A MULTI-DIMENSIONAL INTERACTION BETWEEN SPEECH AND GRASPING

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Dedication

To my Grandma, my favourite heroine.

Abstract

Previous research demonstrated an interaction between speech processes and manual actions. The wide variety of methods and theories used to investigate the interaction highlighted inconsistencies, and raised many questions. The purpose of this thesis was to further our understanding of the interaction of speech and grasping by using ecologically relevant methodology. Two experiments were designed to answer two hypotheses: 1) If speech processing produces a greater effect on ecologically relevant hand actions (e.g. grasp-to-eat); and 2) If performing natural actions should result in greater changes in speech production. Both experiments revealed two similar results which contradicted my hypotheses. The right-handed grasp-to-eat actions did not alter speech production, and were unchanged by speech processing. Additionally, left hand actions interacted with speech production/processing. These findings suggest that the grasp-to-eat (hand-to-mouth) action is highly robust, and that left-handed actions can interact with speech processes.

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Chapter 1: Introduction to Prehension and Speech

1.1 Overview

During a typical day, we execute innumerable combinations of skilled motor actions without any apparent consequences to performance. Examples include walking to a meeting and conversing on the phone, debating with a friend while cutting up vegetables, or talking to a colleague while shuffling through paper work. Despite the regularity in which we appear to flawlessly execute these simultaneous movements, research has demonstrated that there is a cost associated with performing two actions at once. An example is prehension and speech actions. Many studies have endeavoured to quantify the precise impact of executing these two types of motor skills simultaneously by combining a wide variety of methods and measures. The results are confusing at best. Such a range of results makes it difficult to develop theories that can account for the various observed interactions, and the result is an imprecise understanding of the interaction between prehension and speech.

A possible solution for unravelling the complex relationship between prehension and speech is choosing a highly salient, prehensile action, and examining it in different speech contexts (i.e. production or processing). Defining a "salient" prehension action may appear to be a difficult task which is further complicated by disagreement on how we execute prehension actions. However, an argument exists that there is one action which stands out from the others; hand-to-mouth (or grasp-to-eat as it will commonly be referred to in this thesis). In addition to being necessary for survival, a manual movement for grasp-to-eat actions has been related to playing a role in the development of right hand dominance in humans (Flindall & Gonzalez, 2013, 2016), and demonstrating consistent kinematic differences between the dominant- and non-dominant hand (Flindall & Gonzalez, 2013, 2014, 2016; Naish, Reader, Houston-Price, Bremner, & Holmes, 2013). Taken together, these factors contribute to an argument that the grasp-to-eat action is highly ecologically salient, and may hold evolutionary significance. When combined with speech, the action offers the opportunity to examine *both* motor acts in a novel context: ecologically valid actions relevant to evolution. The intent of this thesis is to create a careful examination of the interaction between speech and hand movement using a relevant, natural hand-to-mouth action. The following introduction will present background information on measuring the production of manual actions and speech, research focusing on the hand-to-mouth movement, and the potential role of cerebral lateralization in this interaction. This information serves to complement the conducted research on the interaction, as well as create a better understanding of the relationship between speech and hand movement.

1.2 Manual Kinematics

To appreciate the complex relationship between prehension and speech, it is important to begin with a clear definition of what constitutes a prehension action. For the purposes of this thesis, the terms prehension and "grasping action" will be used interchangeably. A basic prehension action is composed of a reaching stage and a grasping stage. Our ability to precisely measure hand kinematics during both stages drastically increased in the advent of video recording. Jeannerod (1984) first used film to document a simple prehensile action, and made the novel observation that as the hand moves towards the target (reaching/transportation stage), the distance between the thumb and index finger expands only to a certain point until it begins to narrow and successfully 'pinch' the target (grasping/manipulation stage). When participants have a clear view of the target and are asked to execute a simple reach and grasp action, the maximum grip aperture (MGA; the greatest distance between the thumb and index finger during the outward movement of the hand) is relative to the size of the grasped target. Countless studies (including those by Jeannerod) have examined the kinematics of prehension (including MGA) in multiple contexts— grasp to place, manipulate, throw, eat, etc. These studies have revealed the importance of specific context when describing and measuring these motor movements. For example, Marteniuk, MacKenzie, Jeannerod, Athenes, and Dugas (1987) examined differences in reaching movement according to the intended action towards the object. Deceleration time (changes in the length of deceleration phase of reaching) changed if participants grasped a disk to place it versus to throw it. Approximately thirty years later, many other subtle distinctions have been noted between the kinematics of actions that only differ in their ultimate intent (Ansuini, Cavallo, Bertone, & Becchio, 2014). Ansuini et al. (2014) discussed the finding that MGA (a measure of the grasping component) is significantly smaller when grasping an item to place compared to passing the item to another person. A grasping-to-eat (hand-to-mouth) action compared to a grasping-to-place action also results in a smaller MGA. Interestingly, this difference in MGA is only present in right-handed actions (Flindall & Gonzalez, 2013, 2014, 2016). When participants execute a grasp-to-place action by placing a food item in a container near their mouth, the left- and right-hands demonstrate identical accuracy and speed throughout the task (Flindall & Gonzalez, 2013). However, when participants grasp the same food item and place it in their mouth, MGA is consistently smaller in the right-hand compared to the left-hand grasp-to-eat execution and the grasp-to-place condition in both hands. The authors proposed the decreased grip aperture is an effort to conserve energy, creating a right-hand advantage for a skill that evolutionarily speaking, was and is imperative to our survival. Further, they speculated that because the effect only appears in the right hand, the action could be a component which assisted in the development of right-hand dominance observed in humans (Flindall & Gonzalez, 2013, 2016). The suggestion was strengthened when follow-up studies demonstrated the robustness of the grasp-to-mouth effect. Additional manipulations demonstrated that placing the food in the mouth without ingesting it (Flindall & Gonzalez, 2014), or placing a non-edible item in the mouth (Flindall & Gonzalez, 2016) also resulted in a smaller MGA, but only in the right hand. These studies expanded the understanding of the effect from only occurring in very specific grasp-to-ingest situations, to occurring in more general circumstances involving any hand-to-mouth movement, where there is intent to place the item in the mouth. The smaller MGA during hand-to-mouth actions stands out because it is *not* a result of compensatory strategies. Some of these strategies include wider MGA to accommodate uncertainty in target shape/position when the target is not visible, taking longer to grasp an item placed further away, or decreasing reaching speed to ensure accuracy in manipulating the target (Ansuini et al., 2014; Bootsma, Marteniuk, MacKenzie, & Zaal, 1994; Jakobson & Goodale, 1991a; Kudoh, Hattori, Numata, & Maruyama, 1997; Paulignan, Frak, Toni, & Jeannerod, 1997). These contrasts highlight the uniqueness of the hand-to-mouth action.

Selecting the hand-to-mouth action serves several purposes in this thesis. The kinematic persistence of unilaterally smaller MGAs provides a framework from which deviations due to speech manipulation can be measured. For example, if the difference between the grasp-to-eat and grasp-to-place action no longer exists during a concurrent speech task, speech arguably affects manual kinematics. Another important characteristic of the hand-to-mouth action is its left-hemisphere lateralization. If both speech and the hand-to-mouth action are controlled by the same hemisphere, any observed changes in grasping kinematics should be more obvious in right-hand kinematics. Finally, because the tongue is involved in both speech and eating movements, using a hand-to-mouth movement may yield a unique interaction between prehension and speech tasks.

1.3. Effects of Speech on Manual Kinematics

Prehension and speech each play a substantial role in our daily lives, often simultaneously, whether chatting and picking up an apple, or listening to a coworker while grasping and eating lunch items. The natural pairing of manual action and speech has been closely examined in many experimental contexts, resulting in the generalization that speech processing and production alter the execution of prehension. A range of different speech tasks (both processing and production) have been used to exact changes on manual motor kinematics and activation during the reaching and grasping phases. I will start by examining one example where speech significantly altered a grasping action.

Reaction time is a measure of how quickly the reaching phase is initiated. There are several studies investigating changes in reaction time when completing a grasping action according to the speech syllable produced. Researchers found the shaping of the hand in a narrow position for a precision grasp (thumb and index finger) occurred more quickly when producing a vowel sound in which the lips mirrored the narrowed shape of the hands (Tiainen, Tiippana, Vainio, Komeilipoor, & Vainio, 2016a). Similarly, a power grasp (all digits and palm of hand) is performed more quickly when producing a syllable which requires the mouth to open to wider (Tiainen et al., 2016a). Recently, Vainio et al. (2017) replicated these findings using participants who spoke a different language from those in the initial studies (Czech compared to Finnish). Each of these studies focused on the effect of simple speech-syllable production on manual movement. However, when investigating the effects of speech production, meaningful speech cannot be overlooked because words carry numerous associations. For example, the word “cup” could elicit a power grasp if picked up by the larger end, or a precision grasp if picked up by the handle. Also associated with “cup” is the ability to drink, to wash, as well as sensory properties that could influence grasping such as temperature and texture. Similarly, “ball” refers to a spherical object, often used for play or sport. However, upon processing this word, it holds meaning for each individual beyond a sphere. Along with a sphere, you could picture a specific type of ball: too large to grasp with a single hand, whizzing quickly towards you, or rolling slowly away. These implicit associations could affect our kinematics, and how we interact with different objects (Chrysikou, Casasanto, & Thompson-Schill, 2017; Grèzes, Tucker, Armony, Ellis, & Passingham, 2003). Simple syllables cannot hold such associations. When pronouncing meaningful words, research indicates that participants are not objectively combining syllables to pronounce an extended sound, but are simultaneously processing the semantic associations. The various descriptors help highlight the importance of considering not just the definition of a word, but all its associations.

In a study by Glover, Rosenbaum, Graham, and Dixon (2004), participants pronounced different noun-words while reaching and picking up two different sized blocks. As discussed, MGA during a typical grasping action is scaled to reflect the size of the object. However, researchers noted that while pronouncing nouns, accurate scaling ceased, and instead, MGA reflected the relative size of the pronounced noun. When the produced noun signified a relatively larger item (i.e. apple), MGA was larger than expected. The opposite occurred while pronouncing smaller noun-signifiers (i.e. grape). Here, participants allowed associated properties of the word to influence motor execution. Additional studies have noted further effects of our implicit word associations changing MGA. One example is related to the finding that when we perceive lower-pitched sounds, we associate them with larger objects, and vice versa for higher pitched sounds (Rinaldi, Lega, Cattaneo, Girelli, & Bernardi, 2016; Walker & Smith, 1985). When grasping the same sized block and listening to a high-pitched sound, participants produced smaller MGAs compared to grasping the same block while listening to a low-pitched sound (Rinaldi et al., 2016). In this example, participants took an associated quality of a sound (smaller items and higher pitched noises), and allowed it to affect how they executed an action, resulting in changes to scaling. In both studies, the associated qualities of the word or the pitch, caused participants to subconsciously shape their hands to reflect associations with the spoken/processed item. There are several other examples of properties of words affecting grasping kinematics, including verb production changing peak velocity (Fargier, Menoret, Boulenger, Nazir, & Paulignan, 2012), and reading adjectives altering the length of movement phases (Gentilucci & Gangitano, 1998).

Results from functional Magnetic Resonance Imaging (fMRI) studies and neural electrostimulation studies provide insight into how the brain processes different word types (concrete versus abstract), and further, why we observe various kinematic differences according to word characteristics. In one study by Moseley and Pulvermuller (2014), participants listened to both concrete and abstract verbs and nouns (i.e. knit and flute versus heal and luck). Imaging results showed significant differences in activation between the concrete and abstract word classes. The motor and pre-motor areas demonstrated a strong activation during concrete verb production, while the areas activated during concrete noun processing were located slightly more anteriorly. The abstract word classes did not demonstrate activation in the motor and pre-motor areas, which suggests that concrete words may exert a greater effect on motor kinematics. Examples include words which are semantically associated with manipulatable objects (e.g. a flute), actions words (e.g. run) or certain adjectives (e.g. large). These findings have been replicated in several other studies (Pulvermüller, 2001; Pulvermüller, Härle, & Hummel, 2000). A neural distinction based on implicit associations and the properties related to words is in line with the discussed findings of behavioral studies, where simply pronouncing and processing words with concrete associations changed the planning and execution of actions (Fargier et al., 2012; Gentilucci & Gangitano, 1998; Glover et al., 2004). A TMS study provides another example of how implicit associations could affect manual actions. Participants produced both nouns and verbs associated with different actions (i.e. ball, axe, throw, kick) as well as nouns and verbs not associated with actions, or non-manipulatable items (i.e. hill, planet, regret, loathe). Results indicated that only verbs and nouns associated with an action increased the excitability of the motor cortex, measured through increased MEPs (motor evoked potentials) to the thumb (dorsal interosseous muscle) of the right hand (Oliveri et al., 2004). Once again, the qualities associated with the spoken words have the potential to change motor planning and execution.

The discussed studies have exclusively focused on one direction of the relationship- the effect of speech on motor kinematics. In order to better understand the relationship between prehension and speech, I will briefly review the kinematics of speech and then studies that have investigated the effect of prehension on speech kinematics.

1.4 Speech Acoustics (and Kinematics)

Prehension requires precise coordination of the five digits combined with carefully orchestrated arm movement. Comparatively, speech is executed through the combination of action between many components of the throat/mouth, known as articulators. These components include the soft, relatively flexible anatomy such as the tongue, lips and velum (back of the throat), combined with firm, less transitory components; the jaw and palate (Clark, Yallop, & Fletcher, 2007a; Hardcastle, Laver, & Gibbon, 2009). A complicating factor of studying speech is that almost all of its modifiers are located internally, and unlike prehension, we generally cannot film or use common motion-capture methods to measure changes in these articulators. A number of instrumental technologies can be used to overcome this challenge, including imaging (x-ray, ultrasound, fMRI, computed Tomography), motion capture (of lips, and jaw movement), and magnetic scanning (electromagnetic articulometer), which can provide a real-time picture of the location of the tongue relative to the position of the other articulators. Another option is measuring the contact patterns of the tongue with the roof of the mouth through electropalatography or pressure palatography. However, all of these methods can be costly, invasive, or require exposure to dangerous radiation. Invasive is perhaps the most important concern, as several of the technologies require participants' heads to remain stationary, or wear equipment in and/or around their mouth. These 'subtle' interferences could result in a decreased ability to produce speech, and alter production outside of the chosen experimental design. To avoid these complications, but still measure changes in speech production, another commonly used option is acoustic analysis. This analysis only requires a microphone and a simple computer program.

What we comprehend as speech is created by many modifications and rapid adjustments of the articulators and the vocal tract. To examine characteristics and changes of these articulators during production of speech, a mathematical technique known as Fourier's Analysis is applied. This analysis can be used to interpret a complex waveform produced during speech (Hardcastle et al., 2009). The waveform components are typically represented through a spectrogram, a specialized graph that maps audio wave frequency (Hertz on the y-axis) according to time (seconds on the x-axis). There is a third dimension represented in these graphs, indicated by the "darkness" of the graph sections, which correlates with the magnitude of acoustic energy, or amplitude (Clark et al., 2007a). For the purposes of this thesis, I will focus on how spectrograms relate to the measurement of vowel articulation through formants.

Formants are a measure of the resonance of the vocal tract (Clark et al., 2007a; Hardcastle et al., 2009). Changes in formants occur due to changes in resonance, or changes in the shape of the vocal tract. By applying a bandpass filter and Fourier's Analysis, formants can be identified during production of a vowel (Hardcastle et al., 2009). The first three formants are typically measured, with each formant providing information on the relative position of an articulator. Changes in frequency indicate a change of resonance, which often associated with movement of the tongue. There is some debate over the exact associations between formants and tongue position, however, there are some well supported generalizations associated with each of the three formants. The first formant (F1) is related to the height of the tongue in the mouth during vowel production. A vowel where the tongue is positioned near the floor of the mouth would have a larger first formant frequency value. An example is [æ], as in "apple", where the frequency is typically around 850 Hz.

Compared with a "high" vowel, [i], as in "bee", which has a typical F1 value around 300 Hz, the difference between these values represents the distance the tongue moves during pronunciation of each vowel (Clark et al., 2007a). The second formant (F2) is related to the "frontness" of the tongue during pronunciation, which means that if the tongue is located near the front of the mouth during vowel production, it has a larger F2 value. An example of a front vowel is [æ]. In American English, it typically has a value around 1780 Hz indicating the tongue is positioned closer to the front of the mouth, especially compared with a back vowel, such as [ɑ], as in "father," which has a frequency of 1070 Hz. The third formant (F3) is noted as changing in situations where there is significant lip protrusion, as well as rounding (the relative shaping of the lips in a circle) (Hardcastle et al., 2009). However, it does not have as specific association with the position of the tongue shared by the first two formants. Together, these characterizations of the vowels enable utilization of relatively simple technology to record and analyze speech production, and provide valuable information on the position of the articulators in the mouth, much like a motion capture system used for manual kinematics. It is important to note, that unlike a motion capture system, the measurement of formants through acoustic analysis does not provide the same degree of accuracy. However, its validation through other studies (Heald & Nusbaum, 2015; Hillenbrand, 2009; Kuo & Weismer, 2016) qualifies it as an appropriate measure in this thesis.

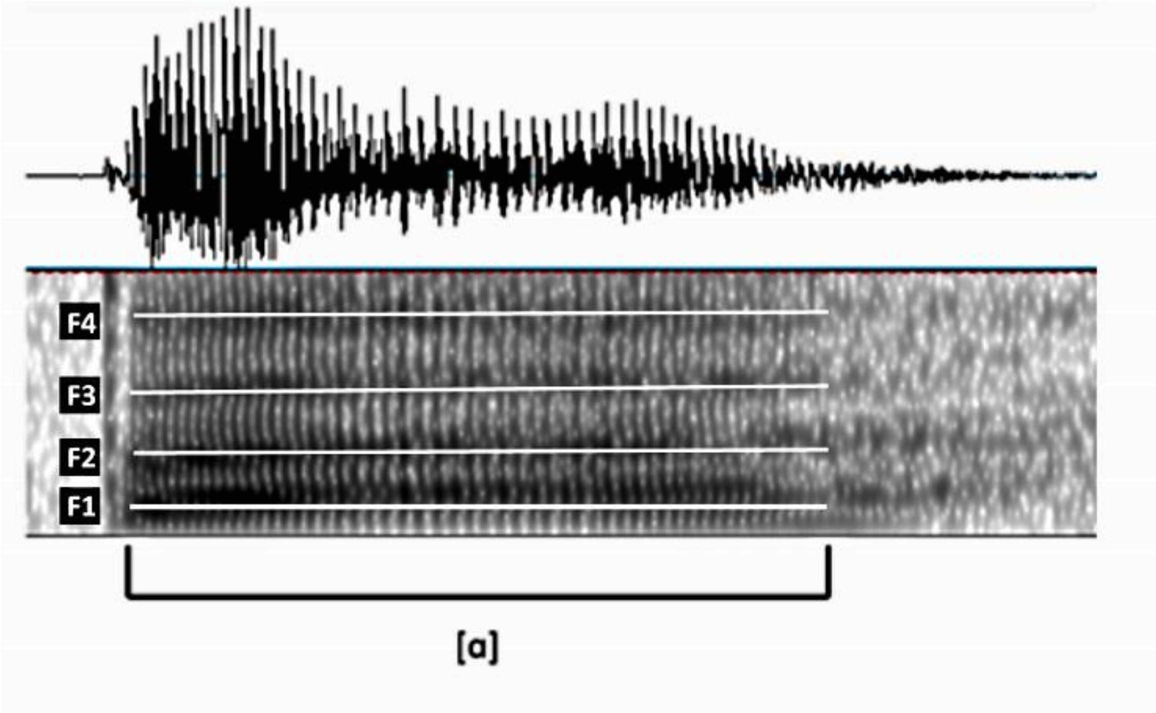

Figure 1. Spectrogram. This graph is a spectrogram, where a participant is pronouncing [bɑ]. Here, a filtered audio wave of speech is plotted as a function of time (x-axis) over frequency (y-axis) with the darkness/intensity of the graph indicating a third measure, amplitude. The four darkened horizontal bars highlighted by white lines each represent a formant. Changes in frequency and levels of each of the first three formants relate to changes in the shaping of the mouth, and enable us to distinguish one vowel from another. The fourth formant (F4) is pictured in this spectrogram, but is rarely used in acoustic analysis.

1.5 Prehension Effects on Oral Kinematics

As discussed, measuring changes in speech production is a more challenging task than measuring changes in manual action. In fact, the few studies that recorded both focused on the kinematics of the hand more than on the changes to speech. When speech is analyzed, changes in the first three formants are commonly used to assess it. A few studies have found significant changes in formants when speech was performed during the manipulation of different sized blocks in infants, children, and adults (Bernardis, Bello, Pettenati, Stefanini, & Gentilucci, 2008; Bernardis & Gentilucci, 2006; Gentilucci, Santunione, Roy, &

Stefanini, 2004a). Changes in aperture and kinematics of the lips are also noted during simultaneous manual action. When participants pronounced a syllable while executing a power or precision grasp, changes in the second and third formants indicated that different shaping of the hands altered the position of the tongue and lips. While reading aloud and organizing washers (Dromey & Benson, 2003; Dromey & Shim, 2008), or when pronouncing syllables and grasping objects of different sizes (Bernardis et al., 2008; Bernardis & Gentilucci, 2006; Gentilucci, 2003), the lips appeared less coordinated (increased variability in maximum lip aperture), opened wider (increased maximum lip aperture) and opened more slowly than expected (delay in reaction time). In each of these studies, it appears that simultaneous grasping changes speech performance. It is important to note, that much like prehension studies, kinematic characteristics showed significant changes, but the motor actions were still successfully executed. In other words, none of the studies report participants becoming incoherent during these manual action tasks, despite significant changes in lip motion and acoustic differences. Unlike with grasping kinematics, these changes to formants do not appear to change as a function of the object's associations (Bernardis et al., 2008; Bernardis & Gentilucci, 2006; Dromey & Benson, 2003; Gentilucci, 2002; Gentilucci, 2003; Gentilucci et al., 2004a; Gentilucci, Stefanini, Roy, & Santunione, 2004b). However, it is difficult to know if this is due to a lack of significant effect, or due to a lack of research designed to specifically investigate this interaction.

Here, it is important to note that I have neglected to discuss one study which did not find any significant effect of manual action on vocal spectra. Tiainen et al. (2016a) reported no significant changes in any of the three formants, or intensity of the produced syllables during execution of a power or a precision grasp. The only significant finding was in reaction time with a decrease in syllable pronunciation depending on the shaping of the hand. When the hand was executing a precision grasp, syllables that caused narrowing of the articulators were pronounced more quickly (as if the precision grasp facilitated pronunciation). The studies discussed used similar methods, but found outright contradictory results; in some cases grasping actions affect formants, while in the last example, no change was reported. The study with null results (Tiainen et al., 2016) required participants to enact only a partial prehension movement— just grasping. In the other studies, where formants changed, participants performed more natural, reach-to-grasp actions. The discrepancies could be due to differences in how natural and unnatural prehensile movements interact with speech. Therefore, in reference to the previous section on the impact of speech on grasping actions, I will investigate the role that natural, ecologically relevant grasping plays in the relationship between speech and grasping.

1.6 A note on hemispheric lateralization of prehension and speech

A topic that has been mentioned, but not fully addressed is cerebral lateralization. It is a long-accepted notion that both the functions of manual motor control and speech production are lateralized (Kolb & Whishaw, 2009). Control of right hand actions and speech are more specialized to the left hemisphere. The similar lateralization of these functions is hypothesized as a factor which contributes to the interaction between speech and grasping. In fact, imaging studies have shown activation in Broca’s area (which is typically associated with language production) and the parietal lobe (associated with sensory integration) during speech production, processing, and right handed manual movements (Grafton, Fagg, & Arbib, 1998). This is evidence that all three functions activate similar neural areas, and that there is definite lateralization in these functions.

Intriguingly, very little is known about the interaction between speech and left-handed actions. This is because the majority of previous studies focused almost exclusively on right-handed actions. A secondary goal of my thesis is to include left-handed manual actions, thus contributing a novel insight into the potential interaction of the left-hand with speech.

1.7 Tying it all Together

There is overwhelming evidence that speech and prehension interact, along with findings which contradict this statement. Such discrepancies may be due to the overwhelming variety in methodology used to investigate this interaction. Within the body of literature, one particular action has not been fully addressed in the context of speech interaction; hand-to-mouth. As previously hinted at, examining this movement in the context of speech offers a unique opportunity to explore the grasping-speech interactions in a new light. Unlike other kinematic actions such as grasp-to-place, the grasp-to-eat action requires coordination of the lips and tongue, which is also a necessity for speech. The common activation of the tongue required for both eating and speaking tasks warrants further investigation, as the resultant interaction has not yet been studied. Another notable characteristic exclusive to the hand-to-mouth action is that it has demonstrated right-hand lateralization. The potential common cerebral lateralization of speech and right-handed motor control presents another compelling reason to utilize the grasp-to-eat action. Finally, this action is a complete, natural movement. This is important because kinematic differentiation between ecologically valid and invalid actions may provide an explanation for several contradictory findings within recent studies. Natural, complete actions may demonstrate a more robust interaction with speech tasks. Therefore, contrasting the grasp-to-eat action (one of the most natural movements) with various other prehensile-like grasps while performing speech tasks should produce a quantifiable difference between grasp-to-eat and the other actions.

Through the experiments contained in this thesis, I investigate changes in manual movement during a very natural movement; grasp-to-eat. In a second study, I contrast natural actions (including grasp-to-eat) with several other movements to ascertain the influence these different movements may have on speech production. These two studies are not designed to build directly on one another, but rather examine the outcomes first on manual kinematics, and then speech production utilizing natural movements. I intend to further develop our understanding of the role natural movement plays in the interaction between speech and prehension.

Chapter 2: Theory, Hypotheses, and Predictions

2.1 Theory, Hypotheses, and Predictions

Theory:

The experiments in this thesis are developed using a theory that natural actions demonstrate a more robust interaction with language processes. Speech processes (listening to speech and producing speech) executed during natural, ecologically relevant grasping actions will produce distinct changes in both manual action and speech when compared with less relevant actions. The hypotheses and predictions are listed below.

Hypothesis 1:

Speech processing produces a greater effect on ecologically relevant hand actions (e.g. grasp-to-eat) than on actions less vital to our survival (grasp-to-place).

Prediction 1:

Speech processing will produce kinematic changes in a more ecologically valid grasp-to-eat task compared to a grasp-to-place task.

Hypothesis 2:

Performing natural, ecologically relevant actions should result in significant changes in speech production, particularly in comparison to less natural movements.

Prediction 2:

Complete prehension actions (such as grasp-to-eat and grasp-to-place) will change simultaneously produced vowels more so than components of grasping actions (such as reach alone or grasp alone).

Prediction 3:

A secondary prediction made regarding both hypotheses is that the common left hemisphere lateralization of speech and right-hand manual motor control will result in greater changes in the manipulated variable when speech is paired with the right-hand.

Chapter 3: Experiment 1: Hear speech, change your reach: Changes in left-hand grasp-to-eat action during speech processing

3.1 Introduction

The sophistication of both our speech and gestural repertoire is one of the features that inarguably distinguish humans from other mammals. However, there is a lack of understanding regarding how language developed into its current form. One theory is that manual actions like prehension played a vital role in the advancement of communication and speech development. The Gestural Theory of Language frames the development of communication in an evolutionary context, taking into account both manual and vocal movement (Waters & Fouts, 2002).

Versions of the Gestural Theory of Language have existed since the late 18th century (de Condillac, 1792). Details of the theory have changed over time, but the central concept remains that spoken language (i.e., a system of *verbal* gestures) is built upon a foundation of manual gestures; early hominids first developed manual gestures for communicative purposes, and gradually paired these movements with vocalizations (Corballis, 2003). Eventually speech sounds became synonymous with specific manual gestures, and vocalisations supplanted manual action as the primary method of communication. The result is a repertoire of standardized symbolic sounds (i.e., language) replacing a set of manual signals (de Condillac, 1792; Hewes, 1973, 1976; Rizzolatti & Arbib, 1998; Rizzolatti & Craighero, 2004; Waters & Fouts, 2002). This theory is important to consider when investigating interactions between speech and grasping, particularly as it underscores the depth and nature of the relationship, and emphasizes functional context (Hewes, 1973).

Evidence of a consistent interaction between speech and manual movements is observable in many studies. One example includes research using transcranial magnetic stimulation (TMS) to measure increases in hand motor-evoked potential (MEP) amplitudes when stimulation is paired with either speech production or speech perception (Floel, Ellger, Breitenstein, & Knecht, 2003). When compared to baseline MEPs, researchers found a significant increase in MEP amplitude (measured from the interosseous muscle of both left and right hands) when participants were asked to either read-aloud or quietly listen to fairy tales. The authors concluded that speech, even passively perceived speech, causes bilateral sub-threshold activation within hand-regions of primary motor cortex (M1), regardless of handedness or language lateralization.

This change in activation may be responsible for changes in prehension kinematics, as evidenced by numerous behavioural studies investigating manual tasks performed during speech production. While participants are speaking, they generally initiate their grasping movements more quickly (shorter reaction times) (Tiainen et al., 2016a; Vainio, Schulman, Tiippana, & Vainio, 2013; Vainio, Tiainen, Tiippana, Komeilipoor, & Vainio, 2015; Vainio, Tiainen, Tiippana, & Vainio, 2014), move faster (higher peak velocities) (Fargier et al., 2012), produce stronger grip-forces (Frak, Nazir, Goyette, Cohen, & Jeannerod, 2010), and change the peak distance between the thumb and index finger (maximum grip aperture) while reaching (Glover et al., 2004). For example, when speaking the name of a large concrete noun (i.e. apple), participants produced larger maximum grip apertures (MGAs) compared to participants pronouncing the name of a smaller noun (i.e. grape) while grasping objects of identical size. These examples describe how speech production may influence grasp-to-transport, grasp-to-lift, or simple grasp-to-hold movements. One specific type of action absent from the described body of literature is the grasp-to-eat movement.

The grasp-to-eat movement is a specific action which features regularly in our daily lives and plays a vital role in our survival. Nearly half of all primate prehension involves hand-to-mouth transport (Graziano, 2008), demonstrating that grasp-to-eat and other hand-to-mouth movements hold special significance not only with respect to our movement repertoire (Graziano, Aflalo, & Cooke, 2005), but with respect to their neural underpinnings (Bonini et al., 2012). Previous studies found a kinematic distinction between grasp-to-eat and grasp-to-place movements, lateralized to right-handed movements (Flindall & Gonzalez, 2013, 2016). Specifically, when grasping-to-eat, the right hand produces consistently smaller maximum grip apertures (MGAs) than when grasping-to-place, despite moving an identical target into a container near the mouth. The reduced grip aperture was framed as an artifact of the postural origins theory of human prehension, which structures right-hand dominance in terms of the tendency for primates to use the right hand for object manipulation and the left hand for stability when manipulating objects (Flindall & Gonzalez, 2013; MacNeilage, Studdert-Kennedy, & Lindblom, 1987).

To avoid the obvious interference of attempting simultaneous mouth movement (opening to accept, closing to chew, and subsequently swallowing a grasped object) while speaking, participants instead actively listened to speech while performing grasp-to-eat actions. According to several recent studies, speech processing activates neural areas in a similar manner to speech production (Agnew, McGettigan, Banks, & Scott, 2013; Cheung, Hamiton, Johnson, & Chang, 2016; Wilson, Saygin, Sereno, & Iacoboni, 2004). As they are, ultimately, distinct processes, there are differences in the strength and pattern of neural activation between *listening* and *producing* speech. Compared to production, speech processing creates more right-hemisphere processing. However, as there is still a significant increase in left hemisphere activity, speech processing can be considered, by some accounts, a left-lateralised function (Specht, 2014; Wilson et al., 2004). All told, the overall similar pattern of neural activation elicited during speech processing compared to speech production qualifies it as an appropriate tool to investigate a possible interaction between speech and the lateralized kinematic signature of grasp-to-eat actions.

The purpose of this study was to examine how speech processing influences performance of a manual action that has a well-documented lateralized kinematic signature – i.e., the grasp-to-eat movement. Participants completed blocks of grasp-to-eat and grasp-to-place actions directed toward small cereal items both while listening to excerpts from an audiobook and when sitting silently in a quiet environment. If there is an interaction based on functional lateralization, then we expect that any significant kinematic effects will be limited to right-hand movements; that is, we expect no speech-dependent effects in left-hand kinematics for either grasp-to-place or grasp-to-eat movements. During quiet trials (control), we expect to observe the same effect demonstrated by Flindall & Gonzalez (2013, 2014, 2016); namely, comparatively smaller MGAs for grasp-to-eat actions when participants use the right hand. As speech production can influence MGA to mimic the symbolic meaning of words (Glover et al., 2004) or the characteristics of the mouth (Vainio et al., 2013), we expect a main effect of speech condition on MGA. Specifically, we predict that MGA and variability of MGA (vMGA) for both grasp-to-eat and grasp-to-place tasks would be greater while listening to speech. This change may wash-out the between-task difference previously described. If the grasp-to-eat kinematic signature is affected by speech processing, we expect that right-handed movements in the speech condition will not differ between -eat and -place tasks.

3.2 Methods

Participants

Thirty-three right-handed young adults (22 females, mean age of 22.1 ± 2.13 years) volunteered to participate in the current study in exchange for course credit. Each completed a language questionnaire, confirming English as their first language and reporting any experience speaking or learning additional languages. Data collected from two bilingual participants were removed from analyses. Participants' hand dominance was determined through self-report, and confirmed via a modified Waterloo-Edinburgh handedness questionnaire (Brown, Roy, Rohr, & Bryden, 2006; Oldfield, 1971). All participants provided informed consent prior to starting the experiment, and were aware of the option to withdraw at any time. These procedures were approved by the University of Lethbridge Human Subject Research Committee (protocol #2016-002).

Materials

Materials and procedures were very similar to those used in previous studies by Flindall and Gonzalez (2013). A Certus Optotrak Camera (*Northern Digital, Waterloo, ON, Canada*) tracked the movement of three infra-red light emitting diodes (IREDs) attached to the hand of the participant. Specifically, we secured the markers with medical tape to the distal phalanges of the thumb and index finger, as well as the medial styloid process of the wrist. Placement of the diodes afforded a comfortable pincer/precision grasp for each participant, while simultaneously providing an unobstructed line of sight between the IREDs and the camera. IRED position information during each trial was collected at 100 Hz for four seconds.

After providing informed consent, participants sat in a stationary chair, an arms-length away from an independent standing pedestal. We adjusted the pedestal to approximately sternum height to enable comfortable grasping of targets without acting as an obstacle for the grasp (Whishaw et al., 2002). The platform of the pedestal was triangular (base 85 mm, height 80 mm), positioned with the base toward the participant. Participants wore a solid plastic bib with an open pocket. We adjusted the pocket to be as near the participant’s mouth as possible (approximately 170 mm below the participant’s mouth) without sacrificing mobility or comfort. Individuals wore Plato Liquid Crystal Goggles (*Translucent Technologies, Toronto, ON, Canada)* to obstruct their view of the pedestal between trials, concealing the precise size of the grasping target until the beginning of each trial. We used Cheerios™ (average diameter 11mm) and Froot Loops™ (average diameter 15 mm) as grasping targets. Experimental timing was coordinated through Superlab (*Cerdus Corporation, San Pedro, CA, USA*) and NDI First Principles (*Northern Digital, Waterloo, ON, Canada*). We used a single analog speaker (*Harmon Kardon Rev A00 Computer Speakers)* to play audio recordings from an Apple iPOD Nano (6th gen). The audio stimuli consisted of four 3-minute excerpts from an audiobook recording of “Percy Jackson and the Olympians: The Titan’s curse” (Riordan, 2007). The excerpts were selected from detail-rich scenes.

Procedure

Participants sat in front of the pedestal and familiarized themselves with the reaching environment before donning the bib and goggles. Before data collection began, we first explained the procedure and guided each participant through several practice trials. Grasp-to-eat trials required participants to grasp the cereal and eat it, while grasp-to-place trials required participants to pick up the cereal and place it in the bib hanging beneath their chin (Figure 2). We organized the blocks according to a 2 (Hand; left/right) x 2 (Task; eat/place) x 2 (Audio; quiet/listen) factorial design, resulting in eight blocks of sixteen trials each, for a total of 136 trials. Two auditory-stimuli conditions required participants to complete each task twice per hand used. Once, during a quiet condition wherein the participant completed all trials without any auditory input, and again during a listen condition wherein the participant (without speaking) listened to excerpts from the audiobook while otherwise completing the tasks as in the quiet condition. Participants completed all four blocks with their starting hand before IREDs were transferred to the opposite hand and all blocks were repeated in the same order. Seventy-five percent of target items were Cheerios™, with the remaining twenty-five percent Froot Loops™, presented in a pseudo-random order. We included different sized targets to ensure that participants were scaling their grip appropriately to the size of each target. If a participant failed to adjust their MGA to the two differently-sized targets, that participant’s data was dropped from analysis as they may not have been focussing on the task, however all participants correctly scaled their MGA to target size. Only the trials with Cheerios as the target item were included in statistical analyses. Hand-, task-, and audio-block start order were counter-balanced between participants.

At the beginning of each trial, the participants rested with their hand on their lap, index finger and thumb lightly resting together. Trials began with the transition of the goggles to a transparent state, enabling sight of the target item; participants then grasped the single cereal piece that had been placed on the pedestal (at “their own comfortable, natural pace”), and either ate it or placed the item in the bib depending on that block’s assigned task. The goggles remained transparent for 3000 ms, allowing participants ample time to complete the full action with vision and return to the rest position. After the goggles returned to an opaque state, the investigator replaced the cereal item on the stand, and triggered the next trial. During the listen condition, the participant was instructed to listen closely to the audiobook. The story segment played from the onset of the block to the conclusion of the story; the experimenter controlled the pacing of the block such that the segment’s end approximately coincided with completion of all sixteen trials, or grasps. After each listen block, participants were asked six questions related to the content of the audiobook excerpt, and required to give a summary of recalled events. This was an effort to ensure participants maintained attention to the story throughout the grasping trials.

Figure 2 - Procedure: Participants initiated a reach upon the opening of the goggles, as pictured in the left panel. According to the block, participants completed the movement by bringing the item to their mouth to eat (center) or placing the food item in the bib (left). Both blocks were repeated with each hand during both a listen condition (paying close attention to presented audiobook sections) and a quiet (no background noise) condition.

Analysis

The primary kinematic variable of interest was maximum grip aperture (MGA), as this variable has consistently revealed a specific Hand by Task effect in previous studies (Flindall & Gonzalez, 2013, 2014, 2016). To enable within-participant between-hand comparisons, we calculated a corrected MGA value by subtracting the participant's average resting grip aperture (the distance between the IREDs on the participant's clasped thumb and index finger while their hand rested on their leg at the beginning of each trial) from the maximum grip aperture of each trial. By correcting MGA independently for each participant, variance in the shape of an individual's hands and the placement of the

IREDs cannot erroneously contribute to any effect of hand on our within-subject analysis of MGA.

The following additional kinematic characteristics were calculated according to Euclidean displacement, or the smallest distance between the IREDs on the wrist, index finger, and thumb during the outward movement toward the target prior to grasp onset. Grasp onset was determined as the point at which a) grip aperture plateaued, indicating prolonged target contact, and b) wrist velocity reached a nadir prior to the return movement toward the mouth. Other kinematic variables included variability of MGA (vMGA), calculated as the standard deviation of MGA within each Hand x Task x Listen block, peak resultant velocity (PV) of the wrist marker, reaction time (RT), defined as the first frame in which the wrist marker achieved a speed exceeding 5% of PV, movement time (MT), measured as the difference between RT and time of grasp onset, and deceleration phase duration (DP), measured as percent of MT that occurred between PV and grasp onset.

We calculated kinematic variables for each trial using unfiltered position values of each IRED in Microsoft Excel (16.0), and averaged these variables per condition block. Data was averaged to provide a better understanding of the typical grasp executed by a participant under the conditions dictated by the trial. If a participant incorrectly completed a trial (e.g., ate instead of placed, or vice versa, or knocked a target to the ground), if line-of-sight errors resulted in critical data loss, or if two or more variables within a trial were outliers (± 2 SDs from the block’s mean) that trial was removed from analysis and not replaced. If more than 50% of trials were lost in a single block or more than 10% of trials overall, data from that participant were not included in the final analyses. Data from four of our original 33 participants were removed from the current study, leaving 29 (average of 6.18±3.0% of trials removed) for inclusion in a 2 (Hand) X 2 (Task) X 2 (Audio) repeated measures analysis of variance (ANOVA). Statistical analyses were conducted using IBM SPSS Statistics (23).

To test recollection of the four audiobook excerpts, average quiz scores used were calculated for each participant. These story scores were used in combination with calculated change in MGA (averaged quiet MGA subtracted from averaged listen MGA) for each hand to assess the presence of any relationship between recall ability and grasp kinematics. Two Kendall-tau b correlations were conducted: one between story score and right-hand MGA change, and one between story score and left-hand MGA change.

3.3 Results

Attention

Audiobook quiz results were assessed, but did not affect our kinematic analysis. On average, participants answered 61 percent (±0.54) of the questions correctly (scores ranged from 35%- 79%). Due to non-normal data, we ran Kendall-Tau b correlations comparing quiz scores to difference in MGA during the quiet versus listen conditions in both the left hand and right hand. No significant correlations were found between the quiz score and MGA difference in the right hand, $\tau = -0.046$, $p = 0.73$ (two-tailed), or the left hand $\tau = 0.030$, $p = 0.82$ (two-tailed). As each participant was able to produce a summary of the excerpt, the story scores were disregarded and all participants were included in the previous kinematic analyses.

Means and standard errors for all variables are reported in Table 1. All significant main effects and interactions are reported below. Post-hoc comparisons (and planned a priori comparisons) were conducted via paired-sample t-test, with Bonferroni correction applied where appropriate.

Table 1. Grasp-to-eat and grasp-to-place kinematics. Listed values are means ± SE of: maximum grip aperture (MGA), variability (within-condition standard deviation) of MGA (vMGA), peak velocity (PV), deceleration phase (DP), movement time (MT), and reaction time (RT), divided according to hand, task, and listen condition.

Hand	Task	Listen	MGA (mm)	vMGA (mm)	PV (m/s)	RT (Myung, Blumstein, & Sedivy)	MT (Myung et al.)	DP (%MT)
Left	Eat	Quiet	21.4 ± 3.8	2.73 ± 1.1	0.64 ± .19	355 ± 133	973 ± 173	72 ± 3.6
		Listen	20.3 ± 3.7	3.23 ± 1.6	0.63 ± .17	376 ± 137	971 ± 191	72 ± 3.4
	Place	Quiet	22.7 ± 4.2	2.89 ± 1.2	0.62 ± .19	337 ± 136	954 ± 165	70 ± 4.8
		Listen	22.8 ± 4.0	3.11 ± 1.8	0.62 ± .20	357 ± 116	952 ± 172	72 ± 3.5
Right	Eat	Quiet	19.8 ± 4.8	2.48 ± 1.2	0.62 ± .19	381 ± 137	956 ± 182	71 ± 2.7
		Listen	19.0 ± 4.6	2.87 ± 1.6	0.62 ± .19	376 ± 125	976 ± 179	72 ± 3.1
	Place	Quiet	22.0 ± 5.2	2.75 ± 1.2	0.61 ± .18	360 ± 131	939 ± 176	71 ± 2.9
		Listen	20.9 ± 4.9	2.66 ± 1.3	0.60 ± .22	374 ± 113	954 ± 157	71 ± 3.2

Hand

There was a main effect of hand on RT, F (1, 28) = 6.449, $p = 0.019$, $\eta^2 = .21$. The right hand (389 ± 127ms) reacted significantly slower than the left hand (371 ± 131 ms).

Task

Main effects of Task were found in MGA, F (1, 28) = 28.42, $p < 0.001$, $\eta^2 = .50$; PV, F (1, 28) = 6.23, $p = 0.019$, $\eta^2 = .18$; RT, F (1, 28) = 5.06, $p = 0.032$, $\eta^2 = .15$; and DP, F (1, 28) = 4.82, $p = 0.037$, $\eta^2 = .15$. **MGA** was smaller when grasping-to-eat the target (20.21 ± 0.62 mm) compared to when grasping-to-place (21.92 ± 0.63 mm). With respect to **PV**, participants moved more quickly when grasping-to-eat (0.63 ± 0.19 m/s) than when grasping-to-place (0.62± 0.20 m/s). A main effect of Task on **RT** revealed participants initiated movement more quickly during grasp-to-place trials (371± 124 ms) than during grasp-to-eat trials (389± 133 ms). Finally, participants spent slightly less time in **DP** when grasping-to-place (71 ± 1 %MT) compared to when grasping-to-eat (72 ± 1 %MT).

Audio

A main effect of Auditory input was found in MGA, F (1, 28) = 4.40, p =0.045, η^2 = .14. **MGAs** were smaller when listening to speech (20.70 ± 0.64 mm) than they were during the quiet condition (21.43 ± 0.62 mm).

Hand x Task x Audio

No significant two-way or three-way interactions were observed between any kinematic variables. However, as we have previously reported a significant hand x task interaction on MGA (smaller MGAs during right-handed grasp-to-eat movements, compared to right-handed grasp-to-place or left-handed movements of either type; see Flindall and Gonzalez (in press). We performed a-priori *t*-tests to investigate the differences between speech, hand, and task MGAs. These planned comparisons revealed a significant difference between right-handed eat and place MGAs in the quiet condition, with eat MGA (19.67±0.84 mm) being significantly smaller than place MGAs (21.80 ± 0.90 mm), t (33) = 5.18, p< .001 (see Figure 3). Consistent with the results of previous studies, the difference between eat and place MGAs in the left hand quiet condition was not significant following Bonferroni correction (p =.03). The same eat<place effect was observed in the right hand during the speech condition, with eat MGAs (18.96 ± 0.78 mm) once again significantly smaller than place MGAs (20.80 ± 0.85 mm), t (33) = 4.29,

p= .002. Unexpectedly, another significant effect was found in the left hand listen condition, where grasp-to-eat MGAs (20.17±0.65) were significantly smaller than grasp-to-place MGAs (22.68±0.68), *t* (33) = 4.82, *p*< .001. These results indicate that when listening to speech, the characteristic kinematic pattern typically observed in the right hand appears in the left hand.

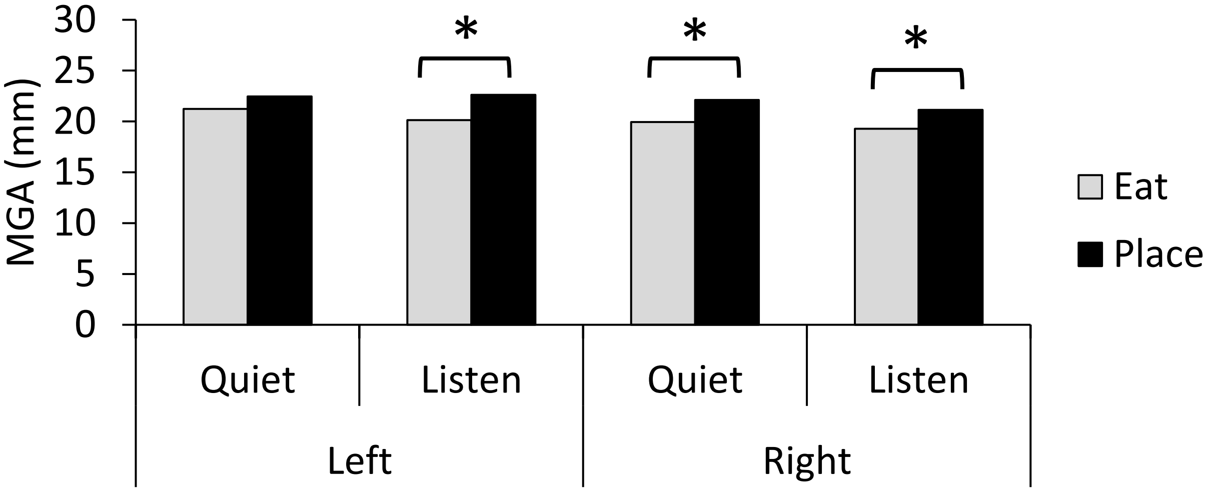

Figure 3. A-priori investigation of Hand x Task x Audio in MGA. While listening to an audiobook, eat MGAs were significantly smaller than place MGAs in both hands. During the quiet condition, only the right hand showed a significant difference according to task through a within participant comparison.

3.4 Discussion

Previous research suggests that a unique relationship exists between speech and the performance of manual actions; that is, speech production and processing influences how we physically perform grasping actions (Fargier et al., 2012; Gentilucci et al., 2004a; Moseley & Pulvermuller, 2014; Rabahi, Fargier, Sarraj, Clouzeau, & Massarelli, 2013; Tiainen et al., 2016a; Vainio et al., 2013; Vainio et al., 2015). In the current study, participants performed functionally distinct grasping actions both a) while the actor and environment were quiet, and b) while actively listening to speech. Several kinematic differences were found in regards to RT, PV, and DP when performing a grasp-to-place or grasp-to-eat action. These differences support previous findings that these movements are kinematically distinct. It is important to note that the main measure of interest was maximum grip aperture. As expected during the quiet condition, the results replicated findings previously reported by Flindall, Gonzalez, and colleagues (Flindall & Gonzalez, 2013, 2014, 2016; Flindall, Stone, & Gonzalez, 2015); namely, the grasp-to-eat action produced significantly smaller MGAs than the grasp-to-place action, limited to right-handed movements. However, when listening to speech, the MGA signature was no longer lateralized. MGA was significantly smaller in the grasp-to-eat condition than in the grasp-to-place condition in both the right and left hands.

The discovery that speech comprehension resulted in the grasp-to-eat kinematic characteristic in both hands is unexpected; because both examined functions are presumed to be left-hemisphere lateralized (i.e., speech processing and right-hand motor control), we predicted that any speech-related kinematic changes would be limited to the right hand. However, the right hand did *not* demonstrate any significant deviation from the previously observed pattern of smaller MGAs during the grasp-to-eat action. One possible explanation is that speech processing did not influence right-hand grasping kinematics. However, considering the discussed literature which demonstrates strong interactions between grasping and speech processes (Dromey & Benson, 2003; Fargier et al., 2012; Frak et al., 2010; Glover et al., 2004; Tiainen et al., 2016a; Vainio et al., 2013; Vainio et al., 2015; Vainio et al., 2014), such an explanation should be approached carefully. Speech processing may not be ale to alter right-handed grasp-to-eat actions.

The persistence of the kinematic effect may be an indicator of the neurological value of the hand-to-mouth action. Previous studies have found evidence supporting the practical and evolutionary value of the action. It is one of the first manual movements infants demonstrate (Hepper, McCartney, & Shannon, 1998), and specialized neural properties have been observed in non-human primates for hand-to-mouth actions (Graziano et al., 2005). These examples highlight the important role of right-handed grasp-to-eat actions both for humans and our evolutionary development. It is possible that the effect may be persistent enough to withstand other secondary tasks, but without further testing this is merely speculation.

In addition to the surprising maintenance of the effect in the right hand, we found that the left-hand adopted the right-handed movement pattern in the presence of a secondary task. While these results are surprising, it is not the first observation of smaller grasp-to-eat MGAs appearing in the left hand. In a 2015 report, Flindall and Gonzalez found that children younger than 10 years old showed the same kinematic signature when performing grasp-to-eat actions with both hands (Flindall & Gonzalez, 2015). The authors speculated that this bilateral task-dependent effect, which becomes right-hand lateralized in children older than 10 years and in adults, may disappear in the left hand as a result of natural synaptic pruning following consistent repeated use of the dominant hand for grasp-to-eat actions (Flindall & Gonzalez, 2015). The results of the current study suggest the specialized grasp-to-eat ability in the left hand may not be completely lost, but rather become inhibited; under specific circumstances this inhibition can be circumvented. It is entirely possible that the ability to generate the kinematic signature in the left hand is not related to pruning, or changes in the right hemisphere, but a result of simultaneous left hemisphere activation during left hand grasping.

This supposition does not completely answer why we observe results similar to Flindall and Gonzalez (2015). The children completed the grasping tasks in a silent environment, and our participants exhibited the bilateral effect while processing speech. Research assessing the developing brain in children has found broader activation patterns during motor and cognitive tasks when compared to adults (Casey, Tottenham, Liston, & Durston, 2005; Thomas et al., 2004). In several studies, speech, a left-lateralized function show more right-hemisphere activation during language tasks in children compared to adults (Gaillard et al., 2000; Holland et al., 2001). As children develop and synaptic pruning occurs, task-specific activation shifts from generalized to precise innervation, resulting in an adult-typical activation pattern. While children are still developing neural sophistication of functions (including motor control), irregular activation patterns might prompt a bilateral reflection of the grasp-to-eat kinematic signature. In adults, activation of the left hemisphere via a lateralized task (speech processing) during left-hand grasping may allow the left hand to access the motor plan responsible for producing the kinematic signature. Therefore, smaller MGAs during grasp-to-eat actions appear in the left hand. This explanation would predict that other tasks causing left-hemisphere activation should also shift the kinematic signature into the left hand (e.g., bimanual movements, or transcranial direct current stimulation, be it magnetic (TMS) or electrical (tCDS)). Comparatively, right hemisphere lateralised tasks should cause no changes in the kinematics of the left hand (i.e. musical or visuospatial processing actions, or right-hemisphere TMS/tCDS).

As our current results offer only a preliminary examination on the effects of performing a speech processing task during execution of a hand-to-mouth action, it is difficult to apply our findings to previously developed theories – namely the Gestural Theory of Language – with any degree of certainty. Given the current evidence, it is possible that the observed interaction is a result of a left-lateralized task influencing manual action, and not a specialized relationship between speech and manual movement. In a previous study, speech processing altered TMS-induced MEPs in both the right and left hands (Floel et al., 2003). In our study, the left hand showed significant changes during speech processing, while the effect was maintained (but not significantly changed) in the right hand. These results do suggest that, if the Gestural Theory of Language is correct, then both the right and left hands may have influenced the development of language, despite its lateralization in humans.

We previously hypothesized that MGA production would be negatively affected in the right hand via larger variability in MGA (indicating a loss of precision), as predicted by the majority of research examining dual-task effects between language and manual action. Past studies focussed on spoken language tasks and kinematic factors such as lip displacement, vocal and manual reaction time, movement time, and maximum grip aperture (Dromey & Benson, 2003; Dromey & Shim, 2008; Gentilucci, Benuzzi, Bertolani, Daprati, & Gangitano, 2000; Glover et al., 2004; Hesse, Schenk, & Deubel, 2012; Singhal, Chinellato, Culham, & Goodale, 2005). Across all studies, dual-task conditions performed concurrently with speech production results in a decrease in performance, evidenced by increased lip displacement, slower RT for both vocal and manual movement, longer MTs, and increased MGAs. We did not replicate the findings of these studies, as RT did not increase and MT did not decrease (or even change) during the dual-task condition. We did observe a change in MGA in response to speech processing, however with respect to the *direction* of this change, our results are at odds with the previous research. Normally, dual-task interference results in a significant increase in MGA, ostensibly because such increases reflect an increase in the grip aperture margin for error (Singhal et al., 2005). In our study, we report a decrease in MGA in left-handed grasp-to-eat movements in response to speech processing as a secondary task. There are two alternative interpretations of this finding. First, it is possible that that the decrease in MGA is not evidence of dual-task *interference,* but rather dual-task *facilitation*. In previous grasp-to-eat studies, authors posited that the observed smaller MGA in the right hand represented a kinematic advantage, based on decreased grip-aperture closing time and a conservation of energy (Flindall & Gonzalez, 2013, 2015). The neural activation that comes from speech processing may be facilitating the grasp-to-eat and grasp-to-place movement, evidenced by smaller MGAs during this action. Alternatively, smaller MGAs may not represent a kinematic advantage *per se*, but instead merely reflect a non-qualitative difference in the production of two movements. After all, while smaller MGAs may present an energetic (or economic) advantage, they do not necessarily increase success while grasping. In conditions of target uncertainty and/or reduced visual feedback, *larger* MGAs represent an advantageous kinematic adaptation (Jakobson & Goodale, 1991b). In this case, we may say that the grasp-to-eat and grasp-to-place movements are *kinematically distinct*; we need not associate a value-judgement with those differences to discuss the relevance of the difference itself, i.e., that the difference arises from distinct neural circuits associated with a movement's function (or end-goal) rather than its mechanics. The manifestation of the kinematic signature in the left hand in this case reflects a change in the accessibility of the grasp-to-eat neural circuit by the left-hand/right-hemisphere system; whether the left-hand/right-hemisphere system can access a stable left-hemisphere grasp-to-eat circuit in the presence of speech, or whether the processing of speech activates a dormant grasp-to-eat circuit in the right-hemisphere, remains to be seen.

A limitation of the current study is that while participants listened to the same length of audiobook excerpt, the timing of individual trials during those excerpts was not controlled, meaning that single grasps could have been completed while listening to a broad variety of individual words. Previous studies have found that the semantic qualities of words, such as the distinction between a large and small item, can result in different patterns of neural processing, and in turn, significantly alter grasping kinematics (Fargier et al., 2012; Moseley & Pulvermuller, 2014; Rabahi et al., 2013).We attempted to minimize potential semantic effects by deliberately choosing audiobook sections rich in description, with little action and minimal mention of tool use or manual action. We collected data from multiple trials with story content counterbalanced between participants and conditions to diminish the chance of specific trials consistently aligning with potential triggers within the speech. With these controls in place, we believe it unlikely that the observed effects were driven by the semantic qualities of individual words.

In conclusion, a novel left-hand manifestation of the grasp-to-eat kinematic signature was observed in adults for the first time. While listening to and processing speech, smaller maximum grip apertures for grasp-to-eat actions were maintained in the right hand, and were (for the first time in adults) manifested in the left hand. The observed change represents the facilitation of a distinct grasping effect during a speech processing task. Another important finding is the conservation of smaller MGAs in the right-hand, despite completing a speech processing task. The resiliency of the characteristic kinematic effect may represent the evolutionary importance of the action. The results contribute to our understanding of the grasp-to-eat kinematic signature, the development of language, as well as provide direction for future research investigating speech and grasping within an ecologically relevant paradigm.

Chapter 4: Experiment 2: Talk through the hand: The effect of different prehension actions on speech

4.1 Introduction

Throughout everyday life, people talk while completing various manual tasks. Despite the appearance of a seamless integration of each motor act, research has demonstrated that executing a motor action while speaking can result in alterations of performance in both hand and speech characteristics. These alterations can affect how we interact with our environment. To understand the exact effects of the interaction, our everyday hand movements (prehension, the act of reaching and grasping a target) must be examined in conjunction with the various speech modalities: word production, speech processing, and syllable production. Prehension actions used during speech production in previous studies include: grasping a block to move, shaping the fingers into a precision or power grasp, and picking up an apple while producing speech sounds (Fargier et al., 2012; Frak et al., 2010; Gentilucci et al., 2004a; Glover et al., 2004; Kritikos, Dozo, Painter, & Bayliss, 2012; Rinaldi et al., 2016; Tiainen et al., 2016a; Vainio et al., 2017; Vainio et al., 2013; Vainio et al., 2015). Many of these studies measured manual kinematics to investigate the interaction between speech and manual gesture. A wide array of results have been obtained: decreased reaction time of grasping when the shaping of the lips mimicked the shaping of the hands (Tiainen et al., 2016a; Vainio et al., 2013), increased peak velocity of the hand while pronouncing verbs related to manual action (Fargier et al., 2012), increased grip force when participants listened to verbs relating to manual action (Frak et al., 2010), and decreased maximum grip aperture when pronouncing a word representing a smaller noun (Glover et al., 2004). By describing only a few studies, the variety of methods and kinematics used are made apparent. Findings from neuroimaging studies support the possibility of a neural basis for the interaction of speech and grasping. While undergoing an fMRI, participants listened to speech, which resulted in increased activation in the premotor and motor areas of the brain (Meister, Wilson, Deblieck, Wu, & Iacoboni, 2007). Another study found that observation of a grasping action activates Broca's area, which is primarily responsible for speech production (Grafton et al., 1998; Iacoboni & Woods, 1999). These studies serve to support behavioural evidence of the interaction between speech and motor movements.

Researchers have also examined changes in *vocal* characteristics during prehension. Measuring changes in speech is less straightforward than measuring manual kinematics, as one of the main manipulators of speech, the tongue, is located internally. Markers can be placed on the lips to measure changes in aperture, variation in aperture, and velocity. To develop an understanding of the tongue position during speech production, particularly during pronunciation of vowels, speech is recorded, and by identifying patterns in the acoustic spectra, formant one, two, and three are calculated. Each reflects changes in resonance to the harmonics of speech, and each individual formant is associated (sometimes controversially) with a direction of change in the tongue and/or lips (Clark, Yallop, & Fletcher, 2007b). Two specific studies relied on these acoustic measures in addition to kinematic changes. Despite assessing nearly identical acoustic characteristics with similar methods, they found very different results. One group of authors noted significant changes in both the second formant (F2) and third formant (F3) during a consonant-vowel pronunciation and a grasping task (Gentilucci et al., 2004a), while a second group conducted a similar study and observed no significant changes in vocal acoustics (Tiainen et al., 2016a). Both studies used a similar research question, but chose different methods, kinematic measurements, and spoke different languages. In the first cited experiment, participants were native speakers of Italian, and were asked to start the action with their hands placed around the stem of an apple or a cherry (power and pincher grasp; (Gentilucci et al., 2004a)). Next, they brought the food item towards their mouth as they produced the syllable BA. Measurements of F1, F2, F3, intensity and pitch were used in the analysis. In the second cited experiment, the participants were native speakers of Finnish, and gripped a device equipped with both a tube affording a power grasp and a smaller switch affording a precision grasp (Tiainen et al., 2016a). According to stimuli presented on a screen, participants would execute one of two actions as quickly as possible without any arm movement (a grasp without the reach component) during syllable production of TI or KA. The authors only chose three acoustic characteristics (intensity, F1, and F2) for analysis.

Comparing the acoustic results of the two studies reveals stark differences between them. In the Gentilucci et al. (2004) study, significant changes occurred in F2 and F3 relative to the size of object being grasped; a larger object resulted in increased frequency for F2 and a decrease in frequency for F3. However, the other study (Tiainen et al. 2016), did not observe changes in acoustic markers. As the study by Tiainen et al. (2016a) was completed after Gentilucci et al. work, they proposed that the lack of similarities in acoustic results was driven by methodological differences. Specifically, they proposed that during simultaneous speech-manual production tasks, a reaching and grasping component is required to create changes in speech formants.

The goal of the present study thus, is to compare the effects of different prehensile movements on speech production of the syllable [bɑ]. These comparisons are made to help elucidate the discrepancies in acoustic results from previous studies (Gentilucci et al., 2004a; Tiainen et al., 2016a) The chosen prehension actions can be divided into two groups; full prehension (grasp-to-place and grasp-to-mouth) and components of, or partial prehension (grasp-alone and reach-alone). The grasp-to-mouth and grasp-alone actions were specifically chosen to mirror the methods used in the previous studies. Further, we use two sizes of target items for grasping; an apple (power grasp) and a Foot Loop (precision grasp). These sizes were chosen to continue to increase the similarities between the previous studies and the present one.

The majority of the discussed studies investigating speech and manual interactions have focused exclusively on actions performed with the right hand. Participants in this study completed the manual actions with both hands. We hypothesized, given the left hemisphere lateralization for language and right-hand movement, formant frequency would show significant changes during right-handed actions compared to the left hand. An additional prediction was that changes would occur in formants according to size of the target, *only* during full prehension actions, as Gentilucci et al. (2004a) observed in their study. We also expected to observe a change in formant frequency between the complete and partial prehension movements.

4.2 Methods

Participants

Forty-one right-handed University of Lethbridge students (22 females, mean age 20.32± 1.90 years) participated in this study. Each person completed a survey of previous language experience, and self-identified as a native English speaker. Additionally, participants completed a modified Edinburgh-Waterloo handedness questionnaire.

Materials

We used a table with a workspace measuring 110 x 76.5 cm for the experiment. The participant sat down and we adjusted a 22 x 14.5 cm black target mat to a comfortable reaching distance. A crosshair was drawn on the mat, with the center five cm away from the far facing edge. All target food items were placed over the crosshairs during the different conditions, except for the grasp-alone condition, where it was placed directly in front of the participant’s hand, near the edge of the table. A Shure SM87A microphone (attached to a Marantz flashcard PMD661 recorder) was used to record speech. It was hung around the participant’s neck, approximately 10 cm below their mouth. Two different target objects were used for the experiment; a red apple (approximate height of 8 cm and horizontal circumference of 21 cm), and a Froot loop™ (15 mm in diameter). A third object, a banana (approximately 23 cm long and 4 cm thick) was also used as a foil (33% of trials). We used a 56 cm Mac computer and the program Superlab to control the presentation of the go signals. The computer was positioned 80 cm from the edge of the table, allowing participants a comfortable space to grasp the required items.

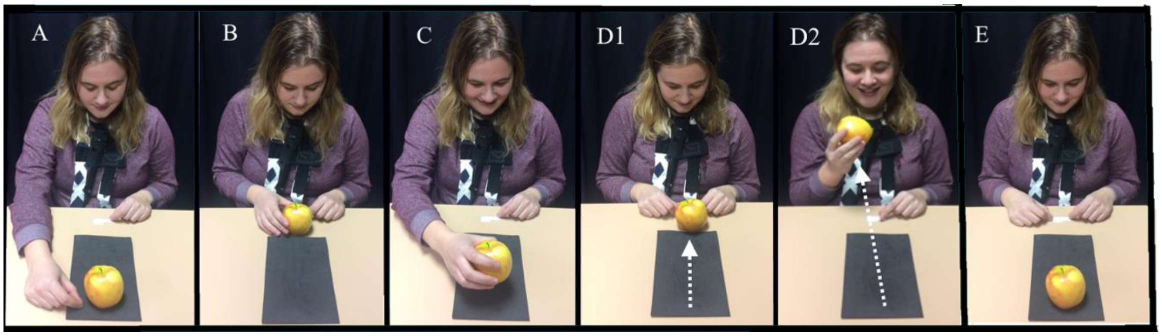

Figure 4. Procedure. Participants would observe the target following a beep. They initiated a grasping action at the sound of a second beep, while producing the syllable "Ba", and less regularly "Gee". Pictured above are the five conditions participants executed with three targets (an apple, Froot Loop and banana). Condition A is reach-alone, and did not require finger movement. Condition B is grasp-alone, and did not require arm movement. Condition C represents the beginning of trials D1 and D2. During the grasp-to-place condition, participants would begin at C, and upon the second beep, grasp the target and place it in front of them as seen in D1. For the grasp-to-mouth condition, participants began positioned as presented in C, and at the second beep, grasp the target and finish in the position pictured in D2. Each action was completed using each hand. After all the action trials, participants completed a control condition, as seen in image E, where no action was performed and participants simply produced the syllable.

Procedure

Participants sat in a chair, and after adjusting the microphone and mat, assumed the rest position. In the "rest position", participants placed their hands so that the ulnar styloid was sitting slightly past the edge of the table, thumb and index finger resting comfortably together, and closed their eyes. During each trial, regardless of the block, participants viewed a target item, and then produced a specific syllable while executing a specific action. The location of the target item was determined by the required action, and would start in the same position for all the trials in a block. There were two different target-item start positions. One position was on the crosshairs of the black mat, approximately an arm's length away from the participant. The additional start position was near the participant, placed just in front of the fingers while in the rest position. At the start of each trial, a beep would sound, indicating that the participant should open their eyes and look at the target item. 1500 ms later, a second, slightly higher-pitched beep played, and the participant executed the action towards the viewed target and simultaneously pronounced the associated syllable. After the action was finished, they returned to the rest position, and waited for the next start beep.

There were four different action conditions- grasp-alone, reach-alone, grasp-to-place, and grasp-to-mouth. A fifth condition (no action) served as a control, and was performed as the last block of the experiment. When completing the grasp-alone condition, participants still viewed the target after the first beep, but at the second beep, they placed their fingers around the object (with minimal arm movement). The condition required participants to keep their arms stationary, using only their fingers to grasp the target placed beside their hands at the beginning of the trial. For the reach-alone condition, participants moved their arm towards the object without grasping it, and placed their hand beside the target. When completing this action, participants were given clear instructions to preserve the rest position of the hand during transport, so the final position was the hand resting beside the food on the mat with thumb and index finger together. During the "grasp-to-place" condition, after hearing the second beep participants reached out and grasped the presented item, lifting it off the table and moving it to a location just in front of their resting hand. Finally, during the "grasp-to-mouth" condition, at the second beep participants reached towards the target, grasped it, and brought it towards their mouth, as if to ingest. At the end of the motion, they held the position for a few seconds, before the experimenter retrieved the target item and placed it back on the crosshairs. Each block consisted of fifteen repetitions of one action. During "no action", participants began in the rest position. After the first beep, they viewed the target item placed on the crosshairs of the mat. Following the second beep, they remained stationary while producing the syllable. See Figure 4 for a visual representation.

Throughout the experiment, we reminded the participant to begin the action and pronunciation of the syllable immediately after the second beep. Therefore, participants were supposed to pronounce the syllable during the outward-transport component of the action. If we observed the pronunciation beginning after the grasping component, the trial was removed from the analysis.

Each block (of 15 trials) was performed twice (30 trials per condition). In order to compare results between the current and previous studies, all participants completed the task with the right hand first followed by the left hand. If the apple or Froot loop™ were presented as the targets, participants pronounced [bɑ]. During trials where the banana was the target, participants pronounced [gi]. We used gi in the experiment for two reasons. The first reason is that in the study by Tiainen et al. (2016a), participants pronounced the vowels [ɑ] and [i], so we wanted participants to have a similar speech pronunciation experience in our methods by including the vowel [i]. The second, and main reason we selected this sound (and peculiarly shaped food item) was to prevent boredom, and discourage a lack of effort/focus from participants due to repetition of the same consonant-vowel [bɑ] throughout the whole experiment. However, as it was a different vowel, and actions were only performed on one object size, we did not conduct analysis on the gi trials. Overall, each participant completed a total of 300 trials with each hand (200 producing Ba). Only the [bɑ] trials were analysed.

Analysis

Recorded files were uploaded and analyzed using Praat (version 6.0.31) (Boersma & Weenink, 2017). A script was created through Praat to select the CV-vocalisation and identify the boundaries of the vowel. Once the beginning and end of the vowel were identified, the script extracted the median of the first, second and third formant values. The extracted values were organised in Microsoft Excel. Here, trials where the participant pronounced the CV before the start of the trial or after the completion of the action were removed, along with any other outliers. Outliers were calculated by determining any formant frequencies which were more than 3 standard deviations away from the mean. A mean of 3.5 trials were removed for each participant. No participant had more than ten percent of data removed, and at least three out of five trials remained in each condition. Statistics were conducted using SPSS 24. Using formants for our dependant variable, we conducted a 2 (Kirschner, Ayres, & Chandler) x 2 (size) x 4 (action) mixed-measures ANOVA with sex as a between factor for all three formant categories- first formant (F1), second formant (F2) and third formant (F3). Male's speech articulators are shaped differently from females' (Scherer & Giles, 1979), so we expected to observe sex as a significant between factor. However, there were no significant interactions between sex and the three other factors, so for the remainder of the analysis we collapsed across sex and proceeded to run three 2 (Kirschner et al.) x 2 (size) x 4 (action) within repeated-measures ANOVAs to determine if there are any differences in each of the three formant levels according to manual actions. To understand if completing any of the actions resulted in an acoustic change compared to the baseline, the final control trials were used as a fifth action to run a 2 (Kirschner et al.) x 2 (size) x 5 (action) repeated measures ANOVA with each of the three formant frequencies. Results are reported below under Control Comparison. Alpha level was set at $p = 0.05$.

4.3 Results

Action Comparison

The following results section examines differences in formants according to hand used, size of the object, and action executed. The control condition is not included in this analysis in order to simplify comparison with the previous studies as both Gentilucci et al. (2004a) and Tiainen et al. (2016a) did not compare their formants with a control.

First Formant

There was a significant main effect of **Hand** $F(1, 40) = 5.13$, $p = 0.029$, $\eta^2 = 0.11$. Moving the left hand during speech (783 ± 14 Hz) resulted in significantly higher frequencies than the moving the right hand (776 ± 13 Hz). There was a significant main effect of **Size** $F(1, 40) = 5.42$, $p = 0.025$, $\eta^2 = 0.12$. When grasping the large item (apple), F1 was significantly higher (781 ± 13 Hz) than when grasping the small item (Froot Loop™) (778 ± 13 Hz). **Action** was approaching significance ($p=0.079$). There were no significant interactions.

Second Formant

We did not observe any significant effects or interactions.

Third Formant

There was a significant main effect of **Action** $F(3, 40) = 5.45$, $p = 0.002$, $\eta^2 = 0.12$. The formant was significantly higher when participants performed a grasp-to-mouth action

(2724.44 ±39) compared to just-grasp (2680.95 ±37.63). After Bonferroni correction, there were no significant differences between the other actions. There were no significant interactions.

Baseline Comparison

Results in the following section closely mirrored that of the previously reported analysis, as the only difference between those analyses and this one is the addition of a fifth “action”, the control, or “no action” condition. As no action was performed during the block, the trial was not repeated with each hand. The same control block was compared to both the right and left-hand action conditions. Examining the change in frequency of the produced formants during each action, it becomes obvious when the identical height of the control condition is noted between each hand. As mentioned in the methods, our main purpose in running this analysis was to determine if any of the actions were causing a significant change in regular speech.

First Formant

There was a significant effect of hand F (1, 40) = 5.53, $p = 0.024$, $\eta^2 = 0.12$. When using the right hand to execute the action, the frequency of the formant is significant higher (784.95±13.63) compared to during left hand movement (779.34±13.19 Hz). The effect of **Size** was significant F (1, 40) = 6.78, $p = 0.013$, $\eta^2 = 0.15$. When grasping an apple, F1 was significantly higher (783.75±13.36) compared to grasping a Froot Loop (780.55±13.38 Hz). We found a strong, significant effect of **Action** F (1, 40) = 4.75, $p = 0.004$, $\eta^2 = 0.10$ (see Figure 5). After Bonferroni correction, only grasp-alone (777.78±13.5) was significantly different ($p=0.018$) from the control condition (792.45±13.4). We also found a significant two-way interaction between Hand used and Action executed during speech production F (4,160) = 2.74, $p = 0.030$, $\eta^2 = 0.06$. However, this difference appears to be due not to a genuine difference between the right and left hands during specific actions, but attributable to the fact that the same control values were used during both the right and left-hand comparison. As such, the interaction will not be discussed.

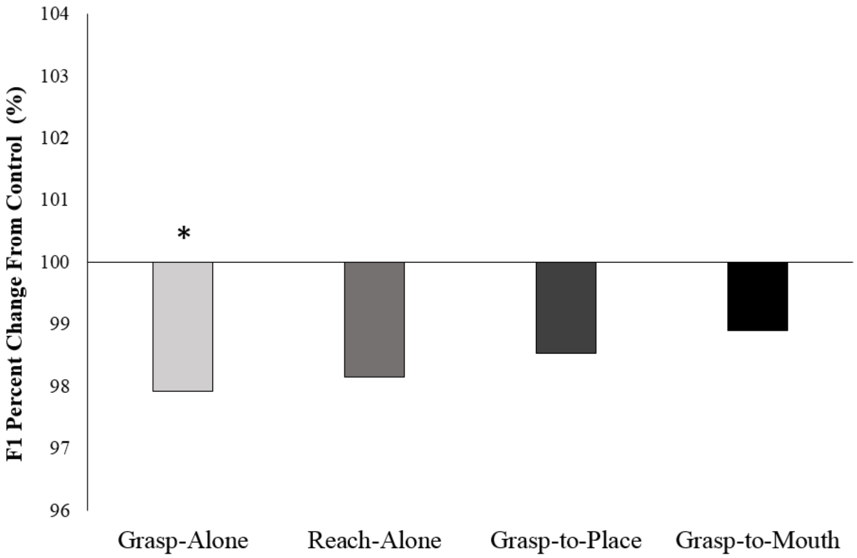

Figure 5. Change in F1 During Action Performance Compared to Control. Each bar represents the average change in frequency of the first formant during the execution of the specified action compared to the control condition. There was a significant difference between the grasp-alone and control condition from within subject comparisons.

Second Formant

There were no significant results or interactions.

Third Formant

There was a significant effect of **Action** F (3,117) = 4.75, $p = 0.004$, $\eta^2 = 0.11$ (see Figure 6). After Bonferroni correction, the effect appears to be driven by a barely significant difference between reach-alone and grasp-to-mouth (p= 0.05). No other significant effects of interactions were observed. A two way interaction of Hand x Action was approaching significance F (3, 102) = 2.03, $p = 0.093$, $\eta^2 = 0.05$.

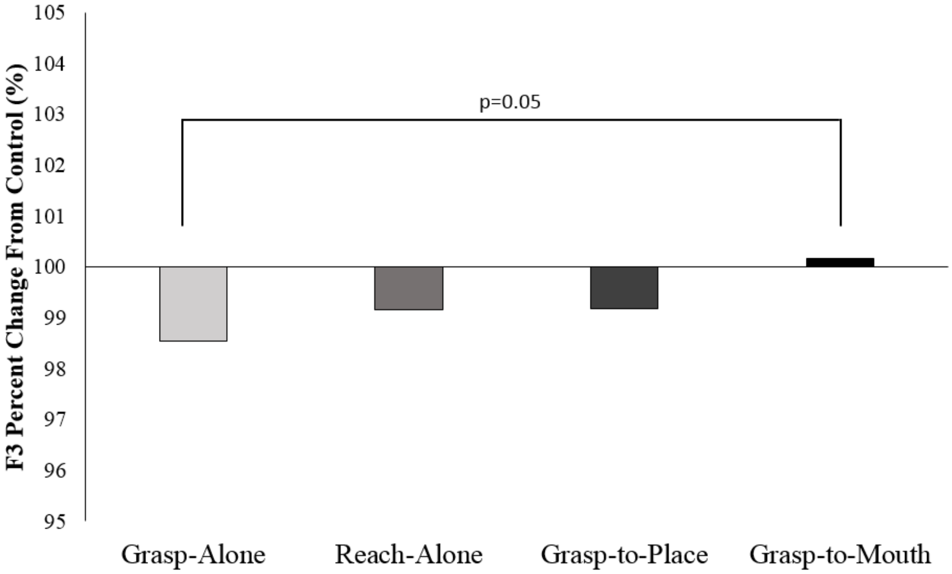

Figure 6. Change in F3 During Action Performance Compared to Control. Each bar represents the average change in frequency of the third formant during the execution of the specified action compared to the control condition. There was a significant difference between the Grasp-Alone and Grasp-to-Mouth condition from within subject comparisons. There we no significant differences in formants between the actions and control condition.

4.4 Discussion

The purpose of the study was to determine the effect of different types of manual movement on vowel production as well as the role cerebral lateralization plays in the interaction between speech and grasping. Participants completed four types of actions (grasp-to-mouth, grasp-to-place, grasp-alone, and reach-alone) with each hand while pronouncing the syllable [Bɑ]. We predicted that formant frequency during right hand movements would be significantly different from vowels produced during left hand actions. As with previous studies, we also expected to observe changes in formants according to size of the object grasped. Finally, we expected formants to change during the full-prehension movements (grasp-to-mouth and grasp-to-place) compared to partial prehension gestures (grasp-alone and reach-alone). Assuming the formants during left hand movements show significant differences compared to the right hand (and does not affect speech production), we should observe several significant interactions between the conditions, hand used versus size of object grasped, as well as hand used versus performed action.

With regard to the action comparison analysis, the significant effect of hand on F1 is a novel observation, as the bulk of speech studies examining acoustic measures have focused exclusively on the interaction between speech and the right hand. The presence of the effect indicates that speech was affected according to the hand completing the action during the vocalisation. However, the lack of significant *interactions* between hand and the other factors (action, size) suggests that the movement of the left hand consistently mirrored that of the right hand. As a result, formant change occurred due to the action executed, regardless of the hand executing the action. Given the similar cerebral lateralization of the functions of speech production and right-hand movement (Brown, 2010; Wildgruber, Ackermann, Klose, Kardatzki, & Grodd, 1996) these results are surprising, but not unprecedented. An imaging study found evidence that speech production alters the threshold requirements for motor evoked potentials in both hands when transcranial magnetic stimulation (TMS) is applied to the corresponding hemisphere (left hemisphere for the right hand and right hemisphere for the left hand) (Floel et al., 2003). If the activation threshold is surpassed in the left hand while completing a typically left lateralized task, the observation that a left lateralized function (speech) can be altered by right-lateralized left-handed movement appears very plausible. Our results imply that the observed relationship of speech and grasping exists between both hands, regardless of lateralisation. If this is the case, then anyone who studies the interaction between language and manual action should consider methods which include the right and left hand. Before these findings are applied to research using word production, it is important to note that syllable pronunciation activates different neural areas compared to semantically valuable speech production (Peeva et al., 2010). During a more phonetically challenging task, such as self-generating syllables or meaningful words, it is plausible that we could observe more distinct changes in speech according to the hand.

The significant differences in formants according to size of object, and according to action executed are important to discuss for three main reasons. The first, is to settle the discrepancies between our results and those from the second paper (Tiainen et al., 2016a). The grasp-alone condition in our study was designed to mirror the grasping action used in the study by Tiainen et al. (2016a), where participants did not execute a reach component, but simply grasped a large or small object. We observed significant changes in F1 according to the size of the target (including during the grasp-alone action), whereas Tiainen et al. (2016a) reported null results. The observed inconsistencies could be the result of slight differences in methodology, such as different go signals (beeps versus colour changes), instructions (complete at a natural pace versus quick execution), or randomization of trials (consecutively produced same syllable versus randomly alternated syllables). However, we propose that the category of the grasping target (edible vs. non-edible) played a significant role. Previous research has noted that when shown images of natural, specifically edible items, our manual reaction times are consistently faster compared to non-edible foods (Meule et al., 2014; Rumiati & di Pellegrino, 2016). Our reactions to such stimuli easily relates to another study, which found when shown manipulatable objects, neural activity is increased in areas which execute actions relevant to that item (i.e. grasping, eating, throwing) (Grèzes et al., 2003). Both of the familiar edible targets in our study carry a host of affordances, or associated actions. Compared to Tiainen et al. (2016a), where participants used a novel, specially designed plastic cylinder and small switch, the apple and Froot Loop in the present study offer a much wider range of associated familiar actions. To further our understanding of the interaction between speech and prehension, it would be valuable to conduct an experiment with similar methods, but the target items consisted of familiar and novel objects, divided into edible and inedible groups. Through this study, we would be able to better understand the role affordances of different objects play in the interaction between speech and prehension.

The second point that must be addressed from the action results is the difference from the action comparison analysis that must be discussed are changes in formants according to both the target size and executed action. Target size only affected F1 frequency in this study, compared to the previously reported changes in F2 and F3 by Gentilucci et al. (2004a). The direction of formant change according to size condition appears to be different, and did not occur in F2 as in Gentilucci et al. (2004a). Similarly to the first paper (Gentilucci et al., 2004a), significant differences in formants did occur according to the executed action, however it was not in the expected formants (F1 changed instead of F2). Grasp-to-mouth manual movement resulted in a significantly higher F3 compared to grasp-alone. Unlike our predictions, speech produced during full prehension movements (grasp-to-eat and grasp-to-place) did not significantly differ from partial prehension actions (reach-only and grasp-only). Given the similarities in methods between the present study and the two previously discussed, these dissimilar results are unexpected. However, Gentilucci et al. (2004a) examined one specific action, and did not compare formant differences according to grasp type across different actions. When the grasp-to-mouth condition is isolated in the right hand, the difference between the large and small condition in F3 follow the direction of the difference observed in Gentilucci et al. (2004a). It is a less straightforward task to interpret the lack of significant changes in any of the conditions in F2, and novel changes in F1. A plausible explanation is that the interaction of speech and grasping is sensitive enough that slight changes in methodology results in a lack of exact replication. Traditionally, changes in F1 are associated with openness of the mouth, which roughly relates to height of the tongue- closer to the palate/roof of the mouth compared to the bottom of the mouth, and changes in F2 are associated with the position of the tongue relative to the front or back of the oral cavity (Stevens & House, 1955). However, a recent study using electromagnetic articulography determined that while F1 does represent height, the connection between F2 and tongue position is much more complex (Lee, Shaiman, & Weismer, 2016). These results indicate that the tongue height changed according to the hand moved, the size of the object, and the action performed. No changes occurred in the more second formant, F2. Such alterations could arise due to the different phases of prehension executed during pronunciation. In Gentilucci et al. (2004a), participants began each trial grasping the target item, and were only required to transport *towards* themselves. Therefore, speech was produced while the object was returning to the participant. In our experiment, participants produced the syllable during outward transport before the grasp. This slight difference in execution may have produced a Previous experiments have demonstrated unique changes in manual kinematics during simultaneous speech dependent upon the timing of the action and speech (Tiainen et al., 2016a; Vainio et al., 2014).

Now that the discrepancies are addressed, the third reason for discussing the action results is the findings of the follow-up tests. The only significant difference found when comparing the actions was between the grasp-to-mouth and grasp-alone movements. This is interesting because grasp-to-mouth contains the grasp-alone action, yet each had a significantly different effect on speech. If grasp-to-mouth is significantly different from grasp-alone, why do we not observe this same effect between grasp-to-place and grasp-alone? An answer is provided through previous studies, which have reported a consistently occurring kinematic characteristic which differentiates grasp-to-eat from grasp-to-place (Flindall & Gonzalez, 2013, 2016). The authors of these studies proposed that the kinematic characteristic movement, which results in significantly decreased maximum grip aperture in the right-hand during grasp-to-eat actions, may have evolutionary relevance (Flindall & Gonzalez, 2016). Further, it is of vital importance to our survival, and one of the first hand actions we exhibit in our development, with the first observations occurring in the first ten weeks of gestation (Hepper et al., 1998). The unique characteristics of the hand-to-mouth action differentiates the execution of the movement from the grasp-to-place action, resulting in a significant change of formants compared to grasp-alone condition.

Grasp-alone displayed significant changes in speech compared to grasp-to-mouth. The value of the grasp-to-mouth action was discussed, but we have not yet addressed why grasp-alone was the only partial prehension to differ from grasp-to-mouth. The explanation simple, as the differences can likely be attributed to the movement of the fingers, and timing of the actions. As mentioned, participants were instructed to initiate movement and speech production simultaneously. This resulted in participants pronouncing sounds while their fingers were completing a grasping action during the grasp-alone condition, versus a reaching action during a grasp-to-mouth condition. The second study proposed that the shaping of the fingers can influence the shaping of our lips and tongue, a claim which is supported in several other studies as well (Tiainen et al., 2016a; Vainio et al., 2013; Vainio et al., 2015). If this is the case, then the catalyst for change in formants appears strongest when executing a just-grasping action, rather than a full prehension action. It is possible that executing less natural actions results in greater changes to speech, and the fact that our study had the benefit of comparing a grasp-alone action with a control condition and other action conditions clarified the distinction, compared to the previous study by Vainio et al. (2016a).

While not fundamental to the study and our hypotheses, the second analysis examining baseline comparisons demonstrates that only the partial-prehension conditions (reach-alone and grasp-alone) caused formants to differ significantly from the baseline control. These differences may suggest that there is something categorically different between executing an ecologically relevant action compared to a single component of prehension. Further, it is interesting to consider why these two very different components resulted in the significant changes in F1, rather than the full prehension actions. As mentioned before, in the second compared study, authors proposed that the observed effects (decreased vocal reaction time) are the result of a facilitation of action between the speech articulators and the digits (Tiainen et al., 2016a). The evidence provided by the baseline comparison indicates that planning a prehension action, or articulation of the fingers are not prerequisite conditions for hand movement to change speech. However, as mentioned earlier, it is important to note the highly familiar and ecologically relevant grasping targets utilized in the study. As participants executed the reach-alone action towards the apple or Froot Loop, the affordances associated with the object are naturally processed (Grèzes et al., 2003). The lack of natural prehension action during the reach-alone condition resulted in different action, and therefore a different interaction with F1. However, the implicit neural expectation of executing a grasp influenced the action in a manner similar to the grasp-alone movement. In the first compared paper by Gentilucci et al. (2004a), there are several additional conditions after the initial experiment where participants physically transported the target to their mouth; participants speaking while observing an experimenter execute the action with the target and pantomime executing the action (to name a few). By simply observing the execution of the action, similar changes to lip kinematics and sometimes voice spectra occur. The result that simply observing an action can enact changes in pronunciation is ascribed to the power of affordances. Each object that we interact with offers specific options for action execution. With an apple, the main affordance it offers is grasping-to-eat, or grasp-to-manipulate, or grasp-to-place. The evidence from this study suggests that not only does observing someone execute an action maintain changes observed in speech, but that observing the item is enough to trigger an association of the various affordances, and create those similar outcomes in speech.

A limitation in this study is that we did not use kinematic measurements of the hand or mouth. In both of the compared studies, additional measures included reaction time of the hand and voice, arm velocity, and lip velocity. As there was such a range in compared kinematic features between these studies, we elected to simplify, and initially focus on changes in speech and determine the role of executed action in formant changes. In the future, we would like to conduct a follow-up study with similar methods to determine how manual kinematics are affected when executing different action components during speech production. Another issue that was not addressed in the discussion is the large number of conditions (resulting in a large number of trials). In both of the previous studies, one type of grasping movement was used, and the only comparison of speech was made between a power and a precision grasp (Gentilucci et al., 2004a; Tiainen et al., 2016a). In this study however, we compared four different grasping movements while each performing a power and precision grasp. The discussion provided several explanations which could explain discrepancies between our findings and those in the previous studies, but a potential argument is that the length and complexity of the study altered speech production in addition to the intended effect of the manipulated variables (type of action and size of the target). To address this issue, it is important to carefully consider the complexity of the study, specifically the number of conditions used in a study. A final limitation is the lack of randomization of the baseline, and the fewer trials recorded. All control trials were recorded at the end of the experiment, when it is possible that pronunciation could have changed over the course of the trials, due to familiarization with the methods, or because of manipulation through our various independent variables. In future studies, we will be using two control trials which will be randomized throughout the trials, with one completed during right hand conditions, and the other during left hand conditions.

In conclusion, this paper serves as a cautionary note to researchers examining the interaction of speech and manual action. Everything from the type of target used for prehension, the specifc intent behind the action, to the phase of prehension can change the outcome. Studies in the future may consider using both hands to execute grasping tasks, as cerebral lateralization of speech and manaul movement may not be a delimitor of the interaction between speech and prehension. Finally, these results demonstrate the importance of action intent in research involving prehension.

Chapter 5: General Discussion

5.1 General Discussion

Speech processes influence prehension, and prehensile actions affect speech processes. Beyond this statement, it is difficult to make any further generalizations, at least according to previous studies. A brief review of the literature exposes the complex nature of this multi-dimensional interaction. Studies have used diverse speech tasks and manual motor actions with various measurements leading to wide variation in effects, and sometimes outright conflicting results. To address some of these issues and provide some clarity, this thesis attempted to ascertain the role methodology played in the outcome of interactions between speech and grasping actions. Specifically, we wanted to understand if the interaction between speech and prehension is shaped by ecologically important actions. The investigation was based on two related hypotheses: 1) Speech processing produces a greater effect on ecologically relevant hand actions (e.g. grasp-to-eat) than on actions less vital to our survival (grasp-to-place), and 2) Performing natural, ecologically relevant actions should result in significant changes in speech production, particularly in comparison to less natural movements.

5.1.1 The effect of speech on grasping (Hypothesis One)

To test the effect that speech *processing* could have on grasping, participants executed two different grasping actions while listening to speech. Participants used each hand to perform a grasp-to-eat (highly ecologically relevant) and a grasp-to-place (less ecologically relevant) action while listening to an audiobook (speech trials) or in a control condition with no speech (quiet trials). As in previous studies, there was a hand difference in MGA when executing these tasks during the quiet trials. Right hand MGAs were smaller for the grasp-to-eat versus the grasp-to-place condition. Left handed grasps were not different between the two conditions. However, when executing these actions and listening to speech, participants produced two surprising results: First, there was no interference of speech on the well-established dissociation between grasp-to-eat and grasp-to-place actions with the right hand; and second, participant's left hand differentiated between the two different actions in the same way the right hand did. Against expectations, both the right and left hands demonstrated smaller MGAs between grasp-to-eat and grasp-to-place actions during speech processing. Regarding the first hypothesis, I predicted that listening to speech would change the manual kinematics produced during the grasp-to-eat action, but not the grasp-to-place action. My prediction was partially correct; kinematics of the grasp-to-eat action did change when compared to the grasp-to-place action but only for the left hand. This was unprecedented, as a similar effect has never been observed in adult participants. However, no changes were found in the right hand. A potential explanation is that the hand-to-mouth (grasp-to-eat) action is highly conserved. It is one of the first actions humans execute, occurring as early as the first trimester (Hepper et al., 1998). In non-human primates, researchers have documented several unique neurological organizational patterns, such as neurons tasked specifically with executing a grasp-to-eat action (Bonini et al., 2010; Bonini et al., 2012; Graziano, 2008; Graziano et al., 2005). Without further studies, it is difficult to know, but it is possible that any type of attempted perturbation of hand-to-mouth actions when executed with the right hand would not yield changes.

The appearance of the kinematic differences between actions in the left hand during speech processing needs to be addressed. Smaller MGA patterns during left-handed grasp-to-eat movements had only been observed in young children (Flindall & Gonzalez, 2015).

To explain this effect, the authors proposed an early non-lateralized advantage for the grasp-to-eat action that is followed by a period of neural maturation (with significant pruning of dendritic connections) where the differentiation between actions is lost in the non-dominant right hemisphere (Flindall & Gonzalez, 2015). The results from my thesis suggest a different scenario: That the ability of both hemispheres to differentiate between the two actions remains into adulthood, but (for whatever reason) it is "dormant" in the right hemisphere. When participants are tasked with processing speech however, disinhibition occurs and the phenomenon is observable in both hands. This proposal needs further investigation to assert if only speech processing enables the distinction between the two actions in both hands or, if it is a result of increase cognitive load (dual-taking).

A second possibility is that speech processing activates neural areas in or around the anatomy controlling the hand-to-mouth motor plan of the left hemisphere. During a left-handed action, this speech activated area (even if from the left hemisphere) influences the motor plan of the left hand. Again, this hypothesis needs further investigation.

5.1.2 The Effect of Prehension on Speech (Hypothesis Two)

In the second study, participants performed a series of partial- and full-prehension actions with each hand while producing a simple syllable. There were two different target items that participants interacted with: an apple (requiring a power grasp) and a Froot Loop (requiring a precision grasp). The conditions selected for this study included grasp-alone, reach-alone, grasp-to-place, and grasp-to-mouth manual actions. An additional control condition was included which required participants to produce the syllable without executing a manual movement (no action). Two analyses were completed, one comparing how the four actions differed from the control condition (control analysis), and a second analysis examining specific differences between each action (action analysis), no longer including the control condition. Both analyses were completed three times, once with each formant (F1, F2, and F3). Contrary to my hypothesis, the more ecologically-relevant manual action (grasp-to-mouth) did not affect speech when compared to the control condition. However, all other actions appeared to change (only the grasp-alone condition was significant) syllable production when compared to the control. This is surprising as I expected that more complete, ecologically valid actions (grasp-to-mouth and grasp-to-place) would be significantly different from the control and from the more artificial actions (grasp-alone and reach-alone). In both analyses, the main difference driving the significant results occurs between the most ecologically important action (grasp-to-mouth), and one of the least executed, least natural actions (grasp-alone). The result is reminiscent of the first study, where MGA was not altered in the right hand during a grasp-to-eat action, despite completing a speech processing task. The apparent similarity in formant level between the grasp-to-mouth and no-action condition may reinforce my earlier suggestion that the hand-to-mouth motion is resilient and therefore we will not observe significant interactions between this specific action and speech.

5.1.3 The Role of Lateralization (Prediction Three)

Regarding the third prediction of my thesis, the impact of cerebral lateralization on the relationship between speech and manual action, the results of both studies suggest that although speech processing and production are more specialized to the left hemisphere, speech affected manual actions in both hands, and actions executed with either hand affected speech. Previous studies investigating the interaction between language and prehension have focused on actions executed with the right hand. The studies contained in this thesis are some of the first to systematically investigate speech and prehension interaction using both hands. The presence of significant alterations in both left-hand kinematics and speech (during left-hand actions) indicate that cerebral lateralization of functions—both speech and manual control—may not be as segregated as previously thought. There are many studies which discuss bi-lateral activation present during unilateral manual actions (Ehrsson et al., 2000; Mutha, Haaland, & Sainburg, 2012; Serrien, Ivry, & Swinnen, 2006), as well as during speech processing and production (Meister et al., 2007; Wilson et al., 2004). The results of my studies suggest that the functions of speech and manual movement incur bilateral activation, and therefore, interactions are not limited by proximity within hemispheres.

5.2 Novel Contributions

Both experiments demonstrated an interaction between speech and prehensile movements. This is in line with many of the previously discussed studies where simple manual actions were affected by speech, and these actions influenced speech (Bernardis et al., 2008; Bernardis & Gentilucci, 2006; Dromey & Benson, 2003; Fargier et al., 2012; Gentilucci, 2003; Gentilucci & Gangitano, 1998; Gentilucci et al., 2004a; Gentilucci et al., 2004b; Glover et al., 2004; Rinaldi et al., 2016; Tiainen et al., 2017; Tiainen et al., 2016a; Tiainen et al., 2016b; Vainio et al., 2013; Vainio et al., 2015; Vainio et al., 2014). Yet, despite this large body of evidence regarding the many ways speech and manual actions affect each other, hand-to-mouth actions did not significantly alter speech production. Furthermore, right-hand kinematics during hand-to-mouth movements were not significantly altered by speech processing. In terms of theoretical implications, these results could suggest that the hand-to-mouth action, particularly of the right hand, played a role in developing language. I would like to speculate that due to the importance and older nature. By the same token, it is possible that the lack of speech production changes initiated by the hand-to-mouth action is a reflection of its evolutionarily older adaptation. This highly salient action may have driven the development of language, and speech. Alternatively, it could be that the tasks of speech (both processing and production) are associated with many manual actions, except the hand-to-mouth movement. This possibility is unlikely given the results of the first experiment in which left-handed grasp-to-eat actions were affected by speech. Regardless, this thesis has deepened the understanding of the hand-to-mouth movement, and provided a unique demonstration of the robustness of an evolutionarily important action, the hand-to-mouth.

Perhaps the most surprising finding from both studies was the significant impact of left-handed actions. The existing literature has predominantly focused on examining kinematic changes in the right hand, or alterations in speech production during right-hand movement. The results from both of my experiments, where left-hand kinematics were altered, and able to alter speech, demonstrate that a cerebral lateralization of function does not limit interactions to occur within one hemisphere. In future studies investigating the impact of one modality on the other, researchers must carefully choose their methods. By excluding the left hand, they are forgoing the opportunity to gain a comprehensive insight into the interaction between speech and prehension.

5.3 Limitations

While this thesis provided several valuable insights into the interaction between speech and prehension, several confines within the studies must be addressed. In the first study examining changes in MGA, the role of speech processing is discussed. It is possible that a more cognitively demanding task, such as original speech production, may produce significant changes in right-handed grasp-to-eat actions. The above statements regarding the resiliency of the grasp-to-eat kinematic characteristic can only be applied during speech processing.

A critique that should be addressed is the impact of using edible food while producing speech. In a previous study, authors admitted the possibility that the observed changes in speech are a result of the mouth preparing to eat the presented item, and not a reflection of the speech-prehension interaction (Gentilucci et al., 2004a). The results from my second study, the effect of manual action on speech, indicate this is not the case. The main effect of action indicates that regardless of the size of the target, different actions evoke different changes in speech production.

Another important point for consideration regarding my second study is the control condition. As there were no associated actions, participants completed the condition once, and always last. In our analysis, participants completed all action trials twice, once with each hand. The absence of a second trial required us to compare both the left and right hand with the same control trial. This method of comparison enabled us to measure any changes the actions caused according to the control condition, but any other interactions/results may largely be caused by the lack of natural variation between the “left” control condition and the “right” control condition.

My thesis did not directly assess the effects of action complexity. Planning and executing a grasp-to-eat action requires participants to coordinate the opening and closing of their mouth in conjunction with the reach-to-grasp movement. Compared to a grasp-alone movement, where only digit articulation is required, there are substantially fewer muscle groups involved, and only a single target to account for (i.e. the food item). According to the results, the relatively simpler actions (grasp-alone and reach-alone) appeared to affect speech more than the complete actions (see Figure 5). This could indicate that simpler actions with relatively minimal planning requirements can instigate a greater change in speech production. As the study was not designed to investigate how action complexity affects the interaction of manual movement with speech, this statement is merely speculation.

A final consideration, related to action complexity, is specific to the second study, and questions how the timing of the action influences speech production. In the grasp-alone condition, a significant change in F3 was observed compared to the grasp-to-mouth action. During the grasp-alone action, speech is produced during the movement of the fingers as they purchase the target. In the grasp-to-mouth action (and the grasp-to-place), speech is initiated early in the reaching stage and mostly completed before the grasping component. It is possible that it is not ecological validity, but rather that coordination between the fingers and speech articulators plays a significant role in the interaction between speech and grasping.

5.4 Future directions

The limitations highlight the need for further investigation into the interaction between speech and prehension. The following suggestions are my recommendations for the required next steps to more clearly understand the interaction between these modalities.

An appropriate first step is to determine if speech (processing and syllable production) is the only modality that can produce the observed effect of limited interference with right-handed grasp-to-eat actions. Regarding the first experiment, this exploration is especially important as there are no other studies specifically examining the effect of speech on grasp-to-eat actions. To determine if other processes could exact change on the right-hand kinematics during the grasp-to-eat action, it is important to choose a process similar to speech processing, and with equal or higher cognitive demand. A similar experimental design could be used to compare the grasp-to-eat action with the grasp-to-place action during differently lateralized tasks, such as music processing (right-hemisphere lateralized), or a more demanding speech generation (strongly left-hemisphere lateralized) task. If the kinematic characteristic is not present in the left hand during music processing, but it *is* present during speech production, it would indicate *both* that cognitive demand and lateralization of the task can influence the interaction between speech and grasping. It would also suggest that the neural mechanism responsible for planning the grasp-to-eat motor plan resides in the left hemisphere, or requires left hemisphere activation to be disinhibited.

In the second study, the methods used were modelled after two separate studies, and developed to dissect how different types of hand movements alter speech. I predicted the speech would change during full prehension movements but not during partial movements. The only significant difference between the two types of actions was for the grasp-to-eat and the grasp-alone movements. Arguably the most and least complex actions respectively. But as discussed earlier, in the grasp-alone condition the timing of the enunciation of the syllable was different than in the other three conditions. A study which more carefully pairs the prehension stage with the onset of mouth movement is needed to address if it is the complexity or the timing which determines the interaction.

A final consideration is the role of semantics and affordances. The studies in this thesis were not designed to examine the role of affordances in the interaction between speech and grasping. It would be valuable to conduct a study measuring the kinematics of the grasp-to-eat action during speech production. Instead of syllables, participants would produce the names of different sized target items, during congruent (pronouncing the name of the observed target) and incongruent (pronouncing the name of the unobserved target) conditions. Alteration of kinematics would demonstrate the important role of affordances in the relationship between speech and grasping.

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