducer with either the upper lip or the lower lip (Barlow & Netsell, 1986). Such tasks manipulate either force or displacement of an articulator, rather than evaluating its movement. Motor control properties of continuous movement of the tongue may differ from measurements of tongue force (e.g., Neel & Palmer, 2012). Therefore, the VMT paradigm provides a useful tool for assessment of tongue motor control properties.

1.6 Statement of Problem

Except for one study examining the difference in the effect of tactual desensitization (anesthetization) of the tongue and use of feedback modalities (Sussman, 1970) and a few studies addressing the effectiveness of the tongue in medical applications, such as mouse/typing systems (Caltenco et al., 2014) or wheelchair steering devices (Johnson et al., 2012), the tracking capabilities of the tongue are not well understood. Indeed, little is known about volitional movement for the tongue, the key articulator directly involved in producing speech (and non-speech) sounds (Hiiemae & Palmer, 2003; Iskarous, 2003; Yano et al., 2015). VMT research has mainly employed the external articulators (i.e., lips and jaw) for assessment of speech motor control, however, the tongue is a complex organ and may require different control processes than the jaw or the lips (Gentil & Tournier, 1998).

A goal of the present work was to determine whether feedforward/feedback systems proposed to control lip/jaw movement (and by extension the limbs) generalize to the tongue. The aim was to provide additional information about volitional control of tongue movement, and help address theories formed for the basis of apraxia of speech (AOS). A series of VMT studies support the notion that individuals with AOS have impairment of feedforward commands (e.g., Robin et al., 2008). When the feedforward control system is impaired, there is assumed to be greater reliance on feedback control to check for correct production of the intended sounds (Maas, Mailend, & Guenther, 2015; Jacks, 2008). However, it is not known if the predictions from these studies, which studied lip/jaw tracking, also generalize to the tongue. Findings from healthy participants in the present study can serve as a starting point for future lingual VMT studies using the AOS population.

Information about lingual motor control of healthy individuals can also address the debate on whether the motor control mechanisms employed for nonspeech movements are the same as those used for speech, especially with respect to selecting suitable therapy approaches in the clinical management of motor speech disorders. For example, nonspeech oral motor exercises (NSOMEs), such as lateral tongue wags, are widely used by clinicians to facilitate speech production (Bahr, 2001; Forrest, 2002; Powell, 2008). These exercises do not involve speech, but are believed to improve speech production through the enhancement of oral function (Bunton, 2008). The use of the techniques, however, in particular for developmental speech sound disorders, has been criticized (Kent, 2015; Lee, 2021). For example, it has been argued that training individual speech movements in isolation will not transfer to the whole speech gesture (Lof & Watson, 2010). Furthermore, the nonspeech oral motor exercises focus on movements which deviate from consideration of phonetic treatment (Ruscello, 2008). Currently, the literature points to insufficient evidence for support of using NSOMEs in treating speech disorders (Kent, 2015; McCauley et al., 2009; Ruscello & Vallino, 2020). As contribution to the discussion, the present work provides, as a first step, data regarding directional differences that can potentially address the question of whether speech-like tongue movement differ from non-speech-movement.

The apparatus used in the first lingual tracking study (Sussman, 1970) required participants to be fitted with a rubber mouthpiece having a plastic mold insert containing two photoconductive cells flanking and a miniature lamp as the tongue motion transducer. The advancement of present-day instrumentation for measuring speech production permits a less cumbersome manner to examine tongue movement.

The present study used three-dimensional (3-D) electromagnetic articulography (EMA) technology, in combination with a visual feedback system and VMT program (see section 2.1.2), to empirically address motor control properties of the tongue. Due to its anatomical position in the oral cavity, tongue movement is largely unseen during speech production. The visual feedback provided with the instrumentation in this study allows for on-line visualization of tongue movements. This type of visual feedback system is advantageous in training paradigms in that it facilitates learning (Katz & Mehta, 2015; Suemitsu, Ito, & Tiede, 2013).

1.7 Research Questions

<u>Experiment 1</u>

Q1) Will healthy adults exhibit more accurate tongue tracking for predictable frequencies when compared to an unpredictable (frequency modulated, or FM) condition, as has been demonstrated in VMT studies of the lip and jaw?

Prediction: *Yes. Motor control for tongue oral movements will show similar patterns to lip and jaw, in which participants form internal models for predictable targets based on feedforward mechanisms. For the unpredictable targets, tongue movement will rely on visual feedback and correction, resulting in decreased accuracy.*

Q2) For predictable target frequencies (0.4, 0.6, and 0.8 Hz), will tongue-tracking accuracy be inversely (negatively) related to speed in continuous tongue movement?

Prediction: *Yes. Based on recent EMA findings for accuracy of tongue repeated speech movements (Kuberski and Gafos 2019), it is predicted that tongue movement will show a speed/accuracy tradeoff, like that demonstrated for lips and jaw (e.g., Hageman et al., 1994; Clark & Robin, 1998; Ballard & Robin, 2007; Robin et al., 2008).*

Q3) Will tongue tracking performance differ across speech-like directions (vertical (y) and horizontal (z)) and non-speech-like lateral (x) directions?

Prediction: *Yes. Tracking accuracy will differ with tracking in different directions. Higher accuracy is expected for vertical and horizontal directions when compared to the lateral direction, because vertical/horizontal tongue movements (midsagittal) are speech-like, highly-practiced, and (ordinarily) braced; while the lateral direction is less constrained and associated with non-speech (vegetative, oral hygiene) function.*

<u>Experiment 2</u>

Q1) When the jaw is stabilized, will tongue motor control properties differ from when the jaw is fixed? Specifically, will tracking accuracy be higher for predictable frequencies than for the unpredictable (FM) condition, and will a speed-accuracy tradeoff be observed?

Prediction:. *Yes. Compensatory mechanisms are expected to contribute during the jaw-fixed condition, leading to similar results as when the tongue and jaw are moving in synergy, like Experiment 1. Tongue motor control while the jaw is fixed by a bite block is expected to show reduced tracking accuracy for the unpredictable condition and higher accuracy for the predictable frequency condition, as well as exhibit speed-accuracy tradeoff.*

CHAPTER 2

EXPERIMENT 1: EFFECTS OF FREQUENCY, PREDICTABILITY, AND DIRECTIONALITY ON TONGUE MOVEMENT

This chapter describes the experimental methodology and statistical analyses used in Experiment 1, an experiment designed to address (1) feedforward/feedback systems (predictability), (2) whether tongue motor control shows a speed/accuracy tradeoff (frequency), and (3) whether differences correspond with speech-like or nonspeech movements (direction). Lingual tracking performance for three predictable frequencies of 0.4, 0.6, and 0.8 Hz, an unpredictable frequency modulated (FM) condition, and lateral (**x**), vertical (**y**), and horizontal (**z**) directions are investigated.

2.1 Methodology

2.1.1 Participants

Ten healthy adults (6 females; 4 males) ranging from 22 to 48 years of age (*M* = 28.8, *SD* = 8.18) participated in the first experiment. Participants were recruited through the University of Texas at Dallas (UTD) Sona system, an online program used for scheduling and managing research participants. All participants who attended the session received class credit, used toward an undergraduate research participation requirement. Participants reported no prior history of speech, language, or hearing difficulties, neurological disorders, or uncorrected vision disorders. Each participant received written informed consent that followed guidelines set by the UTD Institutional Review Board.

2.1.2 Experiment Apparatus

This research used Opti-Speech (Vulintus LLC; Sachse, Texas), a software using Unity engine (Unity®, Unity Technologies, San Francisco, CA). Opti-Speech receives motion tracking data from a 3D electromagnetic articulography (EMA)-based system, Wave Speech Research system (Northern Digital Inc.; Waterloo, Ontario, Canada), which allows real-time motion tracking with an error margin of approximately 0.5 mm (Berry, 2011). Using positional data from 5-Degree of Freedom sensors (3mm x 3mm x 3mm), the Opti-Speech program creates a (pseudo) three-dimensional tongue avatar, displayed on a computer monitor (Dell 22'').

A custom (VMT) program created in C++ and combined with Opti-Speech was used as a graphic user interface (GUI) to create a tongue visuomotor tracking program for this research. The program included a spherical moving target for lingual tracking purposes. The target oscillated in a sinusoidal pattern in the lateral (**x**), vertical (**y**), and horizontal (**z**) directions, according to programmed parameters. The parameters included sinusoidal equations using the *Lerp* function in Unity to determine the target trajectory:

$$Lerp(startPosition, endPosition, t)$$

Where,

$$t = \frac{Cos\left(frequency * 2\pi * \frac{currentTime}{1000}\right) + 1}{2}$$

Lerp runs a linearly interpolated value between start position and end positions, dependent on the value of time (t), which varies sinusoidally. The programmed parameters effectively provide the position of the target with the given time (in milliseconds).

2.1.3 EMA Sensor Placement and Visual Feedback

Nine Wave sensors were used in total for this experiment, with a tenth sensor added for calibration of the tongue model (Figure 2.1). Five sensors were affixed to each participant's tongue using a biocompatible adhesive (PeriAcryl®, GluStitch Inc., Canada). A custom-made template was laid across the ventral surface of each participant's tongue to determine sensor placement. The template ensured that that sensor placement was similar across all participants and that sensors could be reattached to the same location on the tongue if detached during the experiment.

Using a single-use color transfer applicator, the placement of each sensor was marked using the template. One sensor was placed at tongue tip (TT), approximately 1 cm posterior to the tongue apex. Two other sensors were placed at tongue dorsum (TD), and tongue back (TB), approximately 3 and 4 cm posterior to the tongue apex, respectively. A tongue right (TR) and tongue left (TL) sensor were positioned laterally, one on each side of the tongue, approximately 1 cm from the tongue midline (Figure 2.1).

Three other sensors were attached to a pair of plastic glasses; one at the bridge and one on each (left and right) frame temple, approximately 3 cm posterior from the hinge. The plastic glasses were large enough to be worn comfortably over a participant's personal glasses. The purpose of the plastic glasses containing the three sensors was to establish a frame of reference in order to remove head movement data (by subtraction). A single additional sensor was taped to the middle region of the participant's chin to track jaw movement. In order to calibrate the tongue model to each participant's head size, a tenth sensor was briefly placed at the point where the upper incisors meet the gum line, and subsequently removed before experimental sessions began.

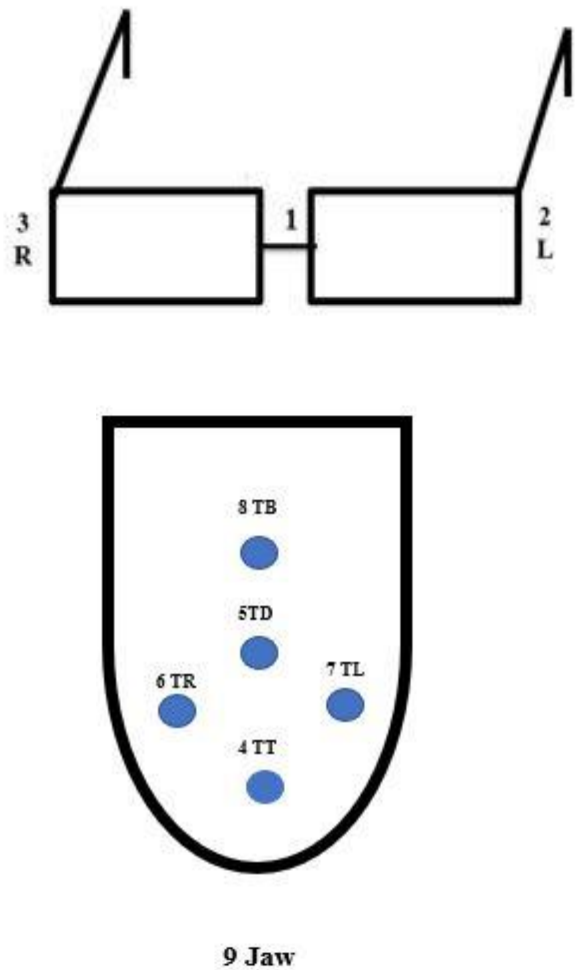

Figure 2.1. Schematic for EMA sensor placement.

Using the sensor position data received through the Wave system, the Opti-Speech program creates a (pseudo) three-dimensional tongue avatar, displayed on a computer monitor (Dell 22’’). At the beginning of the experiment, participants viewed the virtual tongue model (i.e., avatar) and five small blue markers representing the calculated positions of where the TT, TD, TB, TL, and TR sensors lay along the surface of the tongue. The visibility of each of these markers may be adjusted to “on” or “off” in the Opti-Speech program. To remove distractions and reduce the complexity of the visual display, all tongue markers were removed from view, with the exception of TT (tongue tip). Therefore, only the TT marker, which was used for tracking purposes, and the tongue model were seen throughout the experiment.

Participants in the present experiment were instructed to track the moving target with their tongue (see section 2.1.4 for details), where Opti-speech offered external real-time visual feedback for the participants’ tongue movement. While the participants maintained their TT marker in synch with the moving target, the target color changed from purple to green, indicating accurate tracking (Figure 2.2a). If the TT marker was not in synch with the moving target, the target reverted to purple, indicating an incorrect TT position (Figure 2.2b). In this manner, binary real-time visual feedback (knowledge of performance, or KP) for tongue positioning was provided.

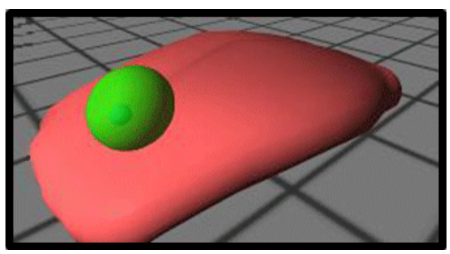

Figure 2.2a. TT marker in synch with moving target (green).

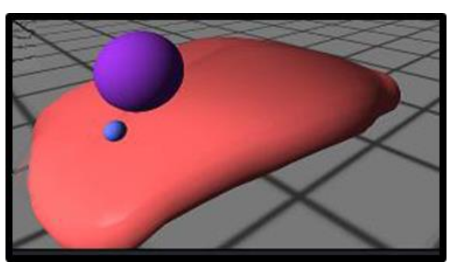

Figure 2.2b. TT marker not in synch with moving target (purple).

The target color change in Opti-Speech is dependent on a collision-detection mechanism (in Unity engine) based on the target's configurable radius. The length of a vector from the target to the TT marker is calculated; If this length is less than the radius of the target, indicating the TT marker is inside the target sphere, the target color will convert to a green color. However, if the length between the target and the TT marker exceeds 2x the radius, the target remains purple. Any length between the two conditions is linearly interpolated between green and purple, using a built-in function in Unity.

To prevent vector interference from other markers on the tongue (e.g., TD, TB, etc.), the target was programmed to detect "collision" from only the TT marker. Furthermore, the 3D plane capability was disabled for the TT marker, allowing a more precise match detection by the target for each specified tracking direction.

2.1.4 Procedure

Prior to the start of the experiment, participants were asked to complete a pre-experiment questionnaire to collect background information and to rule out possible confounds, such as vision or hearing impairment (Appendix A). Next, affixed with sensors and wearing the plastic glasses, participants were seated in a chair facing a computer monitor placed approximately one meter away at eye-level. The Wave system field generator was placed approximately 10 cm to the side of each participant's head and a 500mm volume cube was used to measure positional data.

The experimenter placed a virtual target (i.e., a 12mm sphere) in the animated oral cavity. The target size was selected based on findings from target a previous Opti-Speech experiment (Katz et al., 2014) and additional pilot tests conducted for the current experiment. Participants were instructed to watch the computer monitor and to follow and track the moving purple sphere (target) using their tongue tip (TT) marker. They were asked to keep their TT marker on the target throughout its movement. To familiarize participants with the tracking task and apparatus, all participants received a brief (30-sec) practice trial for each of the conditions prior to data collection. Between each tracking condition, participants were given short (20-sec) breaks. Each experimental session lasted approximately 50 minutes, including sensor setup time and experimentation.

During the experiment, a second computer monitor was used by the experimenter to supervise data collection. This monitor was located approximately one meter away from the main experiment display monitor and was facing away from the participant. After completion of the experiment, participants were asked to fill out a short questionnaire about their experience with the experiment (Appendix B). This questionnaire was included to determine subjective difficulty of the experimental conditions (i.e., predictable versus unpredictable frequencies and different tracking directions).

2.1.5 Stimuli

Three predictable frequencies (i.e., speeds) of 0.4, 0.6, and 0.8 Hz were used for the current study. These frequencies were chosen based on a series of pilot tests, in which two of the three initial chosen frequencies of 0.3, 0.6, and 0.9 Hz, established in previous lip and jaw tracking studies, were found to be difficult for lingual tracking. A frequency of 0.3 Hz caused slow, labored tongue movements, while 0.9 Hz caused excessively fast and uncontrolled movements of the tongue. An unpredictable (frequency modulated, or FM) signal was also included to create a condition that would maximally require feedback, as opposed to feedforward, processing. Ten equal amplitude frequencies comprised the unpredictable signal, with a range of 0.1 to 0.9 Hz, in steps of 0.1 Hz.

Most studies of tongue direction have investigated vertical (**y**) movement, since this direction is thought to be representative of how the tongue moves during speech (Ladefoged, 1975; Wang, Katz, & Campbell, 2014). In addition, with the exception of tongue lateral gestures, most speech researchers consider the vertical (**y**) and horizontal (**z**) target movement directions (i.e., midsagittal) to predominantly represent speech-like movements (Matsuo & Palmer, 2010) and this is the position taken in this study. The lateral (**x**) direction was selected to examine tracking in a non-speech direction. The target moved in these three distinct directions over a span of 9.95mm, which, in pilot studies, participants deemed the most comfortable movement range for tracking in the virtual environment.

The Opti-Speech systems affords different views for subject training, including frontal, midsagittal, and left view. For the current study, a front view of the tongue model was chosen for the horizontal (**x**) target movement, a midsagittal view for the vertical (**y**) target movement, and a left view for the horizontal (**z**) target movement. These tongue model perspectives were chosen based on pilot studies, in which participants reported the (above) views as optimal for accurate target tracking in each direction.

In this first experiment, the stimuli were blocked for the target movement direction, so that all participants tracked in the vertical (**y**) direction first, lateral (**x**) direction second, and the horizontal (**z**) direction last, using the same target frequency order. Presentation order of the four different frequencies (i.e., 0.4 Hz, 0.6 Hz, 0.8 Hz, FM) was randomized across participants.

Each participant produced a total of twelve 60-sec trials ((3 predictable frequencies + 1 FM frequency) x 3 directions).

2.1.6 Data Analyses

Each of the twelve 60-second trials were resampled at 50 Hz and lowpass filtered at 25 Hz to reduce aliasing and eliminate any high-frequency noise. The first and last 10 seconds of each 60-second trial were truncated to eliminate startup and fatigue effects.

Following Moon et al. (1993), Pearson correlation coefficient (Pearson's r) was used to statistically assess overall tracking accuracy. This is a linear correlation between the participant's signal (TT) and the target signal, irrespective of their magnitudes (McClean et al., 1987). Using the *corrcoef* function in MATLAB, correlation coefficients for the 40-second tracked portions and their target signals were computed, which served as a basic measure of tracking accuracy for each participant. A correlation coefficient value of 1.0 (or -1.0) indicates exact alignment of the participant's tracking signal with the target signal (i.e., perfect tracking).

Two additional dependent variables, amplitude ratios and phase differences, were used to further examine spatial and temporal aspects of tracking behavior. Amplitude ratios are a measure of how much the participant's tracking spatially deviates from the target signal. It is a measure of the magnitude difference between the tracked and target signals, giving an overall indication of amplitude accuracy over time, irrespective of frequency. An amplitude ratio of 1 reflects perfect tracking.

Amplitude ratios and phase differences were computed using algorithms described by Zhivomirov (2016), implemented in MATLAB. For the amplitude ratios, the average value of each signal over its period was removed. This is known as direct current (DC) removal, which is a common technique in signal processing. Fourier transform (FFT) of both signals were then completed to obtain a moving window of power spectrum values. In each window, the frequency response amplitude for each signal was calculated by taking the peak of the signal, dividing it by the length of the signal, and dividing that value by the amplification of the window. Next, the amplitude ratio values were obtained by dividing the (frequency response) amplitude of the tongue tip signal (TT) by the oscillating signal (O):

$$\textit{Amplitude ratio (AR)} = TT/O$$

Phase difference is a tracking accuracy measurement of how much the participant's tongue tip signal has shifted from the target signal over time. The phase angle for each signal was first determined, using similar calculations as done for amplitude ratio (DC removal, FFT, complex array for peak). Phase difference was then calculated by finding the difference between the phase angles of the tongue tip (TT) and oscillating target (O) signals:

$$\textit{Phase Difference} = \textit{phase angle (TT)} - \textit{phase angle (O)}$$

Zero degrees phase difference (in degrees) indicates perfect accuracy, and a negative phase difference value represents phase lead (tongue tip signal leading the target signal). For both cases, construction of an internal model of the target signal is required (Flowers, 1978; Moon et al., 1993). Conversely, a phase lag (target signal leading the tongue tip signal) is indicative of the participant relying on feedback processing to guide tracking.

2.1.7 Statistical Analyses

The dependent variables of correlation coefficients and amplitude ratios were separately analyzed in two-way (Frequency x Direction) repeated measures analysis of variances (ANOVA). Planned comparisons were completed for predictable frequencies and the unpredictable (FM) condition, the different levels for predictable frequencies (0.4, 0.6, 0.8 Hz), and the different levels for direction (vertical, lateral, and horizontal) at $p < .05$.

Phase difference data are a circular measure and therefore, could not be statistically treated in the same manner as correlation coefficient and amplitude ratio data. To calculate descriptive statistics for the phase difference data, the CircStat toolbox for MATLAB (Berens, 2021) was used. The phase difference values (angles) were presented as a scatterplot of data points on the circumference of a circle. Each data point was characterized as a vector comprised of its cosine and sine values. By computing the sum of all vectors and varying directions for each phase difference data point (vector), circular means ($\bar{\theta}$) were calculated.

The circle radius resulting from mean angles, called the mean resultant length (R), was calculated. R is a value between 0 and 1 and provides information about the spread of the phase difference data points around the circle (Cremers & Klugkist, 2018). If all phase difference data vectors point in the same direction, R will have a length close to 1, reflecting closely concentrated data and higher tracking accuracy. Circular standard deviation (s) were also computed for the phase difference data using the CircStat toolbox for MATLAB (Berens, 2021). Circular standard deviation is bounded by 0 and $\sqrt{2}$, where lower standard deviations signify higher tracking accuracy (i.e., the phase difference data are clustered closer together), and higher standard deviations indicate lower tracking accuracy (i.e., a larger dispersion of the data around the circle).

Because the present study used a repeated measures design, the circular analogue of the two-factor ANOVA, the Harrison-Kanji test (1988), could not be utilized because it is intended for an independent groups study design. Thus, to statistically analyze the phase difference data, Watson-Williams (multi-sample) tests in the CircStat toolbox for MATLAB (Berens, 2021) were used. In circular statistics, the Watson-Williams test is the equivalent of the one-factor ANOVA, assessing the similarity and differences of means between two or more groups. In the present research, one Watson-Williams test assessed the predictable frequencies compared to the unpredictable (FM) condition, and another compared all predictable frequencies. Findings from correlation coefficients, a global measure for tracking accuracy, were used to exclude analysis of the direction data (see section 2.2.1).

2.2 Results

This section discusses findings for the correlation coefficient, amplitude ratio, and phase difference measures described for Experiment 1. These are measures of tracking performance at three predictable frequencies (0.4, 0.6, 0.8 Hz), an unpredictable (FM) frequency condition, and three directions (lateral (**x**), vertical (**y**), horizontal (**z**)). Results of statistical analyses are first presented; questionnaire and individual participant details are next discussed.

2.2.1 Correlation Coefficients

Pearson correlation coefficients were calculated for the 40-second tracked portions and their target signals. Figure 2.3 shows tracking accuracy based on mean correlation coefficient values for predictable frequencies and the unpredictable (FM) condition. ANOVA results yielded a significant main effect for Frequency [$F(3, 114) = 11.61$, $p < .001$] and no significant interaction. Planned comparisons of main effect of Frequency revealed a significant difference between predictable frequencies and the unpredictable (FM) condition [$F(1,114) = 8.09$, $p < .05$]. Means showed higher accuracy for the predictable frequency conditions ($M = .66$, $SD = .28$) than the unpredictable condition ($M = .51$, $SD = .23$).

There were also significant differences between 0.4 Hz and 0.8 Hz [$F(1,115) = 21.20$, $p < .001$] and 0.6 Hz and 0.8 Hz [$F(1,114) = 22.51$, $p < .001$]. Comparison of means indicated that tracking accuracy was higher at 0.4 Hz (*M* = .81, *SD* = .16) and 0.6 Hz (*M* = .68, *SD* = .28) when compared to 0.8 Hz (*M* = .49, *SD* = .29).

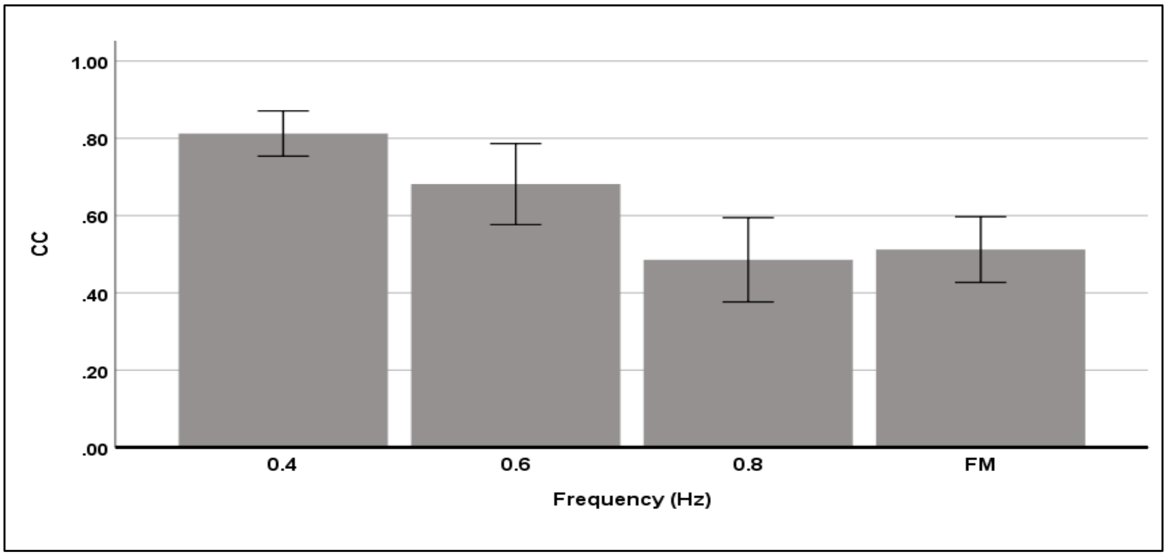

Figure 2.3. Mean tracking accuracy based on correlation coefficient for predictable frequencies and the unpredictable (FM) condition (Error bars = standard error. N = 10).

Figure 2.4 displays examples of high and low tracking accuracy based on correlation coefficient values. Overall, higher accuracy was indicated by participants consistently and closely following the moving target, both in amplitude and phase (e.g., top panel of Figure 2.4). Lower accuracy was associated with visually observed erratic patterns, i.e., substantial spatiotemporal variability. For instance, the example shown in the bottom panel of Figure 2.4 demonstrates both spatial and timing difficulties in tracking from a participant (M3).

Although correlation coefficient values gave an overall indication of how accurately the participants were following the target signal, additional details were provided by amplitude ratio and phase difference values.

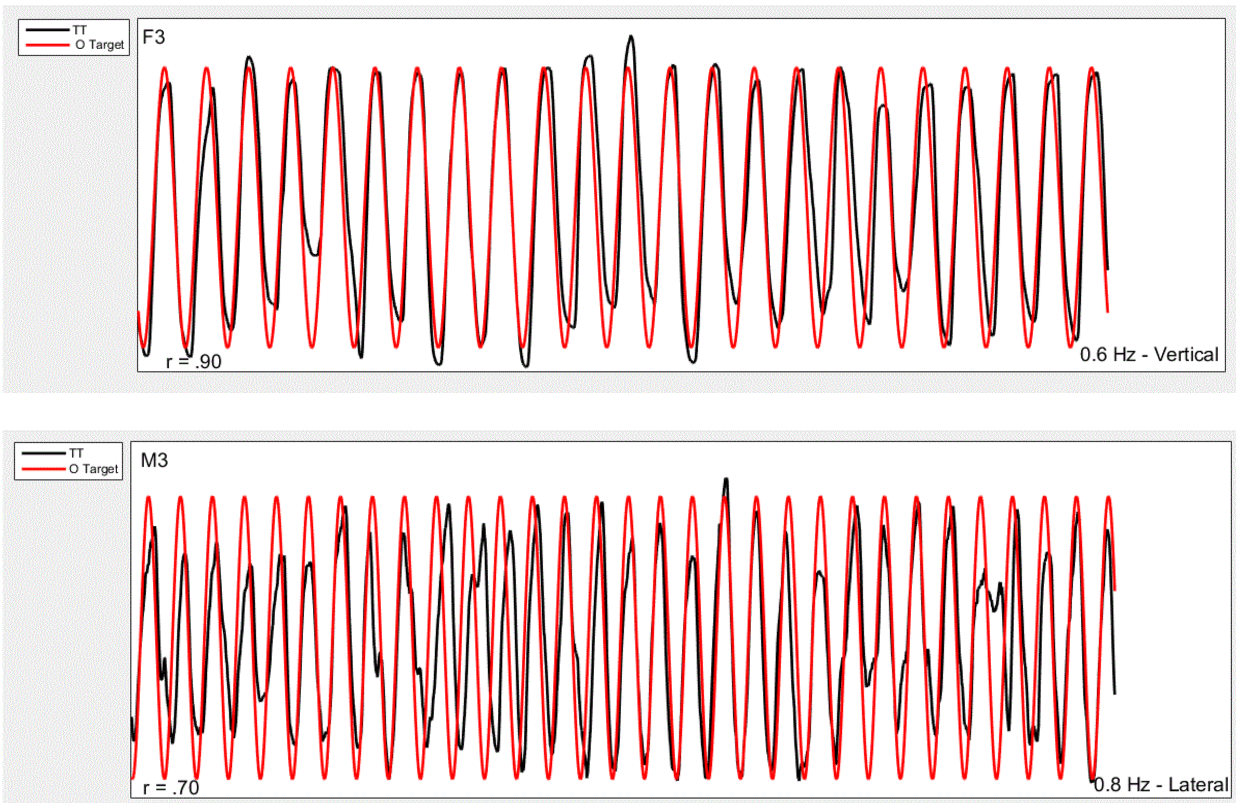

Figure 2.4. Examples of high (top) and low (bottom) accuracies based on correlation coefficient values for 40-seconds of tongue tracking (Participant number, correlation coefficients, and target frequency/directions are shown. The target signal is in red. Participant data are in black).

2.2.2 Amplitude Ratios

Amplitude ratios for the 40-second tracked portions were calculated. ANOVA results indicated significant main effects for Frequency [$F(3,114) = 3.39$, $p < .05$] and Direction [$F(2,114) = 10.85$, $p < .001$]. Planned comparisons of the main effect for Frequency showed a difference between predictable frequencies and the unpredictable (FM) condition [$F(1,114) = 4.58$, $p < .05$], with accuracy higher for the unpredictable condition ($M = .89$, $SD = .23$) than for the predictable frequency conditions (*M* = .80, *SD* = .24). Comparison of the different predictable frequencies revealed a significant difference between 0.4 Hz and 0.8 Hz [$F(1, 114) = 5.57$, $p < .05$], with accuracy higher at 0.4 Hz (*M* = .86, *SD* = .23) than at 0.8 Hz (*M* = .73 *SD* = .25).

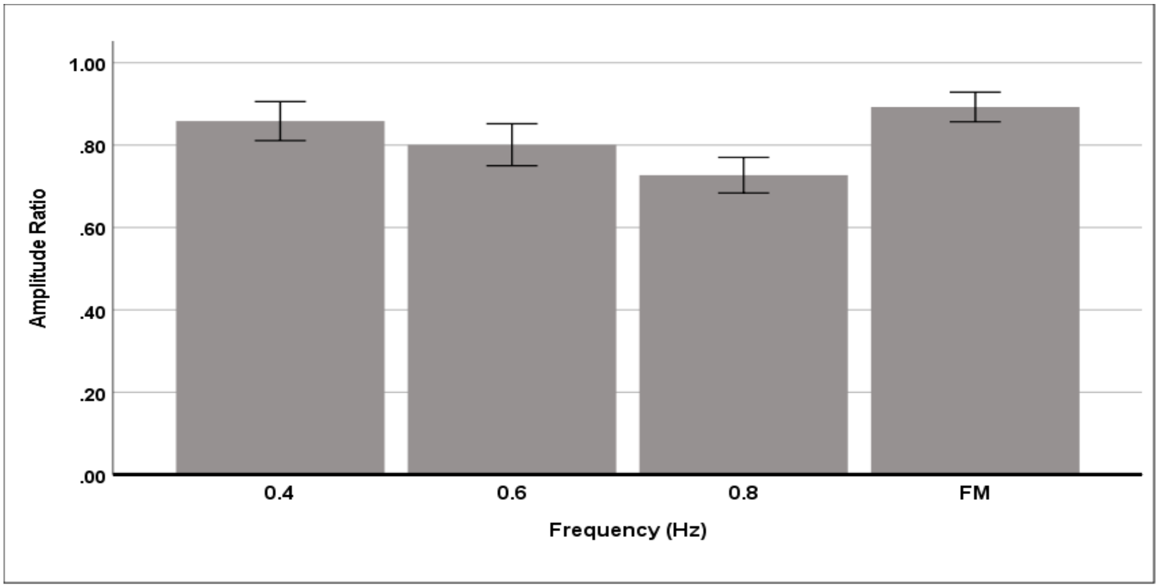

Figure 2.5. Mean tracking accuracy based on amplitude ratio values for predictable frequencies and the unpredictable (FM) condition (Error bars = standard error. N = 10).

Planned comparisons of the main effect of Direction indicated a significant difference between the lateral (**x**) direction than the vertical (**y**) direction [$F(1,114) = 20.62$, $p < .001$], with accuracy higher in the lateral direction (*M* = .94, *SD* = .26) than the vertical direction (*M* = .72, *SD* = .19).

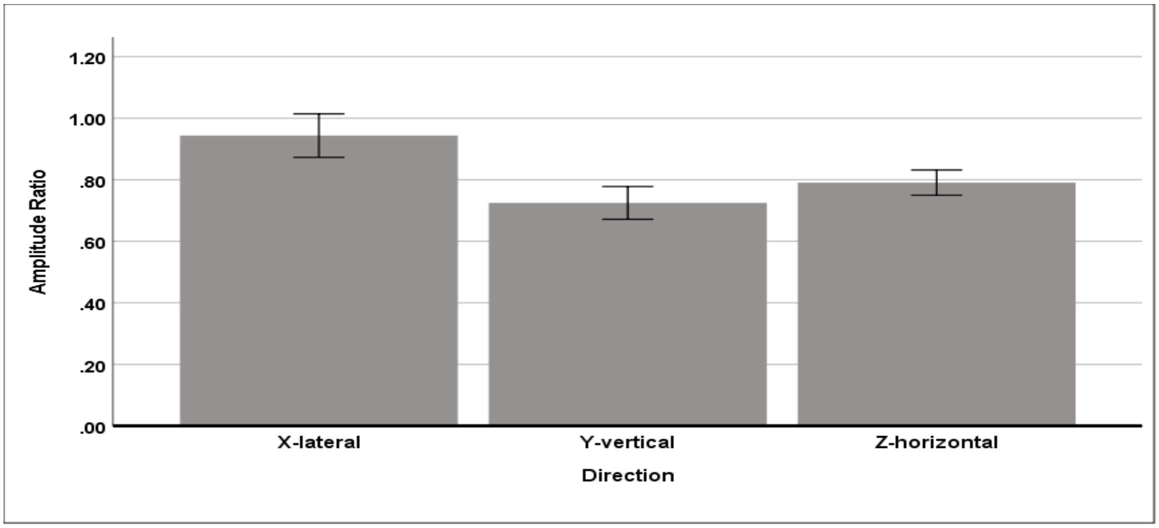

Figure 2.6. Mean tracking accuracy in the lateral (**x**), vertical (**y**), and horizontal (**z**) directions based on amplitude ratio values (Error bars = standard error. N = 10).

2.2.3 Phase Differences

Watson-Williams results revealed a significant effect for Frequency [$F(3,116) = 4.23$, $p < .05$]. A significant difference between predictable frequencies and the unpredictable (FM) condition [$F\ (1,118) = 6.70$, $p < .05$] was found, with tracking accuracy higher for predictable frequencies ($\bar{\theta} = 14.90$, $s = .26$) than the unpredictable (FM) condition ($\bar{\theta} = -38.06$, $s = 1.26$).

Comparison of the different predictable frequencies showed a significant difference between 0.4 Hz and 0.8 Hz, [$F\ (1,58) = 7.79$, $p < .05$]. As seen in Table 2.1, tracking accuracy was higher at 0.4 Hz than at 0.8 Hz. This table shows the phase difference descriptive statistics for each frequency condition and direction, including circular means ($\bar{\theta}$) and mean resultant lengths (R). Higher tracking accuracy is indicated by smaller circular means ($\bar{\theta}$) and mean resultant length (R) values nearing 1.

The right-most circular plot in Figure 2.7 shows participants' tracking for the unpredictable (FM) condition, with the red line indicating direction and magnitude of the mean resultant vector. The shorter length of the mean resultant vector for the FM condition represented higher dispersion of the participants' phase difference data (vectors) around the circle. Corresponding with the statistical results, these plots show lower tracking accuracy and substantial inter-subject variability for the unpredictable (FM) condition, when compared to performance at predictable frequencies. For the predictable frequencies, as target frequency increased, more dispersion in the participant data points was noted, indicating lower accuracy.

Table 2.1. Descriptive statistics for circular mean (direction) ($\bar{\theta}$), mean resultant length (R), and circular standard deviation (s) for frequency and direction based on phase difference data.

Frequency/Direction	$\bar{\boldsymbol{\theta}}$ (degrees)	$\boldsymbol{R}$	$\boldsymbol{s}$
0.4 Hz	1.56	.86	.52
0.6 Hz	13.11	.74	.72
0.8 Hz	37.28	.56	.94
FM	-38.06	.21	1.26
Lateral (**x**)	6.58	.59	.90
Vertical (**y**)	16.16	.54	.96
Horizontal (**z**)	8.91	.55	.95

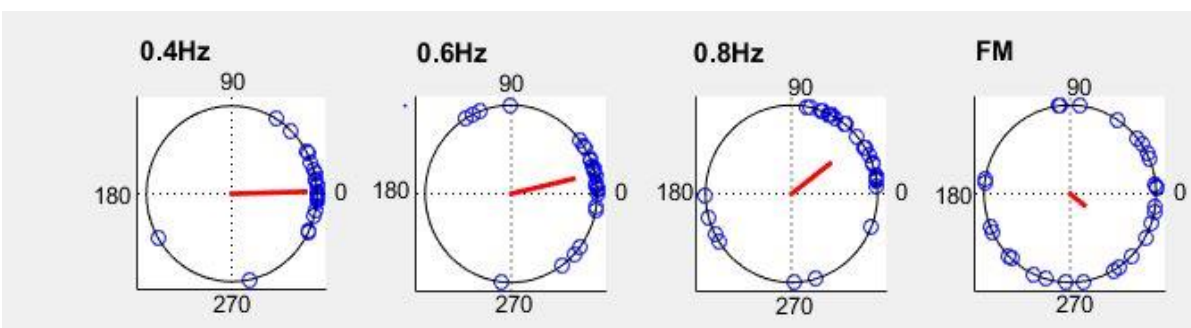

Figure 2.7. Circular plots of phase differences (degrees) for the frequency conditions (Plots each contain 30 data points, which represent participants' (N= 10) phase difference data for the three directions at each frequency. Red lines indicate the direction and magnitude of the mean resultant vector).

2.2.4 Post-Testing Questionnaire Data

A post-experiment questionnaire (Appendix B) provided qualitative assessment of the participants' perception of ease and difficulty of the chosen predictable frequencies (0.4, 0.6, 0.8 Hz) and the three directions (vertical, lateral, and horizontal), as well as any additional feedback regarding their experience with the lingual tracking paradigm. Results showed that 9/10 participants found tracking at 0.8 Hz to be the most difficult, whereas one participant indicated that the slowest frequency, 0.4 Hz, was the most difficult to track. Eight participants stated that tracking at 0.4 Hz was the most comfortable and two found tracking at 0.6 Hz to be easier.

With respect to different tracking directions, seven of the participants found the lateral (**x**) tracking direction to be the most comfortable to track. Two participants found the vertical (**y**), and one found the horizontal (z) directions to be easiest to track. Difficulty tracking in the vertical direction was stated by eight of the participants, with the other two participants finding tracking to be more difficult in the horizontal direction.

Additional feedback provided by one participant (F1) was for the experimenter "to guide the tongue always [with tongue depressor]." Another participant (F3) indicated that the sensor "wires would get caught on lips." Two of the participants commented on the nature of the visual display when the target moved in the horizontal (**z**) direction, where one (M3) suggested that "looking from the top-down [view] would be easier," and the other (M4) recommended having the target "move slightly diagonally" rather than in straight lines.

2.2.5 Individual Participant Patterns

Analysis by Sex

Temporo-spatial (and acoustic) properties of speech production have been noted to differ due to vocal tract size differences of men and women (Pépiot, 2012; Simpson, 2009). To assess if possible sex-specific effects were a contributing factor to the significant difference found between tracking in the lateral (**x**) and vertical (**y**) directions, mean amplitude ratio values for all frequencies in the two directions were calculated for each participant. Table 2.2 lists these values. The results indicate no significant difference between female (*M* = .83, *SD* = .20) or male (*M* = .84, *SD* = .27) participants, suggesting that participants' sex was not a confound.

Table 2.2. Mean amplitude ratio values in the vertical and lateral directions by sex.

Participant/Mean/SD F = female M = male	**Mean Amplitude Ratio Vertical (y)**	**Mean Amplitude Ratio Lateral (x)**
F1	0.66	1.07
F2	0.75	1.22
F3	0.81	0.85
F4	0.51	1.01
F5	0.79	0.86
F6	0.61	0.84
Mean	0.68	0.97
SD	0.12	0.15
M1	1.12	1.35
M2	0.71	0.89
M3	0.70	0.74
M4	0.59	0.61
Mean	0.78	0.90
SD	0.23	0.33

Overshoot and Undershoot of Target

Visual examination of participants' tracking plots showed that low amplitude ratio values were associated with the tongue tip signal overshooting and/or undershooting the target signal's movement. Participant M1 and M4 exhibited the lowest amplitude ratio values when compared to other participants. Visual inspection of their tracking plots revealed participant M1 largely overshooting target movement at peaks and/or troughs in most tracking trials, particularly in the lateral (**x**) direction (Figure 2.8). This pattern of tracking lead to high amplitude ratio values. Review of session notes revealed that prior to tracking in the horizontal (**z**) direction, participant M1 had indicated that the target trajectory range of 9.95mm was "too short," therefore, the target's range of movement was increased to 15.09mm for this direction. Comparison of the participant's amplitude ratio values for the horizontal (**z**) direction with the vertical (**y**) and lateral (**x**) directions showed that the increased target range in the horizontal (**z**) direction lead to slightly higher accuracy values. For example, the amplitude ratio value for tracking at 0.4 Hz in the horizontal direction was .92, whereas for the vertical and lateral directions, it was 1.03 and 1.51, respectively. Thus, low accuracy values for this participant, and possibly others (e.g., F2), could have been caused by the target's trajectory span.

Tracking performance for participant F4 showed the opposite pattern, in that a limited range of movement was observed, specifically in the vertical (**y**) direction (Figure 2.9). This participant tracked at the top half of the target's sinusoid, indicating that the tongue tip was not lowered enough to reach the full downward motion of the oscillating target (i.e., trough of the target signal). This tracking pattern was observed for both predictable frequencies and the FM condition (Figure 2.9), and was associated with low amplitude ratio values, such as .53. Visual examination of the overlapping plot data showed a limited range of movement in the vertical direction for a few other participants (e.g., F1, M4) in some of the trials. For some participants (e.g., F1,F2, M4) tracking at the highest frequency (0.8 Hz) also resulted in reduced range of movement in this direction.

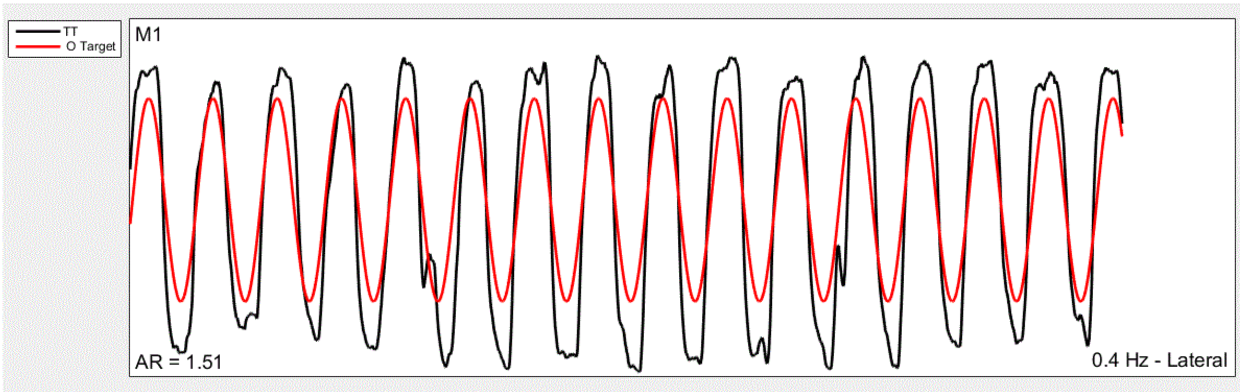

Figure 2.8. Overshoot of target exhibited by participant M1 at 0.4 Hz in the lateral direction.

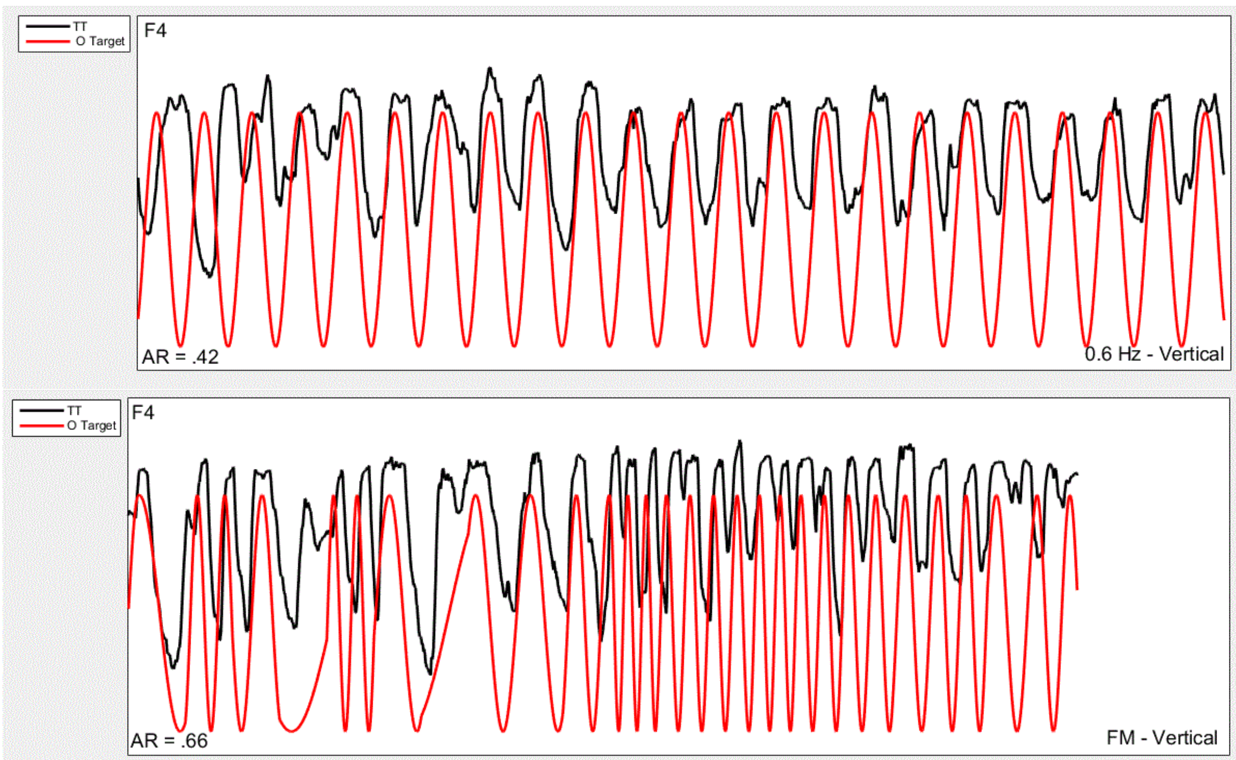

Figure 2.9. Undershoot of target exhibited by participant F4 at 0.6 Hz (top) and in the FM condition (bottom) in the vertical direction.

2.2.6 Summary of Results

In conclusion, findings from correlation coefficient and phase difference data showed that tracking accuracy was higher for predictable frequencies than for the unpredictable (FM) condition. In contrast, the amplitude ratio data showed higher accuracy for the unpredictable tracking condition than for predictable frequencies. Tracking accuracy was shown to decrease with an increase in target frequency. Correlation coefficient, amplitude ratio, and phase difference data all showed that accuracy was significantly higher at 0.4 Hz than at 0.8 Hz. Accuracy was also higher at 0.6 Hz when compared to 0.8 Hz, as confirmed by correlation coefficient data. No significant difference was found between 0.4 Hz and 0.6 Hz.

With respect to directionality, the amplitude ratio data showed tracking accuracy to be significantly higher in the lateral (**x**) direction than the vertical (**y**) direction. No significant difference for direction was found for the correlation coefficient or phase difference data.

CHAPTER 3

EXPERIMENT 2: EFFECTS OF JAW STABILIZATION ON TRACKING

This chapter describes an experiment examining whether tracking for the tongue alone resembles that of the tongue and jaw moving in synchrony (as described in Experiment 1). Using similar experimental parameters as Experiment 1, a second group of adult participants tracked a moving (virtual) target while holding a bite block in their mouth in to remove the effect of jaw motion. Correlation coefficients, amplitude ratios, and phase differences were computed to measure participants' tracking accuracy.

3.1 Methodology

3.1.1 Participants

Ten healthy adults, different from those used in the first experiment, participated in Experiment 2. Participants were young adults, 7 females and 3 males, ranging from 18 to 28 years of age (M = 21.0, SD = 2.87). Like Experiment 1, participants were recruited through the University of Texas at Dallas (UTD) online recruiting (Sona) system and reported no prior history of speech, language, or hearing difficulties, neurological disorders, or uncorrected vision disorders. Written informed consent following guidelines by the UTD Institutional Review Board were received from each participant. All participants who attended the session received class credit.

3.1.2 Experiment Apparatus

Experiment 2 used the same experimental instrumentation and setup as Experiment 1. In addition, this experiment included a jaw-stabilized tracking condition that required the use of a bite block in some of the trials. Bite blocks are small obstructions placed between upper and lower teeth, creating a gap and an effective challenge for articulation. Bite blocks stabilize the jaw, which allows for independent measurement of tongue kinematic performance (Netsell, 1985). The bite blocks used in this experiment were made of a dental compound (vinyl polysiloxane), which upon hardening, gains a hard rubber consistency, like a hard rubber eraser. Each bite block cube was a size of 25 mm cube, large enough to effectively remove jaw participation in tracking. Because dentition and patterns of occlusion vary across individuals (Baum, Kim, & Katz, 1997), for one of the participants who had crowding of teeth, the bite block was reduced in size by trimming off excess material of approximately 5 mm using a Hobby knife. No other modifications were made for the participants. The bite blocks were placed between the right first molars of participants and instructions were given to hold the bite block in place while tracking the moving target (Figure 3.1).

Figure 3.1. Diagram of bite block being held between right back molars.

A string made of dental floss and approximately 18 inches long was sewn through the bite block and tied on one end with a knot. A safety pin was secured to the other side of the floss string and attached to the upper right side of the participant's clothing to decrease the risk of accidental swallowing during tracking, and to aid in removal of the bite block.

3.1.3 Stimuli

As in Experiment 1, the oscillating target was set to move at three predictable (0.4, 0.6, 0.8 Hz) frequencies and at an unpredictable frequency modulated (FM) rate that varied between 0.1- 0.9 Hz, in 0.1 Hz steps. Since it was not feasible to probe all three directions in both jaw-free (i.e., no bite block) and jaw-stabilized (i.e., bite block) conditions, all tracking was conducted in the vertical (**y**) direction with the target moving vertically over a span of 9.95 mm. As noted previously, vertical movement is frequently reported in studies of tongue motion (Wang et al, 2013) and has been the direction studied in previous tracking studies (e.g., Moon et al., 1993; Robin et al., 2008). As in Experiment 1, a midsagittal view was chosen for the tongue model.

Presentation order of tracking conditions was randomized between and within participants, such that each participant received randomized jaw-free and jaw-stabilized trials for all predictable frequencies and the unpredictable (FM) condition. To increase data reliability, each participant produced two repetitions of each predictable and FM frequency. A total of sixteen 60-second trials were produced by each participant: [(3 predictable frequencies x 2) + (1 FM frequency x 2)] x 2 bite block conditions.

3.1.4 Procedure

Prior to the start of the experiment, all participants were given the Dworkin-Culatta Oral Mechanism Examination and Treatment assessment (Dworkin & Culatta, 1996). Although healthy talkers are not ordinarily expected to exhibit any speech motor disorders, this assessment was added to the second experiment as a screening measure in the event that underlying speech disturbances and/or oral anatomic and physiologic abnormalities would affect tracking accuracy.

In addition, results from Experiment 1 indicated that two of the ten participants showed markedly lower tracking performance than others, suggesting a need to examine possible oral mechanism problems, going forward. Results revealed that all participants were within normal limits, apart from participant F4, whose initial score suggested mild abnormality for the *Motor Speech Programming Abilities* section of the assessment. For this participant, a more comprehensive "deep" test was administered, and results indicated that the participant was within normal limits. Therefore, she was encouraged to continue to participate in the study.

Upon completion of the oral mechanism exam, participants were asked to complete the same pre-experiment questionnaire as Experiment 1 (Appendix A) to gather background information and rule out any possible confounds, such hearing or vision deficits, or a history of communication disorders.

The same experimental setup, tracking instructions, and visual feedback received in Experiment 1 were used in Experiment 2. To familiarize participants with the tracking task and apparatus, brief practice trials (30-sec) were received prior to data collection. Between each tracking condition, participants were given short breaks if needed. Each experimental session lasted approximately 75 minutes, including initial experimental set up.

After completion of the experiment, participants completed a short post-experiment questionnaire (Appendix B) regarding their perception of tracking at the different predictable and unpredictable frequencies, and the jaw-free and jaw-stabilized conditions. This was used as a qualitative measure of tracking difficulty for each condition.

3.1.5 Data Analyses

Each of the sixteen 60-second trials were resampled at 50 Hz and lowpass filtered at 25 Hz to reduce aliasing and eliminate any high-frequency noise. The first and last 10 seconds of each 60-second trial were truncated to eliminate startup and fatigue effects. Correlation coefficients, amplitude ratios, and phase differences were calculated for the predictable frequencies (0.4, 0.6, 0.8 Hz) and the unpredictable (FM) condition in the jaw-free and jaw-stabilized tracking conditions using the same analysis methods as in Experiment 1.

3.1.6 Statistical Analyses

The dependent variables of correlation coefficients and amplitude ratios were separately analyzed in two factor (Frequency x Jaw condition) repeated measures analyses of variance (ANOVA). As in Experiment 1, planned comparisons were conducted for predictable frequencies compared to the unpredictable (FM) condition, the different predictable frequencies (0.4, 0.6, 0.8 Hz), and the two jaw conditions (jaw-free, jaw-stabilized) at $p < 0.05$.

For the phase difference data, Watson-Williams tests using CircStat toolbox for MATLAB (Berens, 2021) were conducted to assess the predictable frequencies compared to the unpredictable (FM) condition, the three levels of predictable frequencies, and the two levels of the jaw condition.

3.2 Results

3.2.1 Correlation Coefficients

Pearson correlation coefficients for the 40-second tracked portions and their target signals were calculated. Figure 3.2 displays tracking accuracy based on mean correlation coefficient values for predictable frequencies and the unpredictable (FM) condition. ANOVA results revealed a significant main effect for Frequency [$F(3,155) = 7.68$, $p < .001$] and no significant Jaw condition main effect or interaction.

Planned comparisons showed a significant difference between predictable frequencies and the unpredictable (FM) condition [$F(1,155) = 11.26$, $p < .001$], where comparison of means revealed higher accuracy for predictable frequencies ($M = .66$, $SD = .28$) than the unpredictable (FM) condition ($M = .51$, $SD = .18$).

Comparisons of the levels of predictable frequencies revealed a significant difference between 0.4 Hz and 0.8 Hz [$F(1,156) = 10.39$, $p < .05$] and 0.6 Hz and 0.8 Hz [$F(1,155) = 11.07$, $p < .05$]. Accuracy for tracking at 0.4 Hz ($M = .74$, $SD = .22$) and 0.6 Hz ($M = .69$, $SD = .28$) were higher than for 0.8 Hz ($M = .55$, $SD = .29$).

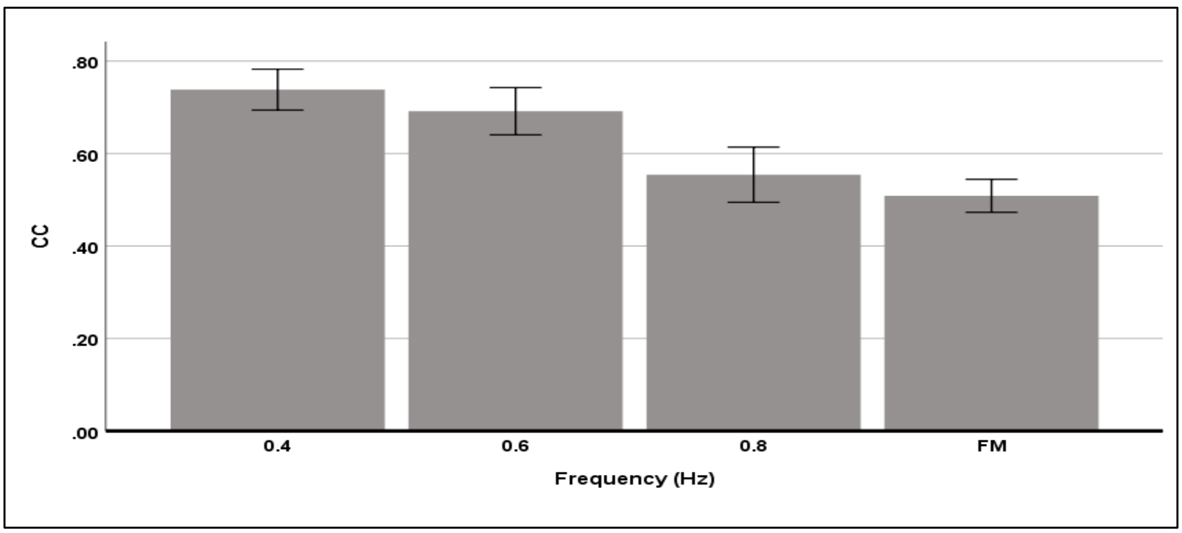

Figure 3.2. Mean tracking accuracy based on correlation coefficient values for predictable frequencies and the unpredictable (FM) condition (Error bars = standard error. N = 10).

3.2.2 Amplitude Ratios

ANOVA results indicated a marginal effect for Frequency [$F(3,155) = 2.53$, $p = .05$] and a significant effect for Jaw condition [$F(1,155) = 8.68$, $p < .05$]. No Frequency x Jaw condition interaction was found. Planned comparison results yielded a marginal significance for the difference between predictable frequencies and the unpredictable (FM) condition [$F(1,155) =$

8.88, *p* = .05], with accuracy higher for the unpredictable condition (*M* = .79, *SD* = .19) than the predictable frequencies (*M* = .71, *SD* = .25). No significant difference was found between the different levels of the predictable frequencies.

Comparison of means for the two jaw conditions revealed higher accuracy for the jaw-free condition (*M* = .78, *SD* = .24) than the jaw-stabilized condition (*M* = .67, *SD* = .23).

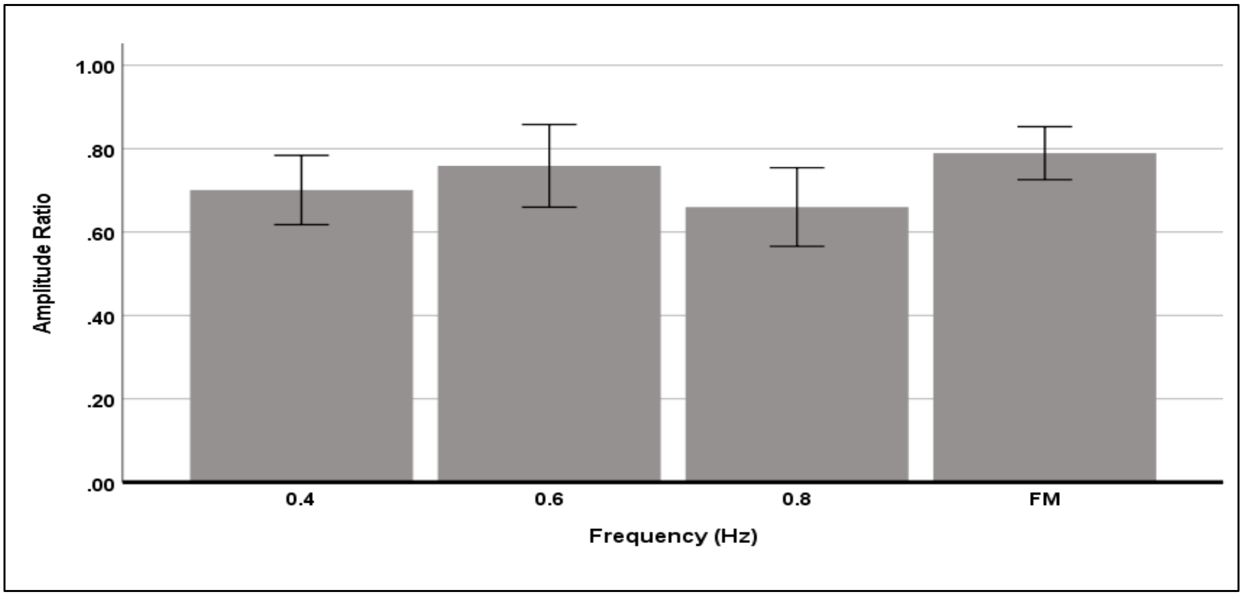

Figure 3.3. Mean tracking accuracy based on amplitude ratio values for predictable frequencies and the unpredictable (FM) condition (Error bars = standard error. N = 10).

3.2.3 Phase Differences

Table 3.1 shows the phase difference descriptive statistics for predictable frequencies and the unpredictable (FM) condition, for both jaw conditions. Figure 3.4 displays the circular plots of phase differences data for the jaw-stabilized condition.

Results from Watson-Williams tests showed a significant effect for Frequency [*F*(3,156) =10.52, *p* < .001] and no significant effect for the Jaw condition. Results also showed a significant effect for the difference between predictable frequencies and the unpredictable (FM) condition [*F*(1,158) =9.93, *p* < .001], where tracking accuracy was higher (i.e., showing a smaller phase difference) for the unpredictable (FM) condition ($\bar{\theta}$ = 23.61, s = 1.37) than the predictable frequencies ($\bar{\theta}$ = 122.24, s = 1.36). Comparison of the predictable frequencies showed a significant difference between 0.6 Hz and 0.8 Hz [$F(1,78) = 8.65$, $p < .05$]. Examination of means revealed tracking accuracy was higher at 0.6 Hz ($\bar{\theta}$ = 94.94, s = 1.21) than at 0.8 Hz ($\bar{\theta}$ = -146.34, s = 1.36).

Table 3.1. Descriptive statistics for circular mean (direction) ($\bar{\theta}$), mean resultant length (R), and circular standard deviation (s) for frequency and jaw condition based on phase differences data (JF = Jaw-Free; JS = Jaw-Stabilized).

Frequency/Jaw Condition	$\bar{\theta}$ (degrees)	***R***	***s***
0.4 Hz_JF	-1.52	.78	.66
0.6 Hz_JF	19.48	.89	.47
0.8 Hz_JF	27.80	.67	.81
FM_JF	-21.14	.12	1.33
0.4 Hz_JS	-1.34	.82	.61
0.6 Hz_JS	15.76	.91	.43
0.8 Hz_JS	27.80	.67	.81
FM_JS	16.11	.12	1.25

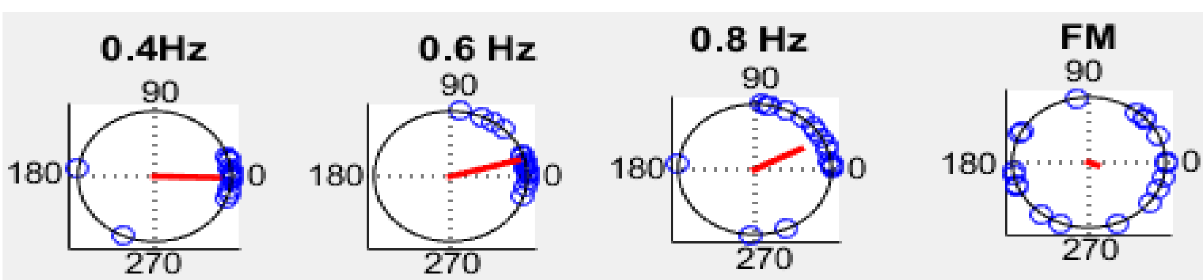

Figure 3.4. Circular plots of phase differences (degrees) for frequency conditions in the *jaw-stabilized* condition (Plots contain 20 data points, which represent participants' (N = 10) phase difference data for two trials at each frequency. Red lines indicate the direction and magnitude of the mean resultant vector).

3.2.4 Post-Testing Questionnaire Data

Like Experiment 1, a post-experiment questionnaire (Appendix B) assessed participants' perception of ease and difficulty of the predictable frequencies and the two jaw conditions (bite block versus no bite block). Feedback regarding participant level of attention and general experience with the lingual VMT paradigm was received. Results showed that 7/10 participants perceived 0.8 Hz as the most difficult frequency to track, while three stated 0.4 Hz was more difficult to track. Five, three, and two participants felt tracking to be most comfortable at 0.4 Hz, 0.8 Hz, and 0.6 Hz, respectively.

For the jaw-stabilized (i.e., bite block) and jaw-free (i.e., no bite block) conditions, seven participants indicated that tracking with a bite block was most difficult, while three found that with the jaw stabilized, tracking was more comfortable. Additional feedback included three participants suggesting a reduction in the number of trials.

3.2.5 Individual Participant Patterns

Analysis by Sex

Like Experiment 1, amplitude ratio values for males and females were examined to determine if the significant finding for the jaw-free versus jaw-stabilized distinction found in this measure was driven by sex-specific effects. Table 3.2 lists mean amplitude ratio values for individual participants by jaw condition. The results resembled Experiment 1, in that no significant difference was found between female (M = .70, SD = .18) or female (M = .79, SD = .13) participants in the jaw-free condition. In the jaw-stabilized condition, males had a slightly higher average, although the study only had three male participants.

Table 3.2. Mean amplitude ratio values in the jaw-free (JF) and jaw-stabilized (JS) conditions by sex.

Participant/Mean/SD	**Mean Amplitude Ratio Jaw-Free**	**Mean Amplitude Ratio Jaw-Stabilized**
F1	0.99	0.80
F2	0.71	0.67
F3	0.82	0.47
F4	0.38	0.40
F5	0.73	0.68
F6	0.91	0.73
F7	0.89	0.64
Mean	0.78	0.63
SD	0.20	0.14
M1	0.64	0.64
M2	0.79	0.78
M3	0.95	0.93
Mean	0.79	0.78
SD	0.15	0.14

Target Undershoot

The lowest overall accuracy in both jaw conditions was exhibited by participant F4 (jaw-free *M* = .20, *SD* = .11; jaw-stabilized *M* = .20, *SD* = .17). This participant exhibited large timing difficulties (manifested in phasing) and appeared to track in the middle to top portions (peaks) of the target sinusoid signal at 0.4 Hz. For some trials, this participant revealed a limited range of tongue movement, restricted mainly to the top half (i.e., peaks) of most predictable target signals and the middle region of the FM target signal in both jaw conditions.

3.2.6 Summary of Results

The main results can be summarized as follows: Overall, the findings resembled that of the tongue and jaw moving in synchrony (i.e., Experiment 1). Correlation coefficient data supported that tracking accuracy was significantly higher for the predictable frequencies when compared to the unpredictable condition, as noted in Experiment 1. There was no main effect of jaw condition. Amplitude ratio was the only dependent variable to support a significant difference between the two jaw conditions, with tracking accuracy being significantly higher in the jaw-free condition. The phase data also suggested no main effect of jaw condition, although these data also showed an unexpected pattern of accuracy significantly higher for the unpredictable frequency condition than the predictable frequencies.

CHAPTER 4

GENERAL DISCUSSION

This research is concerned with speech motor control and, in the long term, whether indices of its planning can be obtained to understand apraxia of speech (AOS), a motor speech disorder thought to result from a breakdown in the planning and/or programming of speech articulators (Deger & Ziegler, 2002; Duffy, 2013; Maas, Mailend, Guenther, 2015; Maas et al., 2008; McNeil, Robin & Schmidt, 2008; Van der Merwe, 2008). The present study is intended to provide information on tongue motor control in healthy populations, to serve as a basis for eventual comparison against participants with AOS.

Speech motor control can be described using predictive feedforward/feedback systems based on general theories of motor control (Wolpert & Miall, 1996). Movement commands from an internal model are issued via the feedforward mechanism and a prediction about the desired movement outcomes are made. Feedback regarding the state of realized movements are used to monitor errors and update the internal model. Although the relation between speech motor and limb motor control processes remains controversial (Grimme et al., 2011), this basic architecture derived from models designed to account for more manual motor processes may be useful for understanding speech motor movements.

Visuomotor oral tracking of a moving target (VMT) has been useful in studying model predictive/feedback control systems. By varying the predictability of the moving target, researchers have been able to gain information about an internal model and test reliance on visual feedback. Evidence has suggested that an internal model guides movement of limbs and articulators (e.g., lips and jaw), and feedback processing serves as an error-detection mechanism (Robin et al., 2008; Wolpert et al., 1998).

Little is known about the tracking capabilities of the tongue, and it is not known if the motor control mechanisms (i.e., feedforward/feedback) suggested for the lips, jaw, and the limbs also apply to tongue motor control. Tongue movement control is generally assumed to parallel other body parts, and the tongue has even been shown to influence lower limb muscle strength and posture (Bordoni et al., 2018). However, the organ is structurally unique (i.e., a muscular hydrostat) which may contribute to a difference in underlying control mechanisms.

Determining whether tongue movement control resembles findings from the lip and jaw is important because a series of studies based on VMT has suggested that individuals with apraxia of speech have an underlying impairment of feedforward processing that accounts for their speech production deficits (Ballard et al., 2001; Ballard & Robin, 2007; Hageman et al., 1994; Moon et al., 1993). Findings from lip and jaw VMT indicate that individuals with AOS exhibit consistently poorer performance than their healthy counterparts in the tracking of predictable target signals (Ballard et al., 2001, Ballard & Robin, 2007; Hageman et al., 1994; Moon et al., 1993), suggesting a deficit in forming an internal model, from which movement can be guided. It is not known, however, if these predictions extend to the tongue. If it is determined that tongue motor control parallels that of previously studied articulators, then the "feedforward deficit" hypothesis can be further explored using lingual VMT.

To examine tongue motor control in healthy adults in the present study, two experiments were conducted using lingual VMT tasks. A first experiment examined tracking accuracy at predictable and unpredictable frequency modulated (FM) frequencies to examine whether two properties of speech motor control noted for limb motor (as well as the lips and jaw) apply to tongue movement: feedforward/feedback processes in visual target tracking and a speed-accuracy tradeoff.

Predictable frequencies were used to test internal model information. Participants were predicted to exhibit higher tracking accuracy when following predictable (sinusoidal) target patterns, suggesting the formation of an internal model for target movement. Tracking of randomized, unpredictable patterns, in contrast, were assumed to prevent the creation of an internal model, leading to reduced tracking accuracy and the use of visual feedback information for online error correction.

Three predictable frequencies (0.4, 0.6, 0.8 Hz) were used to confirm whether a widely accepted principle of motor control, the speed-accuracy tradeoff (i.e., Fitts' Law) applies to tongue motor control. This principle predicts that as speed of a task increases, the accuracy of performance declines. Findings from lip and jaw studies suggest that this principle applies to the motor control for these articulators (Ballard & Robin, 2007; Moon et al., 1998; Robin et al., 2008). Recently, evidence of this principle has also been shown for the tongue in a metronome-driven speech elicitation paradigm, where participants produced repetitive /ta/ and /ka/ sequences in rates ranging from extremely slow to extremely fast (Kuberski and Gafos, 2019). These data address whether the tongue is also guided by the same principles of motor control as the other articulators (and limb).

This first experiment also examined what tongue movement in different directions might reveal about motor control strategies. Because most speech behavior is in the midsagittal plane (Perkell et al., 1992), tracking in the vertical (**y**) and horizontal (**z**) directions were expected to differ from tracking results than the lateral (**x**) direction, which is generally not speech-like. Findings provide baseline work for future VMT studies addressing the topic of whether tongue motor control may differ as a function of speech versus non-speech like movement. While some investigators suggest a continuum between speech and volitional nonspeech tasks (e.g., Ballard et al, 2003), others propose that speech is controlled by an entirely separate motor control system than nonspeech motor actions, such as chewing (e.g., Ziegler, 2003). Future VMT studies testing tracking of targets in more speech-like target patterns, such as curved motions (Mooshammer, Hoole, & Kühnert, 1995) could provide further information on this issue.

In a second experiment, bite blocks were used to isolate tongue motor control in to assess whether patterns of movement observed for the tongue and jaw moving in synergy (Experiment 1) extend to the case of the tongue moving in isolation. Compensatory behavior was predicted to occur when the jaw was stabilized, leading to tongue tracking accuracy similar in both jaw-free and jaw-stabilized conditions. Thus, even without the benefits of jaw contribution, tongue motor control was expected to comply with predictions regarding model predictive feedforward/feedback processing and a speed-accuracy tradeoff.

Experiment 1: Predictable versus Unpredictable Frequencies

Correlation coefficient and phase difference data from Experiment 1 supported the prediction that accuracy for predictable frequencies would be higher than for the unpredictable (FM) condition. Except for a few participants, most produced relatively accurate tracking (mean correlation coefficient = .66) and kept in-phase (range 1.56 to 37.28 deg) with the target's movement when the frequencies were predictable.

Phase shifts, where participants anticipated the phase of the moving target (i.e., phase-lead), were also observed for all participants (100%) when tracking predictable frequencies. Phase leads are used in both speech and nonspeech VMT studies to support the notion that when the target frequency is predictable, and internal model of the motion can be created. In other words, the pattern is learned and allows a participant to even advance slightly ahead of the expected movement (e.g., Ballard & Robin, 2007, Craik, 1947; Flowers, 1978; Hageman et al.,1994). This has been observed even when visual feedback has been removed during tracking tasks (Ballard and Robin, 2007; Beppu et al., 1987; Clark & Robin, 1998). Phase leads are suggested to occur when internally stored information of the target movement is being used to provide predictive feedforward commands instead of following the target signal through visual feedback (Flowers, 1978).

Examination of tracking patterns for the unpredictable (FM) condition in both experiments revealed all participants having spatially irregular movements and exhibiting phase lags during transitions of the target signal from one frequency component to the next. Furthermore, larger phase difference values indicated a greater discrepancy between the tongue tip and target signals, reflecting that accuracy was in fact lower. Thus, whereas participants used internal models to provide smooth tracking patterns in the predictable conditions, for the unpredictable conditions, online visual feedback information was used to continually adjust for errors, as participants lagged from the target signal, caught up, and at times, moved ahead of the target in phase (i.e., phase lead). The findings confirm that tongue motor control is like that of the lips and jaw in that healthy adults develop an internal model for the target movement when viewing predictable frequency signals, providing better tracking accuracy. In addition, visual feedback information is used to guide movement when an internal model cannot be formed and serves as an error detection mechanism.

In contrast to the correlation coefficient and phase data, the amplitude ratio data from Experiment 1 showed higher accuracy for the unpredictable tracking condition than for predictable frequencies. A possible explanation for these discrepant amplitude ratio findings is that participants may have had adopted tracking strategies involving a reduction of tongue movement. At the maximum target frequency (0.8 Hz), nine of the participants restricted their tongue movements to a smaller range of movement, leading to lower amplitude accuracy (Mean amplitude ratio = .70). Six of the participants also showed this behavior at 0.6 Hz. However, at the lower frequency (0.4 Hz) all participants exhibited a larger range of movement, specifically in the lateral direction, raising their performance accuracy (Mean amplitude ratio = .86). In the post-experiment questionnaire, 90% of the participants indicated that tracking at 0.8 Hz was the most difficult. Thus, the reduced range of movements (i.e., undershooting target movement) may have been an attempt at reducing the complexity of the task for tracking at higher frequencies, given that larger movements place a greater demand on the motor system. Similar behavior has been reported in jaw and manual tracking studies (Ballard & Robin, 2007, Flowers, 1978).

In summary, the weight of the predictable/unpredictable frequency processing evidence from Experiment 1 suggest tongue motor control resembles that of the lip, jaw, and limbs, where a predictive internal model is used to guide movement, and feedback mechanisms are used to check for accuracy of movements and update the internal model.

Experiment 1: Speed-Accuracy Tradeoff

Experiment 1 results supported the prediction that tracking accuracy would decline with an increase in target frequency. Accuracy at 0.4 Hz was significantly higher than at 0.8 Hz. This finding was observed in all three dependent variables (correlation coefficients, amplitude ratios, and phase differences). Tracking accuracy was also higher at 0.6 Hz when compared to 0.8 Hz (confirmed by correlation coefficient data). However, no significant difference was found between the two lower frequencies (0.4 Hz and 0.6 Hz), as had been predicted. The speed-accuracy tradeoff was observed in lingual movement when frequencies were distinctly "slow" and "fast." Thus, overall, the present findings suggest that speed-accuracy tradeoff exists for continuous tongue movement, confirming that tongue motor control properties share similarities with other articulators and non-speech systems.

Experiment 1: Movement Directions

The amplitude ratio data showed an effect for directionality, with accuracy being significantly higher in the lateral (**x**) direction than the vertical (**y**) direction. No directional differences were found for the correlation coefficient or phase difference data. Eighty percent of participants indicated in the post-experiment questionnaire that tracking in the vertical direction was most difficult. We speculate that tracking a vertically oscillating target with the tongue might prove relatively challenging, due to the tongue's hydrostatic properties. In support of this notion of a tracking strategy, eight participants were noted to reduce their range of movement for the vertical direction, perhaps as a tracking strategy.

Mean amplitude ratio values for the lateral and vertical directions were examined to determine if the findings were driven by sex-specific effects. Anatomically, the vocal tract length of adult females differs from that of adult males. The adult female vocal tract has a length of approximately 14.5 cm and the male vocal tract averages from 17 to 18 cm in length (Simpson, 2009). These vocal tract size differences have been noted to cause acoustic and temporo-spatial differences in the speech production of men and women (Pépiot, 2012; Simpson, 2009). A hypothesis for lower accuracy and reduced range of motion in the vertical direction, therefore, was that a female's smaller vocal tract, housing a smaller tongue, may constraint the shape the tongue can adopt when moving (tracking) in the vertical direction. Although no significant difference was found between mean values for male and female amplitude ratios (male M = .78, SD = .23; female M = .68, SD = .12) in the vertical direction, it is plausible that individual differences in anatomy (e.g., size of tongue and oral cavity) may have contributed to the present findings, given that a fixed movement was used for tracking.

Participant M1 (of Experiment 1) indicated that the target's range of movement was too small for tracking in the horizontal (**z**) direction. In comparison to the amplitude ratio values for the vertical and the horizontal directions, the values in the horizontal direction for this participant were higher, possibly because the target range was increased. Thus, it is possible that the chosen target range of 9.95mm may have been too limiting in the vertical direction for some participants based on varying tongue sizes.

Another possible explanation for the relatively high accuracy for lateral movement could be that this direction ordinarily entails less proprioceptive feedback (in the form of tongue contact) in comparison to vertical and horizontal movement. During speech, the sense of tongue position may depend on tongue shape changes brought on by pressure against an oral structure, such as the hard palate or teeth (Adatia & Gehring, 1971, Wilson & Gick, 2006). When performing controlled tongue movements for tracking in the vertical and horizontal directions, the tongue does not make direct contact with a structure. Thus, no tactile feedback is received to guide movement. For example, some participants (e.g., F1, F4) were observed to retract or retroflex the tongue instead of elevating it during vertical tracking, perhaps uncertain of what direction their tongue was moving. During lateral tracking task, however, the tongue was observed to touch the corners of the mouth, providing participants with tactile feedback in addition to visual feedback, and potentially leading to higher accuracy of tracking.

In summary, in Experiment 1, data from correlation coefficient and timing aspects (phase), provided support for significantly higher accuracy in the predictable condition than the unpredictable, suggesting the creation of an internal model guiding movement. This finding was not confirmed by spatial measurements (amplitude ratio), which may have been due to motor control strategies or study design effects. A speed-accuracy tradeoff was noted across all three measures (correlation coefficient, amplitude ratio, phase difference), with a significant difference seen between the slowest (0.4 Hz) and fastest (0.8 Hz) frequencies. Correlation coefficient data also showed a significant difference between 0.6 Hz and 0.8 Hz. Findings from directional tracking differences suggested that movement in speech-like directions (vertical) is different from non-speech-like directions (lateral). Taken together, these findings reinforce that tongue motor control resembles that of the lips and jaw, and the findings serve as a basis for future tracking work involving tongue VMT methods.

Experiment 2: Predictable versus Unpredictable Frequencies and Speed-Accuracy Tradeoff

When tongue movement was isolated, results resembled that of the tongue and jaw moving in synchrony (i.e., Experiment 1). Correlation coefficient data supported that tracking accuracy was significantly higher for the predictable frequencies when compared to the unpredictable condition, and significantly higher at 0.4 Hz and 0.6 Hz when compared to 0.8 Hz. Phase difference data also revealed a significant effect for frequency, where tracking accuracy was higher at 0.6 when compared to 0.8 Hz. These findings further confirm that like the lip and jaw, an internal model guides movement of the tongue, and that accuracy of movement is reduced with an increase in speed.

Amplitude ratio data showed a marginal effect of frequency. However, close examination of the data showed that higher accuracy was exhibited for the unpredictable tracking condition than for predictable frequencies. A significant difference between the two conditions was also found for the phase difference data. Because both amplitude ratio and phase difference data showed these findings for Experiment 2, a factor that likely contributed to the unexpectedly high accuracy for the unpredictable target condition is the nature of the FM (randomly generated) unpredictable signal. The frequencies used to build this condition may have been comprised of slower speeds during the one-minute of tracking, which paradoxically could have led to higher accuracy. Specifically, the target signal ranged from 0.1 through 0.9 Hz, in 0.1 Hz steps, modelled after some of the lip and jaw VMT research (Ballard & Robin, 2007; Moon et al., 1993; Robin et al., 2008). As this signal was randomly generated, it is possible that some participants received a back-to-back series of lower frequencies, leading to higher accuracy. For example, during the 60-sec tracking sweep, the signal generator may have provided a participant a series of sequential 0.4 Hz signals, causing accuracy levels for the unpredictable condition to be higher than when the participant is continually tracking at 0.8 Hz. A suggestion for future experiments is to design the unpredictable signal to include equal segments of slow, medium, and fast frequencies in the randomly generated combinations.

Experiment 2: Jaw Condition

Amplitude ratio data revealed a significant effect for jaw condition, with accuracy being higher in the jaw-free condition (M = .78) than the jaw-stabilized condition (M = .67). Data for correlation coefficients and phase differences showed no significant effect for jaw-condition. Participant F4, who exhibited the lowest amplitude ratio values across all frequencies (M = .39), stated in the post-experiment questionnaire that stabilizing the jaw aided in achieving higher tracking accuracy by preventing the tongue "from moving everywhere." However, the data did not confirm higher accuracy for the jaw-stabilized condition (correlation coefficient, amplitude ratio, phase difference). For this participant, a more comprehensive deep probe test was administered when results from the *Motor Speech Programming Abilities* section of the initial oral mechanism exam indicated a mild abnormality. Although the results of the deep probe test indicated that the participant was within normal limits, there may have been underlying motor control issues playing a role in the low accuracy values for this participant.

Some research using biomechanical tongue models (Hashimoto & Suga, 1986; Sanguineti, Laboissiere, & Payan, 1997) suggest that the jaw plays a role in tongue movement. It is possible that when the tongue is isolated from the jaw, spatial movement aspects of the tongue (amplitude) are particularly affected, in that the jaw ordinally acts as support for tongue movement. While compensatory feedback mechanisms may have been able to keep timing aspects intact, as reflected in the measure of phase differences, the spatial extent of movement was more likely to be affected when the synergy of tongue/jaw coupling was interrupted.

Additionally, results from Experiment 1 indicated that participants exhibited difficulty tracking in the vertical direction. Thus, the removal of the support from the jaw, paired with the difficulty of the task (i.e., tracking in the vertical direction) could have contributed to the significant jaw condition finding for the amplitude ratio analyses.

In summary, results from correlation coefficient and (partially) phase difference data confirmed that basic motor control principles noted for the tongue and jaw moving in synchrony were also found for movement of the tongue alone. The spatial aspects of movement, however, may require contribution from the jaw.

4.1 Study Limitations

There are several potential limitations in the current study. One issue is the size of the target tracked by the participants. During the experiments, participants were instructed to maintain their tongue tip cursor on the 12mm moving sphere (target) to produce accurate tracking, as indicated by a change in color of the target (i.e., purple to green). However, it was not necessary for participants to keep their tongue tip cursor exactly in the middle of the target to achieve immediate feedback. The Opti-Speech program calculates the length of a vector from the target to the tongue tip marker. If this length is less than the radius of the target, the target color will convert to green. Placing the tongue tip marker at the edge of the target would result in similar feedback as placing it in the center of the target. Thus, target size could have influenced accuracy outcomes, as the received feedback may not have necessarily been an indication of exact cursor and target matching. A smaller target size should be tested in future studies.

Lack of control for divided attention and anxiety is another possible limitation, potentially affecting accuracy outcomes. Prior to the start of the experiments, participants completed a pre-experiment questionnaire screening for these variables. However, during the 60-second tracking task, participants could nevertheless experience a decrease in attentional resources. In fact, three of the participants in Experiment 2 suggested on their post-experiment questionnaire to reduce the number of trials, as the repetitive nature of tracking caused their minds to wander. Similarly, mood states, such as anxiety could potentially alter motor control (Bolmont, 2005). For example, if the unpredictable nature of the FM signal causes anxiety in a participant, accuracy would undoubtedly be affected. One way to reduce the effects of these factors is to offer longer breaks between the tracking sweeps to relieve the possible effects of reduced attention and anxiety. Alternatively, it might be possible to gamify the procedure to relieve anxiety for those participants who might be affected.

Another possible limitation of the present study is the nature of the movement transduction apparatus (NDI Wave System). Although the wires attached to the sensors are designed not to impede tracking, it is possible that they may have interfered with movement, especially for tracking in the lateral direction. In the post-experiment questionnaire, one participant reported that the wires would get caught on the lips, which might also have caused some interference with movement. Current research on creating wireless systems (Sebkhi, 2020) could eliminate the need for probes attached to wires in future speech VMT research.

4.2 Future Directions

Despite the study's limitations, results from the present study contribute to our current knowledge of oral motor control by confirming that the tongue shares motor control properties like those of previously studied speech articulator systems. These findings suggest that despite its unique biomechanical structure, the tongue is controlled by shared motor control mechanisms.

This information is valuable because established motor control principles of learning for the limbs can be applied to the study and treatment of speech motor speech disorders, including tongue movement. Clearly, more research is needed to understand how these principles generalize to speech. However, the present results provide groundwork that suggests because the tongue shares motor control properties with non-speech effectors, learning principles such as variable practice may also be beneficial in rehabilitation of speech motor disorders (Maas et al., 2008), including during visual feedback paradigms.

The present findings can also be extended to studies of the feedforward deficit theory in individuals with AOS. Previous speech VMT research has proposed that individuals with AOS are unable to form an internal model when compared to healthy individuals. With no internal model in place, online feedback information received from the visual input must be used to continuously monitor the changing movement pattern. With the present study results confirming the lip and jaw findings for healthy adults, the data could serve as a basis of comparison for future studies testing hypotheses about speech motor control breakdown in AOS populations. As an initial study, tongue tracking of predictable and unpredictable frequencies can be tested in talkers with AOS.

Moreover, the present findings may also contribute to the development of improved intervention tools for enhancing quality of life of patients with ambulatory disabilities. Specifically, with the present understanding of tongue kinematics, improved tracking parameters for the tongue VMT task can be established. This information could be useful for researchers interested in pursuing technology development in the area. For instance, the recently developed tongue-operated Tongue Drive System (TDS) is an assistive technology that identifies tongue motion with a magnetic field around the mouth (Johnson et al., 2012). The device provides real - time tongue motion tracking and offers people with severe disabilities that prevent them from using their hands (i.e., spinal cord injury) an alternative motor modality for controlling their wheelchairs, computers, and smartphones using voluntary tongue motion (Kim et al., 2016). Differences in tracking directions found in the present study may be important in the development of such technology. Future VMT studies that extend the current findings by examining different tracking patterns (e.g., curvilinear, speech-like) may also be instructive.

In summary, the present findings offer novel information regarding tongue motor control that is potentially useful for our understanding of speech motor disorders and their treatment. It is hoped this initial research will spur additional study of tongue kinematics, speech tracking paradigms, and visual feedback.

APPENDIX A

EXPERIMENTS 1 AND 2 PRE-EXPERIMENT QUESTIONNAIRE

1) Have you had a history of speech and/or language therapy? If yes, please list what type(s) of therapy and when received.

2) Do you or have you had any trouble hearing? If yes, please list what type and if you received treatment.

3) Do you or have you had any trouble with your vision? If yes, please list what type and if have you received treatment.

4) Do you wear glasses?

5) Do you experience eye strain or eye fatigue when staring at a computer screen for long periods of time?

6) Do you have any back pain or other issue that would prevent you from being seated during this study (approximately 1 ½ hours)?

7) Do you have trouble concentrating? If yes, please explain.

8) Do you, or have you had any significant cognitive, emotional, psychological, or behavioral diagnoses that would prevent you from participating in this study? If yes, please explain.

9) Do you have, or have you been diagnosed with any disorder affecting your muscle or motor control? If yes, please explain.

10) Are you feeling tired or sleepy at the moment?

11) Have you had any prior experience with augmented visual feedback systems/studies (i.e., EMA)?

APPENDIX B

EXPERIMENTS 1 AND 2 POST-EXPERIMENT QUESTIONNAIRE

Experiment1

1) Of the three speeds you tracked (0.4 Hz, slowest; 0.6 Hz, medium; and 0.8 Hz, fastest), which was most comfortable? Which was most difficult? Your comments would be appreciated!

2) Of the three directions you tracked the target (up and down, left to right, back to front), which was most comfortable? Which was most difficult?

3) What part(s) of the experiment would you keep the same? What part(s) would you change?

4) Please provide any additional feedback you have below:

Experiment 2

1) Of the three speeds you tracked (0.4 Hz, slowest; 0.6 Hz, medium; and 0.8 Hz, fastest), which was most comfortable? Which was most difficult? Your comments would be appreciated!

2) Which of the two conditions (bite block versus no bite block) was most comfortable? Which was most difficult? Why?

3) What part(s) of the experiment would you keep the same? What part(s) would you change?

4) Please provide any additional feedback you have below:

APPENDIX C

EXPERIMENTAL SETUP FIGURE

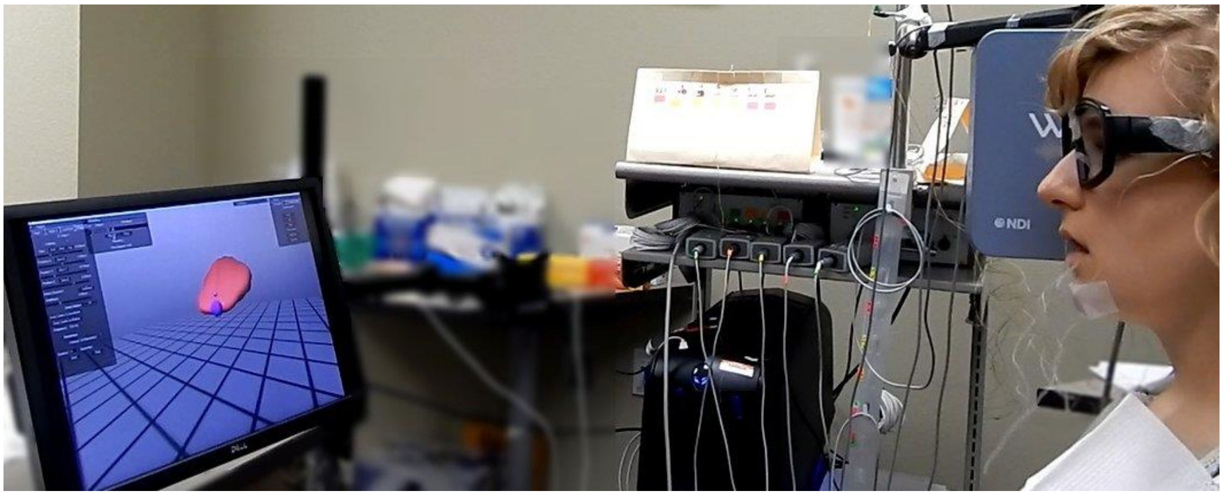

Figure C.1. Participant viewing tongue avatar, tongue tip marker, and oscillating target on computer monitor during tracking task.

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BIOGRAPHICAL SKETCH

Vedad Fazel received a Bachelor of Arts in Linguistics, with a minor in Language Studies (Spanish) from The University of California, San Diego. She continued to complete a Master of Arts degree in Linguistics at California State University, Fullerton, where she conducted research on cross-linguistic differences in spatial language. Her passion for understanding how “language works” initiated a desire to explore what processes occur during speech breakdown, ultimately, leading Vedad to pursue a PhD in Communication Sciences and Disorders at The University of Texas at Dallas. During her doctoral training, she worked as a research assistant in the Speech Production Lab under the direction of Dr. William F. Katz, conducting research on speech motor control using electromagnetic articulography (EMA) and visual feedback systems. En route to completion of her doctoral degree, Vedad received a second master’s degree in Communication Disorders from The University of Texas at Dallas, where as part of her training on becoming a speech-language pathologist, she gained clinical experience in different settings, such as inpatient and outpatient hospital, skilled nursing facility, schools, and accent reduction programs. Vedad is fond of teaching students and holds a Graduate Teaching Certificate from the Center for Teaching and Learning at The University of Texas at Dallas. In her spare time, she enjoys word puzzles and beginning cello lessons.

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M.A. 2007, Linguistics (emphasis in Spanish) - California State University Fullerton
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PUBLICATIONS

Fazel, V., & Katz, W. F. (2016). Visuomotor pursuit tracking accuracy for intraoral tongue movement. *The Journal of the Acoustical Society of America*, 140(4), 3224-3224.

MacKay, D. G., Johnson, L. W**.**, **Fazel, V**., & James, L. E. (2013). Compensating for language deficits in amnesia I: H.M.'s spared retrieval categories. *Brain Sciences, 3*(1), 262—293.

ORAL AND POSTER PRESENTATIONS

Fazel, **V**. (2019) Visuomotor pursuit tracking (VMT) accuracy for intramural tongue movement. Oral presentation at *Friday Seminars in Speech*, *Language and Hearing* (FLASH) Brownbag Series. Dallas, TX.

Doli, E., **Fazel**, **V.**, Mehta, S., Mock, T., Berglund, A., & Katz, W. F. (2019). Implicit learning of morphology by patients with aphasia. *Promotion of Academic and Clinical Excellence* (P.A.C.E.). Dallas, TX.

Fazel, **V.**, & Katz, W. F. **(**2018). Intraoral tongue tracking capability of healthy adults using a visuomotor pursuit tracking task. Penn State - University Park, PA: *Progress in Clinical Motor Control I: Neurorehabilitation* conference.

Fazel, **V.** (2015) Pursuit - tracking studies: Investigation the functional basis of apraxia of speech. Oral presentation at *Friday Seminars in Speech*, *Language and Hearing* (FLASH) Brownbag Series. Dallas, TX.

Katz, W. F., & **Fazel, V.** (2014) Visual augmented feedback training for dysarthria. *Promotion of Academic and Clinical Excellence* (P.A.C.E.). Dallas, TX.

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- 2013-2020: Speech Production Laboratory, The University of Texas at Dallas
- 2010- 2011: Language Emotion and Memory Lab, The University of California, Los Angeles

TEACHING EXPERIENCE

Graduate Teaching Assistant

2013- 2020, The University of Texas at Dallas, School of Behavioral and Brain Sciences

TEACHING EXPERIENCE (continued)

- Methods in Communication Disorders: Preschool Intervention Methods
- Professional Issues in Speech Language Pathology
- Communication Disorders
- Social Communication in Early Childhood Disorders
- Phonetics
- Communication Sciences
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Lab Instructor

2013- 2017, The University of Texas at Dallas, School of Behavioral and Brain Sciences

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2010- 2013, AFI College, Los Angeles, CA

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CLINICAL EXPERIENCE

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- Presbyterian Village North (Skilled Nursing Facility); Dallas, TX
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AWARDS & SCHOLARSHIPS

2016: Student Travel Award, University of Texas at Dallas

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