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COORDINATION BETWEEN TONGUE AND LOWER LIP IN /W/ PRODUCTION IN ADULT MALE SPEAKERS WITHOUT SPEECH DISORDERS

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ABSTRACT

Acoustic characteristics of /w/ words have been reported to be sensitive to speech intelligibility in speakers with dysarthria. The current study investigates the uniqueness of the /w/ word production. To be specific, the current study was conducted to determine the coarticulatory pattern of the tongue body and lower lip in production of the semivowel /w/. In addition to /w/ words such as "whip", speakers produced /b/ words which have been assumed to have less protrusion of lower lip than /w/. Acoustic and kinematic data was collected from a group of 19 typical male speakers using 3 dimensional electromagnetic articulography. Speakers produced three tokens of each target word: "whip" and "bib". The findings revealed different patterns in both coordination timing as well as tongue and lip movement in "whip" and "bib" production. Interestingly, the amount of lip protrusion was not different between “whip” and “bib” but more tongue retraction was observed in “whip” than “bib”. "Whip" production showed a pattern of greater tongue movement, particularly, tongue advancement when compared to "bib". Further analyses suggested a more synchronous movement between the tongue and lower lip in "whip" production when compared to "bib". Results from the current study will serve as a norm reference for data collected in a future study on speakers with dysarthria.

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Introduction

People with neurological disorders experience various speech production related difficulties. One of the most common speech disorders observed in this population is dysarthria. Dysarthria is a disorder characterized by these neurological speech disturbances (Duffy, 2005). According to Duffy (2005), dysarthria negatively affects the strength, speed, range, steadiness, tone and accuracy of speech movements necessary to the control the respiratory, laryngeal, velopharyngeal, articulatory subsystems and prosodic elements for speech production. Due to these impairments, speakers with dysarthria produce speech that can be difficult for others to understand.

Speech intelligibility is the amount of information that listeners can understand. Decreased speech intelligibility is frequently observed in speakers with dysarthria. Speech intelligibility is also important for understanding the effect of the disorder on the speaker and for tracking the progress of speaker throughout the treatment process (Yorkston, 1978). The ultimate goal of treating dysarthria is to increase speech intelligibility because this measure reflects a speaker's functional communication with others in their daily lives. Speech intelligibility measures are derived from the listener's ability to interpret an acoustic signal. Those who measure speech intelligibility in production rely on measurement techniques based solely on acoustic interpretation.

To understand the speech characteristics in speakers with dysarthria and their influences to speech intelligibility, various studies have been performed. Specifically, the relationship between speech acoustics and speech intelligibility has been extensively investigated. Speech intelligibility in speakers with dysarthia is known to show a strong relationship between different acoustic variables. These include second formant (F2) slope (Weismer et al., 2001), segment durations (Weismer, Jeng, Laures, Kent, & Kent, 2001), vowel formant frequencies (Weismer & Martin, 1992), acoustic vowel space (Turner, Tjaden & Weismer, 1995) and speaking rate (Weismer, Jeng, Laures, Kent, & Kent 2000).

Among these variables, F2 slope has been identified as one of variables that is highly correlated with speech intelligibility in speakers with dysarthria. Kim, Kent and Weismer (2011) studied acoustic characteristics of speakers with dysarthria by examining multiple acoustics measurements including (a) sentence duration, (b) vowel duration, (c) voiceless interval duration, (d) first and second formant frequencies from four corner vowels, (e) first moment for fricatives (/s/ and /ʃ/) during three 50 ms-long windows approaching the vocalic nuclear, (f) transition duration and extent for second formant (F2) transitions, (g) fundamental frequency (F0) contour and (h) RMS intensity contour. Based on the regression analysis between speech intelligibility and the acoustic measures, second formant frequency (F2) slope is found to be sensitive to speech intelligibility Other studies have also shown a correlation between speech intelligibility and F2 slope.

Among these, Kent, Weismer, Kent, Martin, Sufit, Rosenbek, & Brooks (1992) compared women speakers with ALS and typical speakers. A shallower F2 slope was observed in speakers with dysarthria in the word “wax”. Reduced lip rounding in speakers with dysarthria accounts for the shallow slope observed. Yunusova, Green, Greenwood, Wang, Pattee, & Zinman (2012) measured the correlation between F2 slope and speech intelligibility for the word “doily”. The study concluded an r value of = -0.50 (r^2 =.25). Kim, Weismer, Kent, & J.R. Duffy (2009) revealed r values for the words “shoot” (r = .374) and “wax” (r=. 372). From the following studies, it can be concluded that the strength of the relationship between speech intelligibility and F2 varies upon the target word.

Among the target words measured in previous studies, /w/ words are highly correlated with F2 slope and speech intelligibility. Kim, Weismer, Kent, & Duffy (2009) studied the characteristics of F2 slopes in speakers with dysarthria and typical speakers using six different words: coat, hail, sigh, shoot, row and wax. The results concluded that speakers with dysarthria produced reduced F2 slopes when compared to typical speakers except for in one word row. Among these words, the F2 slopes of “shoot” and “wax” showed a significant correlation with speech intelligibility while the other words did not. According to Kim, Weismer, Kent & Duffy (2009) and Lee, Hustad and Weismer (2014), the F2 slope of target words that contain /w/ such as “whip” and “wax” tend to be more sensitive in terms in speech intelligibility. Based on the definition of the dysarthria introduced above, difficulties in coordination among various subsystems including articulators influence people with dysarthria. As certain words’ acoustic characteristics have been identified as a sensitive indicator of speech intelligibility, investigation of the articulatory kinematic characteristics of the words will aid our understanding of the disorder.

The production /w/ words require the articulatory coordination of the lip rounding and the tongue. The issue of coordination of lip and tongue movements was investigated by Weismer, Yunsova and Westbury (2003). Weismer, Yunsova and Westbury (2003) studied the coordination difficulties of speakers with dysarthria. It is known that low F2 of /u/ can be produced by tongue backing/raising and lip protrusion. The study involved 48 participants with and without dysarthria. Each speaker was instructed to read the sentence “She has your dark suit in greasy wash water all year” twice with the word “suit” being the target word. Using an X-ray microbeam technique, kinematic data was recorded. The researchers were interested in the intergesture lag of the three groups of speakers. Intergestural lag is defined by the timing of the relationship between lip separation and tongue retraction movements. In this study, typical speakers showed a minimal amount of intergestural lag. Speakers with dysarthria exhibited a greater intergestural lag, most notably in those with speakers with dysarthria secondary to ALS. These findings suggest a disruption in coordination between the tongue and lower lip in speakers with dysarthria whereas other studies previously deemed coordination as unaffected.

Characteristics of F2 slope are inherently different depending on different sounds. The strength of the relationship between F2 slope and speech intelligibility tends to vary depending on target words (Rosen, Goozee, & Murdoch 1998). As described above, the F2 slope of /w/ seem to be sensitive to speech intelligibility in speakers with dysarthria. It is important to understand the movement pattern of /w/ words which will provide further information in regards to understand speech impairment in speakers with dysarthria.

The purpose of this current study was to identify the coarticulatory pattern of the tongue and the lower lip in /w/ production in adult male speakers without speech disorders. The findings of the quantified coarticulatory characteristics in /w/ production will help in the understanding of articulatory kinematics function in speakers with dysarthria. The amount of displacement in each dimension (e.g., anterior-posterior, superior-inferior) and the time difference between tongue and lip movement were analyzed to identify the required degree of coordination between the tongue and lips in the words “whip.”

The coarticulatory features in /w/ were compared to words that had the “simpler” coarticulatory gestures such a bilabial words in particular those that started with the stop /b/ (e.g., “bib”). Both /b/ and /w/ require active labial movement to produce the sounds, however, the nature and pattern of the movement are quite different. To produce the sound /b/, a labial contact is required to build up the intra-oral pressure before it is released. In comparison, /w/ does not require the labial contact but a certain extent of lip rounding is observed when producing the sound. The acoustic characteristics and differences between /b/ and /w/ have been previously studied by Mack and Blumstein (1983). Based on Mack and Blumstein (1983) findings, they reported that F2 onset transition for /w/ was noticeably lower than F2 for /b/. The interpretation they applied is that the F2 difference reflects the lengthening of vocal tract for /w/ production due to lip rounding and protrusion. The study conducted by Mack and Blumstein was based solely on acoustic findings. The present study in this paper is currently focusing on the relationship between the acoustic characteristics and the kinematic findings of /b/ and /w/.

Due to the notable difference in lip gesture for /b/ and /w/, the acoustic characteristics of these sounds have been studied as reported above. However, its influence to the kinematic execution remains unknown. As /w/ words have been reported to be sensitive to speech intelligibility in speakers with dysarthria, the kinematic characteristics of the sounds will be investigated in the current study. In addition, the kinematic characteristics of /w/ will be compared to the bilabial /b/-words when other surrounding sounds are identical to capture the prominent kinematic characteristics of /w/. The data collected will be used as a norm reference to data collected on speakers with dysarthria.

Method

Speakers

The current study included 19 typical male speakers between the ages of 18-28. The participants included in this study were from Pennsylvania, central New Jersey and surrounding areas of New York. All participants were required to meet certain criteria in order to participate. Participants involved with the study were between the ages of 18 to 28, a young adult male, a native speaker of American English and from one of three areas listed above. Additionally, these speakers were to be free from any known disorders and have no history of medications. All participants passed a bilateral hearing screening at 25 dB HL for the frequencies of 250, 500, 1000, 1000, 2000, 4000, and 6000 Hz was administered. IRB approval was given by the Pennsylvania State University.

Materials

For this study, consonant-vowel-consonant words with /w/ and /b/ such as *whip* and *bib* were utilized. Each target word was embedded in the following carrier phrase: “I say a _____ again”. Each speaker produced three repetitions of the token word using a habitual speaking manner.

Procedures

Data samples were collected using 3-dimensional electromagnetic articulography: WAVE system (Northern Digital Inc.). The WAVE system gathered both acoustic and kinematic information through various sensors. Sensors were attached to the speaker’s tongue tip (approximately 10 mm from tongue apex), tongue body (approximately 110 mm from tongue tip sensor), lower lip and jaw on the midsagittal plane. Sampling rate of the kinematic data was 100Hz. For the current study, data from sensors on the tongue body and lower lip were analyzed. Each participant was given two minutes to familiarize themselves to the sensors before beginning the task.

Analyses

Acoustic analyses. Acoustic data was analyzed using a TF32 (Milenkovic, 2002). Word starting time point and vowel ending time point of each target word were collected using waveform and spectrogram displays on TF32. These temporal boundaries were used for kinematic data analyses.

Kinematic Analyses. The kinematic data collected were rotated to the speaker's bite plane. The kinematic data (tongue body and lower lip) of the target segment were extracted based on the temporal boundaries provided by acoustic data. Data were collected from a three dimensional plane; therefore, have three coordinates x, y, and z. Figure 1 displays the orientation of the speaker relative to both x and y planes. X coordinate values increase as the target articulator moves forward. Y coordinate values increase as the target articulator moves upward. Z coordinate values increase as the target articulator moves to the speaker's right side.

Both /w/ and /b/ target words were analyzed. Time interval between incremental kinematic data was 10 ms (sampling rate of 100Hz). The following measures for the tongue and lower lip were calculated for the current study.

Tongue Body Measures

Tongue 3-dimensional (3D) Euclidean Distance (ED). 3D Euclidean distance (ED) (x, y, and z) was used to calculate the overall distance of tongue involved in each target word production. ED was measured between the kinematic data of each time interval and summed throughout the target segment. Euclidean distance of each interval was calculated using the following formula:

> Square root ((tongue x timepoint 2 – tongue x timepoint 1)* (tongue x timepoint 2 – tongue x timepoint 1) + (tongue y timepoint 2 – tongue y timepoint 1)* (tongue y timepoint 2 – tongue y timepoint 1) + (tongue z timepoint 2 – tongue z timepoint 1)* (tongue z timepoint 2 – tongue z timepoint 1))

Tongue X Distance. The changes of x coordinate values between each time interval were measured. These changes were summed across the target segment to determine the amount of x distance. This variable is employed to determine the *direction* of movement in x-axis (anterior-posterior). A positive number of tongue x distance represents the tongue advancement. (tongue x timepoint 2 – tongue x timepoint 1)

Tongue Absolute X Distance. The absolute changes of x coordinate values between each time interval were measured. Absolute values of tongue x distance presented above were used to calculate the absolute x distance. These changes were summed across the target segment. This variable is employed to determine the *total amount* of tongue movement in the x-axis (anterior-posterior). Absolute value of (tongue x timepoint 2 – tongue x timepoint 1)

Tongue Minimum X Position. Throughout the target segment, the minimum x position was collected. This would represent maximum tongue retraction position while producing the target word.

Tongue Y Distance. The changes of y coordinate values between each time interval were measured. These changes were summed across the target segment to determine the amount of y distance. This variable is employed to determine the *direction* of movement in y-axis (inferior-superior). A positive number of tongue y distance represents upward tongue movement. (tongue y timepoint 2 – tongue y timepoint 1)

Tongue Absolute Y Distance. The absolute changes of y coordinate values between each time interval were measured. Absolute changes were summed across the target segment to determine the amount of y distance. This variable is employed to determine the *total amount* of tongue movement in the y-axis (inferior-superior). Absolute value of (tongue y timepoint 2 – tongue y timepoint 1)

Tongue Z Distance. The changes of z coordinate values between each time interval were measured. These changes were summed across the target segment to determine the amount of z distance. This variable is employed to determine the *direction* of movement in z-axis (right-left). A positive number of tongue z distance represents tongue movement towards the right side of the speaker. (tongue z timepoint 2 – tongue z timepoint 1)

Tongue Absolute Z Distance. The absolute changes of z coordinate values between each time interval were measured. Absolute changes were summed across the target segment to determine the amount of z distance. This variable is employed to determine the *total amount* of tongue movement in the z-axis (right-left). Absolute value of (tongue z timepoint 2 – tongue z timepoint 1)

Lower Lip Measures

Lower Lip 3-dimensional (3D) Euclidean Distance (ED). Euclidean distance was used to calculate the overall distance of lower lip involved in each target word production. ED was measured between the kinematic data of each time interval and summed throughout the target segment. Euclidean distance of each interval was calculated using the following formula:

Square root ((lower lip x timepoint 2 – lower lip x timepoint 1)* (lower lip x timepoint 2 – lower lip x timepoint 1) + (lower lip y timepoint 2 – lower lip y timepoint 1)* (lower lip y timepoint 2 – lower lip y timepoint 1) + (lower lip z timepoint 2 – lower lip z timepoint 1)* (lower lip z timepoint 2 – lower lip z timepoint 1))

These values were summed throughout the target segment.

Lower Lip X Distance. The changes of lower lip x coordinate values between each time interval were measured. These changes were summed across the target segment to determine the amount of lower lip x distance. This variable is employed to determine the *direction* of movement in x-axis (anterior-posterior). A positive number of lower lip x distance represents the lip protrusion. (lower lip x timepoint 2 – lower lip x timepoint 1)

Lower Lip Absolute X Distance. The absolute changes of x coordinate values between each time interval were measured. Absolute changes were summed across the target segment to determine the amount of lower lip x distance. This variable is employed to determine the *total amount* of lower lip movement in the x-axis (anterior-posterior). Absolute value of (lower lip x timepoint 2 – lower lip x timepoint 1)

Lower Lip Y Distance. The changes of y coordinate values between each time interval were measured. These changes were summed across the target segment to determine the amount of y distance. This variable is employed to determine the *direction* of movement in y-axis (inferior-superior). A positive number of lower lip y distance represents upward lower lip movement. (lower lip y timepoint 2 – lower lip y timepoint 1)

Lower Lip Absolute Y Distance. The absolute changes of y coordinate values between each time interval were measured. Absolute changes were summed across the target segment to determine the amount of y distance. This variable is employed to determine the *total amount* of lower lip movement in the y-axis (inferior-superior). Absolute value of (lower lip y timepoint 2 – lower lip y timepoint 1)

Lower Lip Z Distance. The changes of z coordinate values between each time interval were measured. These changes were summed across the target segment to determine the amount of z distance. This variable is employed to determine the *direction* of movement in z-axis (right-left). A positive number of tongue z distance represents lower lip movement towards the right side of the speaker. (lower lip z timepoint 2 – lower lip z timepoint 1)

Lower Lip Absolute Z Distance. The absolute changes of z coordinate values between each time interval were measured. Absolute changes were summed across the target segment to determine the amount of z distance. This variable is employed to determine the *total amount* of lower lip movement in the z-axis (right-left). (lower lip z timepoint 2 – lower lip z timepoint 1)

Time-lag Measures

Time-lag measures were calculated to better understand the timing of articulator movement during target word production. The time-lag data in typical speakers in the current study will provide norm values in a future study. In the current study, time-lag between tongue and lower lip is employed to determine the required coordination for the production of each target word.

To obtain time-lag information between the tongue and lower lip, three different timepoints were measured: the timepoint of minimum x position of tongue (maximum tongue retraction), the timepoint of maximum x position of lower lip (maximum lip protrusion), and the timepoint of minimum y position of lower lip (maximum lip opening). Using these timepoint values, two different time-lag variables were measured. One was to determine the time-lag between tongue retraction and lip protrusion (Absolute Time-lag 1) and another was to determine the time-lag between tongue retraction and lip opening (Absolute Time-lag 2).

Absolute Time-lag 1. Absolute Time-Lag 1 is the calculated difference between the time point of minimum-x position (retraction) of the tongue and the time point of maximum x-position (protrusion) of the lower lip. The following formula was used: *Time-lag 1 = Absolute value of (tongue minimum-x time point – lip maximum-x time point)* In addition to the Time-lag 1, articulatory movement sequence data for Time-lag 1 were collected to determine which articulator occurred first (lip protrusion or tongue retraction). All segments were coded using the following system: 0 (tongue first), 1 (lip first), and 2 (simultaneously).

Absolute Time-lag 2: The calculated difference between the time point of the minimum-x position (retraction) of the tongue and minimum y-position of the lower lip (maximum lip opening). The following formula was used: *Time-lag 2 = Absolute value of (tongue minimum-x time point – lower lip minimum-y time point)* In addition to the Time-lag 2, articulatory movement sequence data for Time-lag 2 were collected to determine which articulator occurred first (lip opening or tongue retraction). All segments were coded using the following system: 0 (tongue first), 1 (lip first), and 2 (simultaneously).

Experimental Design and Analysis

A paired t-test was conducted to compare the following measures between *whip* and *bib*: tongue 3-dimensional (3D) Euclidean Distance (ED) tongue X distance, tongue absolute X distance, tongue Y distance, tongue absolute Y distance, tongue Z distance, tongue absolute Z distance, lower lip 3-dimensional (3D) Euclidean Distance (ED), lower lip X distance, lower lip absolute X distance, lower lip Y distance, lower lip absolute Y distance, lower lip Z distance, lower lip absolute Z distance, absolute time-lag 1, time-lag 1 sequence, absolute time-lag 2, and time-lag 2 sequence.

Results

Table 1 shows the descriptive data of the tongue and lower lip distances and the time lag measures during the production of “whip and “bib”. Table 2 displays the statistical data of the tongue and lower lip distances and the time lag measures during the production of “whip” and “bib” target words.

Tongue Kinematic Variables

Tongue Euclidean Distance. Tongue Euclidean distance reveals the overall distance of the tongue movement during the production of the target word. As displayed in Table 1 and Figure 2, the average distance of the overall tongue movement during “whip” production was 8.61 mm with a standard deviation of 2.98 mm. The average distance of the overall tongue movement during the production of “bib” was 3.4 mm with a standard deviation of .28 mm. The overall distance during tongue movement was greater during “whip” production than “bib”. The results of these findings were statistically significant, as seen in Table 2 ($p < .001$). This value indicates that the overall amount of the tongue movement was greater during the production of “whip” versus “bib”.

Tongue X Distance. A greater Tongue X Distance during target word production indicates the direction of tongue movement (anterior-posterior). In this variable, a positive numeric value is related to tongue advancement and a negative numeric value is related to tongue retraction. As displayed in Table 1, there was greater advancement of the tongue during the production of “whip” rather than “bib.” The average distance changes of the tongue during “whip” production was 6.11 with a standard deviation of 3.06 while the production of “bib” averaged a distance change of -.75 and a standard deviation of .20. A larger standard deviation for the production of “whip” as compared to “bib” can be attributed to variability of tongue advancement among speakers. The findings of this measure were statistically significant, as seen in Table 2. ($p < .001$). These results indicate greater tongue advancement during the production of “whip” versus “bib” words.

Tongue Absolute X Distance. A greater Tongue Absolute X Distance during target word production indicates the total amount of tongue movement in the x-axis (anterior-posterior). As displayed in Table 1 and Figure 3, the total amount of tongue movement in the horizontal plane (anterior-posterior) was greater during the production of “whip” versus “bib” target words. The average distance changes of the tongue during “whip” production was 7.20 mm with a standard deviation of 2.69 mm while the production of “bib” averaged a distance change of 2.09 mm and a standard deviation of 1.53 mm. The findings of this measure were statistically significant, as seen in Table 2 ($p < .001$). These results indicate a greater total tongue movement in the x-axis (anterior-posterior) during the production of “whip” versus “bib” words.

Tongue Minimum X Position. A lesser tongue minimum x position value was observed in “whip” than “bib”. The average minimum x position for “whip” was -34.53 mm with a standard deviation of 1.55 mm. The average minimum x position for “bib” was -27.72 mm with a standard deviation of 1.59 mm. This indicates that the tongue retracted more for “whip” production than “bib”. The statistical result showed that this effect is significant as seen in Table 2 ($p <.001$).

Tongue Y Distance. A greater Tongue Y Distance during target word production indicates the direction of tongue movement (inferior-superior). In this variable, a positive numeric value is related to upward tongue movement and a negative numeric value is related to lowering tongue movement. As displayed in Table 1, there was greater upward tongue height change during the production of “whip” rather than “bib”. The average distance changes of the tongue height during “whip” production was .62 mm with a standard deviation of 2.01mm, whereas the production of “bib” had an average distance change of -.75 mm and a standard deviation of 2.03 mm. The findings of this measure were statistically significant, as seen in Table 2 (p < .001). These results indicate a greater upward tongue height during the production of “whip” versus “bib” target words.

Tongue Absolute Y Distance. A greater Tongue Absolute Y Distance during target word production indicates the total amount of tongue movement in the y-axis (inferior-superior). As displayed in Table 1, the total amount of tongue movement in the vertical plane (inferior-superior) during the production of “whip” was slightly greater than “bib”. The average distance changes of the tongue during “whip” production was 2.63 mm with a standard deviation of 1.40 mm while the production of “bib” averaged a distance change of 2.17 mm and a standard deviation of 1.55 mm. The findings of this measure were not statistically significant to the study, as seen in Table 2 (p < .063). This value indicates that total tongue movement in the y-axis during the production of “whip” and “bib” was not meaningful to the study.

Tongue Z distance. A greater Tongue Z Distance during target word production indicates the direction of tongue movement (left-right). In this variable, a positive numeric value is related to tongue movement toward the right side of the speaker and a negative numeric value is related to tongue movement towards the left side of the speaker. As displayed in Table 1, there was greater tongue movement towards the left side during the production of “whip” rather than “bib” which had more tongue movement towards the right side. The average distance changes of the tongue during “whip” production was -.12 mm with a standard deviation of 1.83 mm, whereas the production of “bib” had an average distance change of .21 mm and a standard deviation of .56 mm. The findings of this measure were not statistically significant, as seen in Table 2. (p = .207). These results indicate that the direction of the tongue movement towards the right or left side of the speaker was not significantly different between “whip” and “bib”.

Tongue Absolute Z distance. A greater Tongue Absolute Y Distance during target word production indicates the total amount of tongue movement in the z-axis (left-right). As displayed in Table 1, the total amount of tongue movement either to the left or ride side of speaker during the production of both “whip” and “bib” was consistent with the right side of the speaker. The average distance changes of the tongue during “whip” production was 1.92 mm with a standard deviation of 1.37 mm, whereas the production of “bib” had an average distance change of .92 mm and a standard deviation of .64 mm. The findings of this measure were statistically significant to the study, as seen in Table 2. ($p < .001$). These results indicate a greater total tongue movement towards the right ride of the speaker during the production of “whip” versus “bib” words.

Lower Lip Kinematic Variables

Lower Lip Euclidean Distance. Lower Lip Euclidean Distance reveals the overall distance of the lower lip movement during the production of the target word. As displayed in Table 1, the average distance of the overall lower lip movement during “whip” production was 5.35 mm with a standard deviation of 1.93 mm. The average distance of the overall lower lip movement during the production of “bib” was 5.60 mm with a standard deviation of 2.97mm. The overall distance during lower lip movement was greater during “bib” production than “whip”. The results of these findings were not statistically significant, as seen in Table 2 (p = .527). This value indicates that the overall distance of lower lip movement was not significant when comparing “whip” and “bib” words.

Lower Lip X Distance. A greater lower lip X Distance during target word production indicates the direction of lower lip movement in the x-axis (anterior-posterior). In this variable, a positive numeric value is related to lip protrusion and a negative numeric value is related to maximum lip opening. As displayed in Table 1, there was greater lip protrusion during the production of “bib” rather than “whip”. The average distance changes of the lower lip during “whip” production was -.19 mm with a standard deviation of 1.22 mm and the production of “bib” had an average distance change of .29 mm and a standard deviation of 1.04 mm. The findings of this measure were not statistically significant, as seen in Table 2. (p = .632). These results indicate that lip protrusion during the production of “whip” or “bib” was not significant to the study.

Lower Lip Absolute X Distance. A greater lower lip Absolute X Distance during target word production indicates the total amount of lower lip movement in the x-axis (anterior-posterior). As displayed in Table 1, the total amount of lower lip movement in the horizontal plane during the production of “whip” was slightly less than “bib”. The average distance changes of the lower lip during “whip” production was 2.04 mm with a standard deviation of 1.08 mm and the production of “bib” had an average distance change of 2.17 mm and a standard deviation of 1.38 mm. The findings of this measure were not statistically significant, as seen in Table 2 (p = .400). These results indicate that total lower lip movement in the horizontal plane during the production of “whip” versus “bib” words was not significant to the current study.

Lower Lip Y Distance. A greater lower lip Y Distance during target word production indicates the direction of lower lip movement in the y-axis (inferior-superior). In this variable, a positive numeric value is related to upward lower lip movement and a negative numeric value is related to the lowering of the lower lip. As displayed in Table 1, there was greater downward movement of the lower lip during the production of “whip” rather than “bib”. The average distance changes of lower lip upward movement of the lower lip during “whip” production was. -1.04 mm with a standard deviation of 1.85 mm, whereas the production of “bib” had an average distance change of .38 mm and a standard deviation of 1.10 mm. The findings of this measure were statistically significant, as seen in Table 2 ($p < .001$). These results indicate more downward lower lip movement during the production of “whip” versus the production of “bib” words.

Lower Lip Absolute Y Distance. A greater lower lip Absolute Y Distance during target word production indicates the total amount of lower lip movement in the y-axis (inferior-superior). As displayed in Table 1, the total amount of lower lip movement in the vertical plane during the production of “whip” was less than “bib”. The average distance changes of the lower lip during “whip” production was 3.95 mm with a standard deviation of 1.73 mm, whereas the production of “bib” had an average distance change of 4.58 mm and a standard deviation of 2.67 mm. The findings of this measure were not statistically significant to the study, as seen in Table 2 ($p = .110$). These results indicate that total lower lip movement in the y-axis during the production of “whip” versus the production of “bib” words was not significant to the study.

Lower Lip Z distance. A greater Lower lip Z Distance during target word production indicates the direction of lower lip movement in the z-axis (left-right). In this variable, a positive numeric value is related to movement towards the right side of the speaker and a negative numeric value is related to movement towards the left side of the speaker. As displayed in Table 1, both “whip” and “bib” production of target words were consistent with lower lip movement towards the right side of the speaker. The average distance changes of the lower lip towards the right side of the speaker during “whip” production was -0.13 mm with a standard deviation of

1.59 mm and the production of “bib” had an average distance change of -0.09 mm and a standard deviation of 0.91 mm. The findings of this measure were not statistically significant, as seen in Table 2 (p = .882). These results indicate that the direction of the lower lip movement towards the right or left side of the speaker was not significantly different between “whip” and “bib”.

Lower Lip Absolute Z distance. A greater Lower lip Absolute Y Distance during target word production indicates the total amount of lower lip movement in the z-axis. As displayed in Table 2, both “whip” and “bib” production showed lower lip movement towards the right side of the speaker. The average distance changes of the lower lip during “whip” production was 1.72 mm with a standard deviation of 1.23 mm, whereas the production of “bib” had an average distance change of 1.31 mm and a standard deviation of .90 mm. The findings of this measure were statistically significant to the study, as seen in Table 2 (p = .038). This value results indicate that total lower lip movement towards the right side was greater during the production of “whip” when compared to the production of “bib” target words.

Time-lag Variables

Absolute Time-lag 1. Absolute Time-lag 1 was measured to determine the time lag between lip protrusion (lower lip maximum x protrusion) and tongue retraction (tongue minimum x position). As displayed in Table 1 and Figure 4, the time lag was shorter for the production of “whip” rather than “bib”. This means the production of “whip” required less time for the articulators to reach tongue minimum x position (tongue retraction) and maximum x-position (protrusion) of the lower lip. The average time-lag of “whip” production was -.055 s with a standard deviation of .052 s. The average time-lag of “bib” production was .093 s with a standard deviation of .066 s. The findings of this measure were statistically significant as seen in

Table 2 ($p < .001$). These results reveal that maximum tongue retraction and maximum lip protrusion occurred more simultaneously for “whip” production.

Time-lag 1 Sequence. The current study measured the order in which articulator movement occurred during target word production. A sequencing system was implemented to determine the order in which tongue (maximum tongue retraction) and lower lip (maximum lip protrusion) movement occurred. As mentioned in the Method section, a dummy code was assigned to each token depending on the articulator that showed the extreme position first: 0 (tongue first), 1 (simultaneously), and 2 (lip first). In Table 1, the average of the time-lag 1 sequence for “whip” is .667 s. This indicates that, for “whip” production, either maximum tongue retraction occurred first followed by maximum lip protrusion or both actions occurred simultaneously. The average of the time-lag 1 sequence for “bib” is 1.404 s. This indicates that, for “bib” production, either maximum lip protrusion occurred first followed by maximum tongue retraction or both actions occurred simultaneously. The findings were statistically significant to the study, as seen in Table 2 ($p < .001$).

Absolute Time-lag 2. The current study measured absolute time lag 2 to determine the time lag between lip opening (lower lip minimum-y position) and tongue retraction (tongue minimum-x position. As displayed in Table 1 and Figure 5, the time lag was greater for the production of “whip” rather than “bib”. This means that production of “whip” required more time for the articulators to reach minimum y position (lip opening) and minimum x position (tongue retraction) . The average time-lag of “whip” production in the study was .073 s with a standard deviation of .025. The average time-lag of “bib” production was -.064 s with a standard deviation of .032. These findings were statistically significant as seen in Table 2 ($p = .099$). It was concluded that the time-lag between articulator movements during the production of the word “whip” and “bib” was not significant to the study.

Time-lag 2 Sequence. The current study measured the order in which articulator movement occurred during target word production. A sequencing system was implemented to determine the order in which tongue (maximum tongue retraction) and lower lip movement (maximum lip opening) occurred. For this analysis, a dummy code was assigned to each token depending on the articulator that showed the extreme position first: 0 (tongue first), 1 (simultaneously), and 2 (lip first). In Table 1, the average of the time-lag 2 sequence for “whip” is .123 s. This indicates that, for “whip” production, maximum tongue retraction occurred first followed by maximum lip opening. The average of the time-lag 2 sequence for “bib” is 1.544 s. This indicates that, for “bib” production, maximum lip opening occurred first followed by maximum tongue retraction. The findings were statistically significant to the study, as seen in Table 2 ($p < .001$).

Discussion

The current study was conducted to identify the coarticulatory pattern of the tongue and lower lip during the production of /w/ words produced by adult male speakers without speech disorders. From previous research, it is known that F2 slope is a strong predictor of speech intelligibility in speakers with dysarthria (Kent, Weismer, Kent, Martin, Sufit, Rosenbeck, & Brooks, 1989). The strength of the relationship between F2 slope and speech intelligibility relies heavily on the target word produced (Rosen, Goozee, & Murdoch, 1998). The F2 slope of /w/ target words such as “wax” and “whip” are known to be sensitive to speech intelligibility (Kim, Weismer, Kent & Duffy, 2009; Lee, Hustad, & Weismer, 2014). The current study investigates the kinematic characteristics required for the production of “whip.” The kinematic features in “whip” were also compared to “bib” which contains the same vowel /ɪ/ and requires less coarticulation. Findings showed that the coordination timing and tongue and lip movement patterns are different between “whip” and “bib”. In the following section, the findings are elaborated by articulators in addition to the topic of coordination timing.

Lip Movement

As described in previous literature, Mack and Blumstein (1983) reported a lower F2 onset transition for /w/ versus /b/ production. A lower F2 was speculated to occur because of a lengthened vocal tract during /w/ production which requires lip rounding and lip protrusion. While Mack and Blumstein’s study was based on acoustic findings, the current study investigated the relationship between both acoustic and kinematic findings of each target word. Contrary to Mack and Blumstein’s interpretation, the current study revealed that lip protrusion was not significantly different in the production “whip” compared to “bib.” This finding can be explained by the variability of lower lip movements across speakers. Additionally, more downward lip movement was observed in “whip” when compared to “bib” as seen in Figure 7.

Perkell, Matthies, Svirsky, and Jordan (1992) were interested in limiting the variability of F2 slope across speakers producing /u/. /u/ is similar to the production of /w/ as it requires tongue retraction and lip rounding. Tongue and lip movements were measured from each participant using an electro-magnetic midsagittal articulometer (EMMA). Speakers in Perkell et al. (1992) were able to achieve production of /u/ by manipulating different parts of the pharyngeal oral subsystem other than lip rounding while keeping a consistently lower F2 value. This process is described by the Motor Equivalence Theory. The motor equivalence theory explains the phenomenon when speakers are able to produce the same acoustic goal with various vocal tract configurations. This theory can help explain why lip protrusion was not exhibited by the speakers of the current study. These speakers likely achieved /w/ production by configuring their vocal tract in a way to produce their acoustic goal without exhibiting lip protrusion.

Tongue Movement

In contrast, greater tongue movement and tongue advancement was seen during the production of “whip” when compared to “bib.” The current study showed that the production of “whip” requires greater tongue movement, particularly in horizontal dimension. These movement patterns can be seen in Figure 6. Additionally, more tongue retraction was observed in “bib” when compared to “bib”. This finding reveals more space within the vocal tract for the greater amount of movement required for “whip” production. The word “whip” is selected for the current study due to its sensitivity to speech intelligibility in speakers with dysarthria. Based on the current finding, the greater tongue movement that is required for this word makes it more challenging for speakers with dysarthria to produce the word. Therefore, it is hypothesized that the reason F2 slope of /w/ words was sensitive to speech intelligibility in speakers with dysarthria is partly due to its required greater tongue movement.

Previous studies in tongue movement in speakers with dysarthria showed that the control of tongue movement for speech production is impaired. Murdoch, Spencer, Theodoros and Thompson have previously found that tongue movements were more affected than lip movements in speakers with Multiple Sclerosis (1998). Similarly, Hartelius and Lillvick (2003) also found impaired tongue movement in speakers with dysarthria. Wong, Murdoch, and Whelan (2012) were also interested in lingual movement in speakers with dysarthria secondary to Parkinson’s disease (PD). It was concluded from the study that speakers with PD exhibited more lingual movement resulting in a longer duration and increased range of movement. Interestingly, in Kuruvilla, Green, Yunusova, & Hanford (2012), speakers with more severe dysarthria presented with less tongue movement. Even though these findings are conflicted, it is clear that the control of lingual movements is affected in speakers with dysarthria. How the impairment of lingual movement control impacts on “whip” production remains unknown. The data recorded from the current study will be used as a norm reference for speakers with dysarthria.

Coordination Timing

As previously mentioned, time-lag 1 was measured to determine the time-lag between maximum lip protrusion and maximum tongue retraction. Time-lag 1 revealed a shorter time lag for “whip” rather than “bib.” This result indicates that maximum tongue retraction and maximum lip protrusion occur more simultaneously for “whip” production. This finding also suggests more synchronous coordination of the lower lip and tongue in “whip” production versus “bib.” The sequencing pattern for “whip” revealed that either maximum tongue retraction occurred first following maximum lip protrusion or both actions occurred simultaneously. The sequencing pattern for “bib” indicated that either maximum lip protrusion occurred first followed by maximum tongue retraction or both actions occurred simultaneously.

Time-lag 2 measured the time-lag between maximum lip opening and maximum tongue retraction. The sequencing pattern for “whip” concluded that maximum tongue retraction occurred first followed by maximum lip opening. For “bib” production, the sequencing pattern confirmed that lip opening occurred first followed by maximum tongue retraction. This finding suggested depending on the initial consonant, the coordination patterns of lips and tongue are different.

Limitations

The findings of the current study need to be interpreted and applied carefully considering the following limitations. The study included 19 speakers which is a small sample size. A small sample size can limit generalization across populations. It is also important to keep in mind that subjects of this study were male speakers without disorders who were between ages 18-28. The current study did not include female speakers and did not include any participants outside of the 18-28 age range.

Summary

In the current study, conclusions were made using lip and tongue movement data as well as coordination timing and sequencing. In regards to lip movement, more lip protrusion was not observed in typical speakers during the production of “whip” than “bib”. This suggests that speakers achieved “whip” production through the manipulation of other parts of their pharyngeal oral subsystem and not necessarily through lip protrusion. Greater tongue movement and increased tongue advancement was exhibited by speakers during the production of “whip” when compared to “bib”. This indicates that the production of “whip” requires greater tongue movement in the horizontal plane when compared to “bib”. In addition, the amount of lip protrusion was not significantly different between “whip” and “bib” production however more tongue retraction was observed in “whip” than “bib”. Timing difference and the order of articulator movement sequence were examined and showed that a more synchronous movement between the tongue and lower lip in “whip” production.

The coarticulatory pattern between the tongue and lower lip in “whip” was examined due to the previous findings in speakers with dysarthria. It is known that the F2 slope of words such as “whip” and “wax” are sensitive to speech intelligibility (Kim, Weismer, Kent & Duffy, 2009; Lee, Hustad, & Weismer, 2014). Based on this information, /w/ words such as “whip” were chosen for the study due to its unique characteristics. Additionally, the features of “whip” were compared to “bib” which was assumed to have different lip protrusion movement (Mack and Blumstein, 1983). The current study revealed that “whip” production differed from “bib” production. Most notably, “whip” required increased tongue movement, especially in the horizontal dimension. It is speculated that this increased tongue movement required in /w/ production may be more difficult for speakers with dysarthria to coordinate than the typical speakers. The current data will serve as norm reference when examining the coarticulatory pattern of “whip” in speakers with dysarthria in the future.

Appendix A

Tables

Table 1. *Descriptive Data of tongue and lip distance and time-lag measures.*

Variable	Target Word	Mean	Standard Deviation
Tongue 3D ED Sum (mm)	*whip*	8.61	2.98
	bib	3.47	2.17
Tongue X Distance (mm)	*whip*	6.11	3.06
	bib	-0.76	1.51
Tongue Absolute X Distance (mm)	*whip*	7.20	2.69
	bib	2.09	1.53
Tongue Minimum X Position (mm)	*whip*	-34.53	1.55
	bib	-27.71	1.59
Tongue Y Distance (mm)	*whip*	0.62	2.01
	bib	-0.75	2.03
Tongue Absolute Y Distance (mm)	*bib*	2.63	1.40
	bib	2.17	1.55
Tongue Z Distance (mm)	*whip*	-.12	1.83
	bib	.21	0.56
Tongue Absolute Z Distance (mm)	*whip*	1.92	1.37
	bib	0.92	0.64
Lower Lip 3D ED Sum (mm)	*whip*	5.35	1.93
	bib	5.60	2.97
Lower Lip X Distance (mm)	*whip*	-0.19	1.22
	bib	0.29	1.04
Lower Lip Absolute X Distance (mm)	*whip*	2.04	1.08
	bib	2.17	1.38
Lower Lip Y Distance (mm)	*whip*	-1.04	1.85
	bib	0.38	1.10

Lower Lip Absolute Y Distance (mm)	*whip*	4.00	1.73
	bib	4.58	2.66
Lower Lip Z Distance (mm)	*whip*	-0.13	1.59
	bib	-0.09	.91
Lower Lip Absolute Z Distance (mm)	*whip*	1.72	1.23
	bib	1.31	.90
Absolute Time- Lag 1 (s)	*whip*	0.055	0.05
	bib	0.093	0.07
Time-Lag 1 Sequence	*whip*	0.667	0.83
	Bib	1.403	0.78
Absolute Time-Lag 2 (s)	*whip*	0.073	0.02
	bib	0.064	0.03
Time-Lag 2 Sequence	*whip*	0.123	0.47
	bib	1.544	0.80

Table 2. *Paired-Sample T-test Statistical Results of tongue and lower lip distance and time lag measures.*

Variable	t	df	p-value
Tongue 3D ED*	12.43	56	<.001
Tongue X Distance *	15.17	56	<.001
Tongue Absolute X Distance*	13.96	56	<.001
Tongue Minimum X Position*	-10.94	56	<.001
Tongue Y Distance*	3.74	56	<.001
Tongue Absolute Y Distance	1.90	56	.063
Tongue Z Distance	-1.28	56	.207
Tongue Absolute Z Distance*	5.94	56	<.001
Lower Lip 3D ED Sum	-0.64	56	.527
Lower Lip X Distance	0.48	56	.632
Lower Lip Absolute X Distance	-0.85	56	.400
Lower Lip Y Distance*	-4.91	56	<.001
Lower Lip Absolute Y Distance	-1.63	56	.110
Lower Lip Z Distance	-0.15	56	.882
Lower Lip Absolute Z Distance*	2.13	56	.038
Absolute Time- Lag 1	-3.45	56	<.001
Time-Lag 1 Sequence*	-5.16	56	<.001
Absolute Time-Lag 2	1.68	56	.099
Time-Lag 2 Sequence*	-11.37	56	<.001

*indicates a significant main effect (p<0.05)

Appendix B

Figures

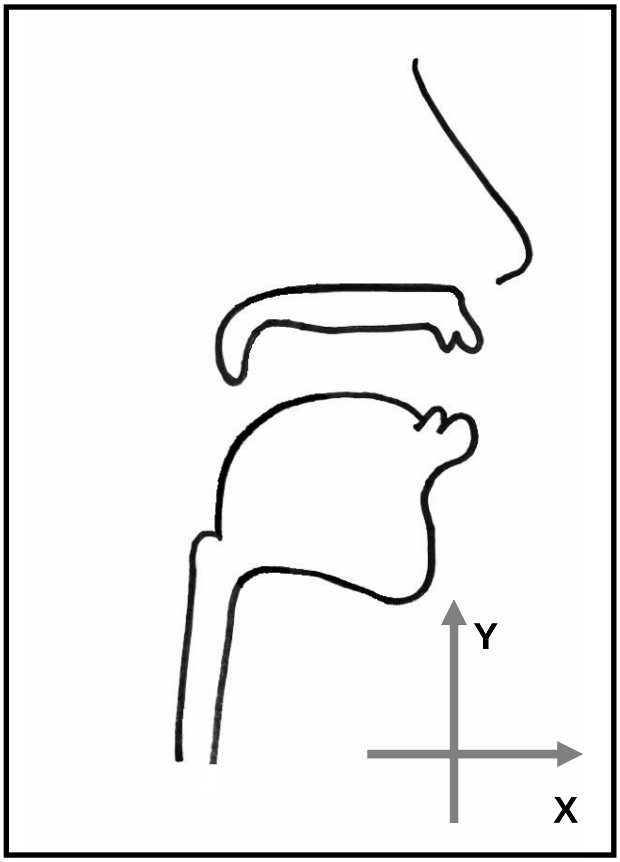

Figure 1. This figure displays the head orientation of each speaker involved in the current study. It includes visuals of both X and Y planes.

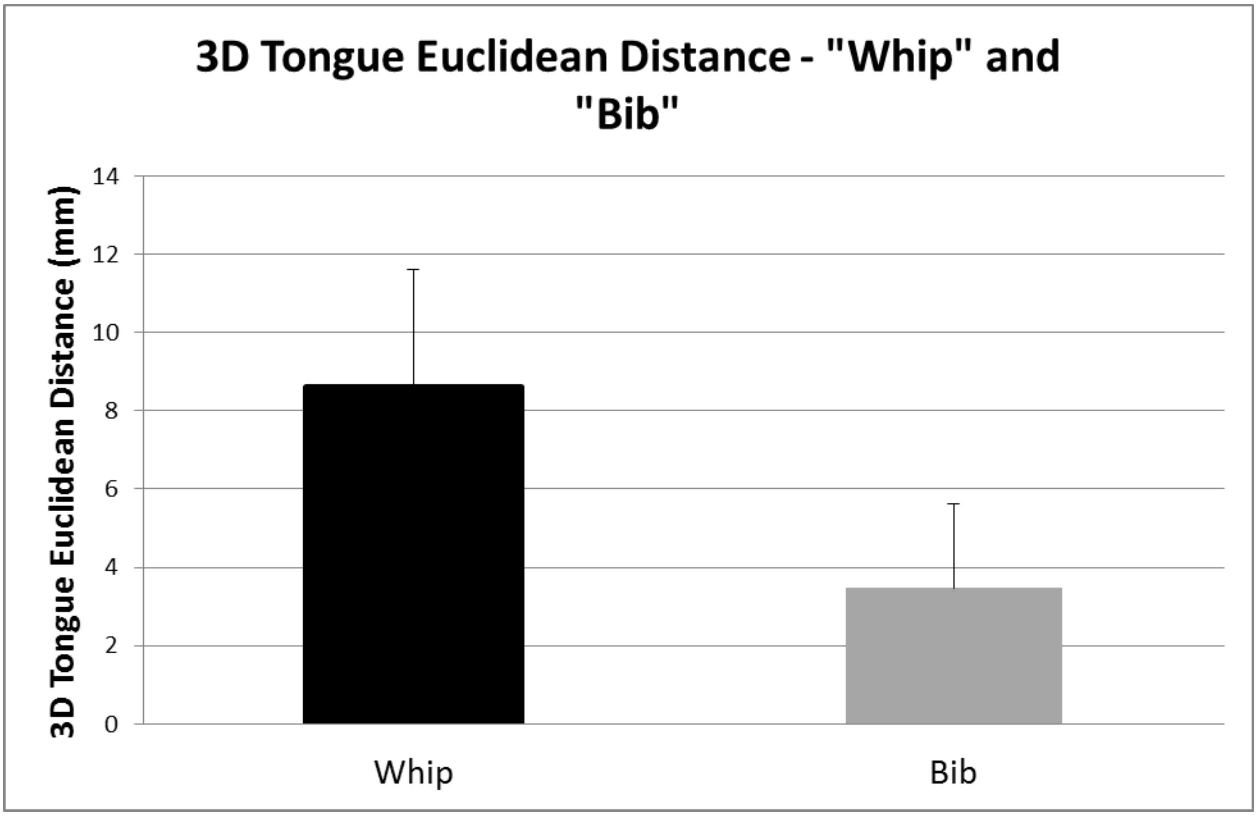

Figure 2. This graph displays the Average 3D Euclidean Distance of the tongue during both “whip” and “bib” production. “Whip” was found to have an overall greater movement of the tongue when compared to “bib”.

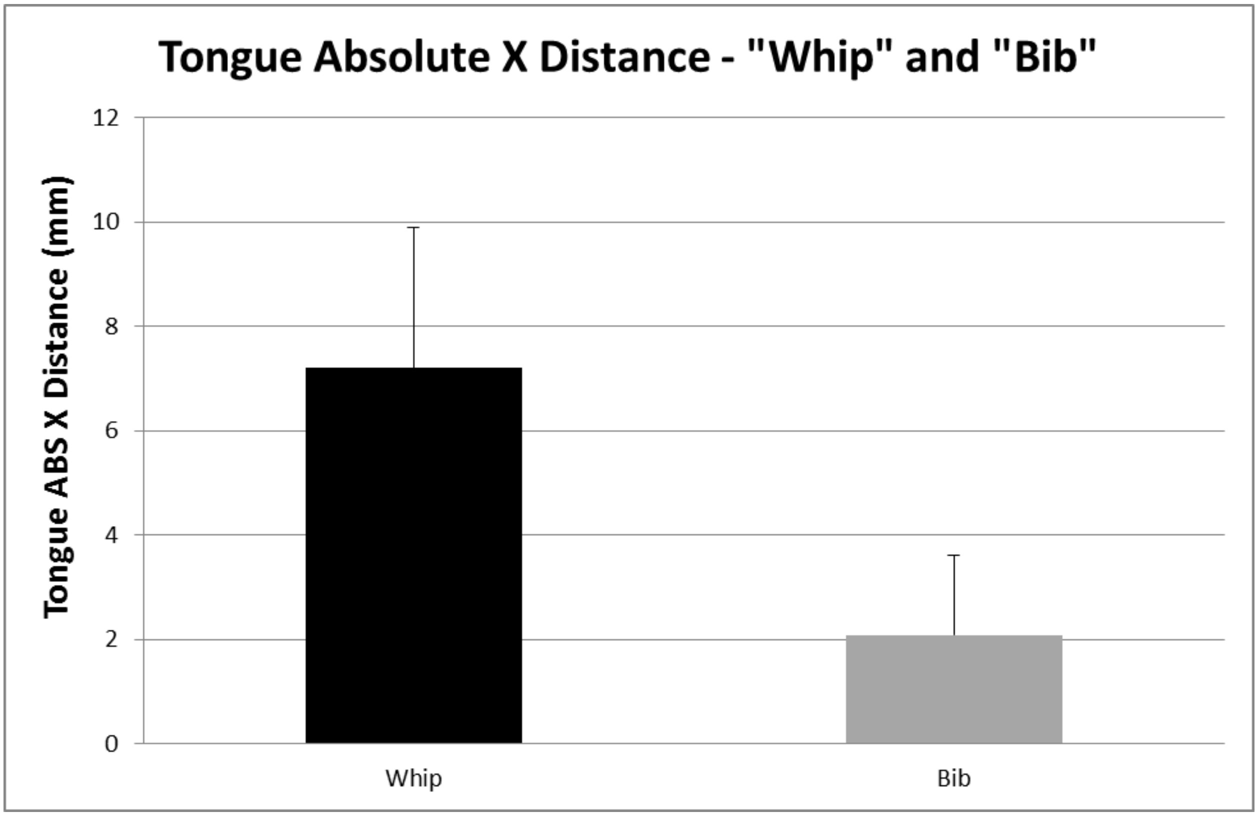

Figure 3. This graph displays the average Tongue Absolute X Distance in “whip” and “bib” production. “Whip” production was found to have a greater total tongue movement in the horizontal plane when compared to “bib”.

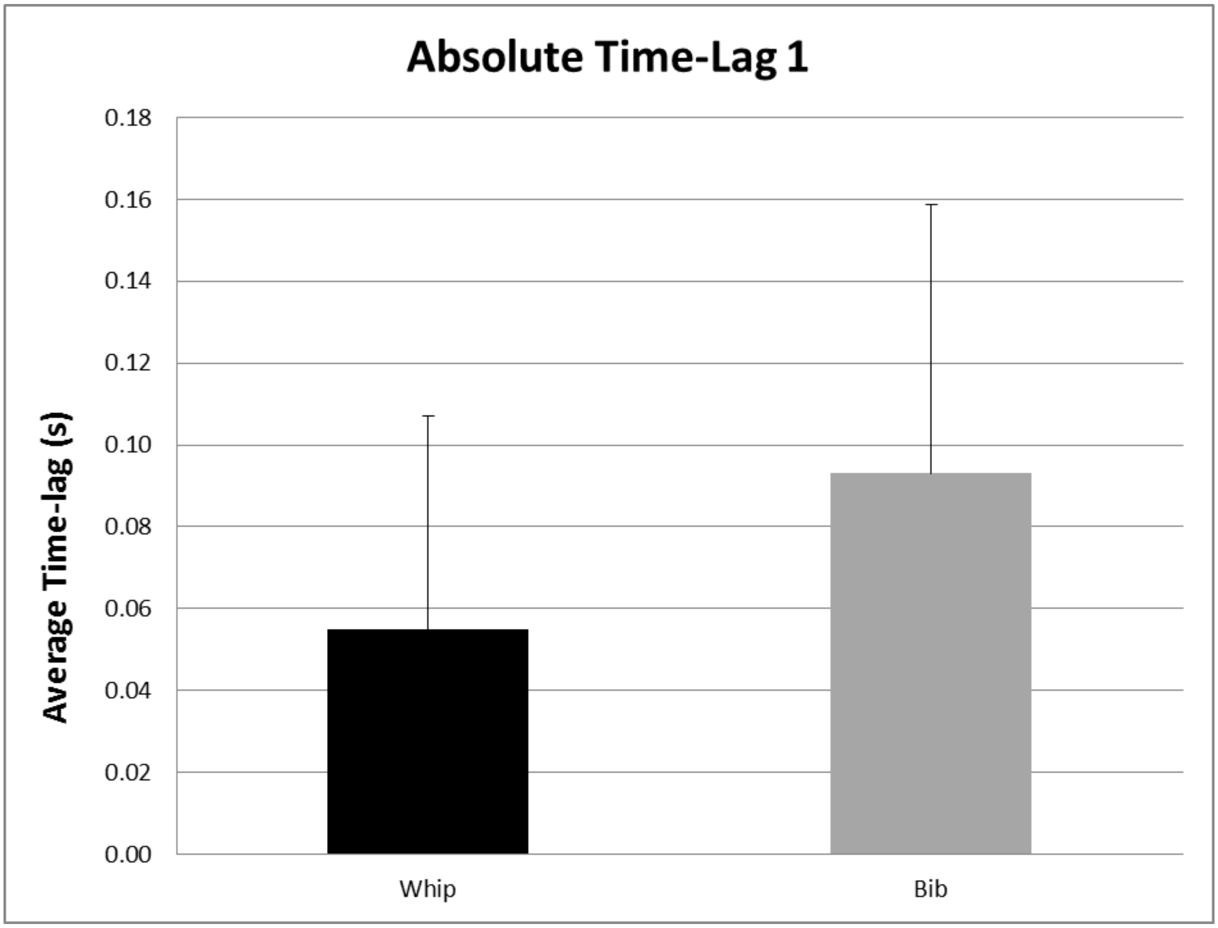

Figure 4. This graph displays the average time-lag of "whip" and "bib" for Absolute Time-Lag 1. "Whip" production revealed a shorter time-lag when compared to "bib". "Whip" required less time for the articulators to reach tongue minimum x position (tongue retraction) and maximum x-position (protrusion) of the lower lip. These results reveal that maximum tongue retraction and maximum lip protrusion occurred more simultaneously for "whip" production.

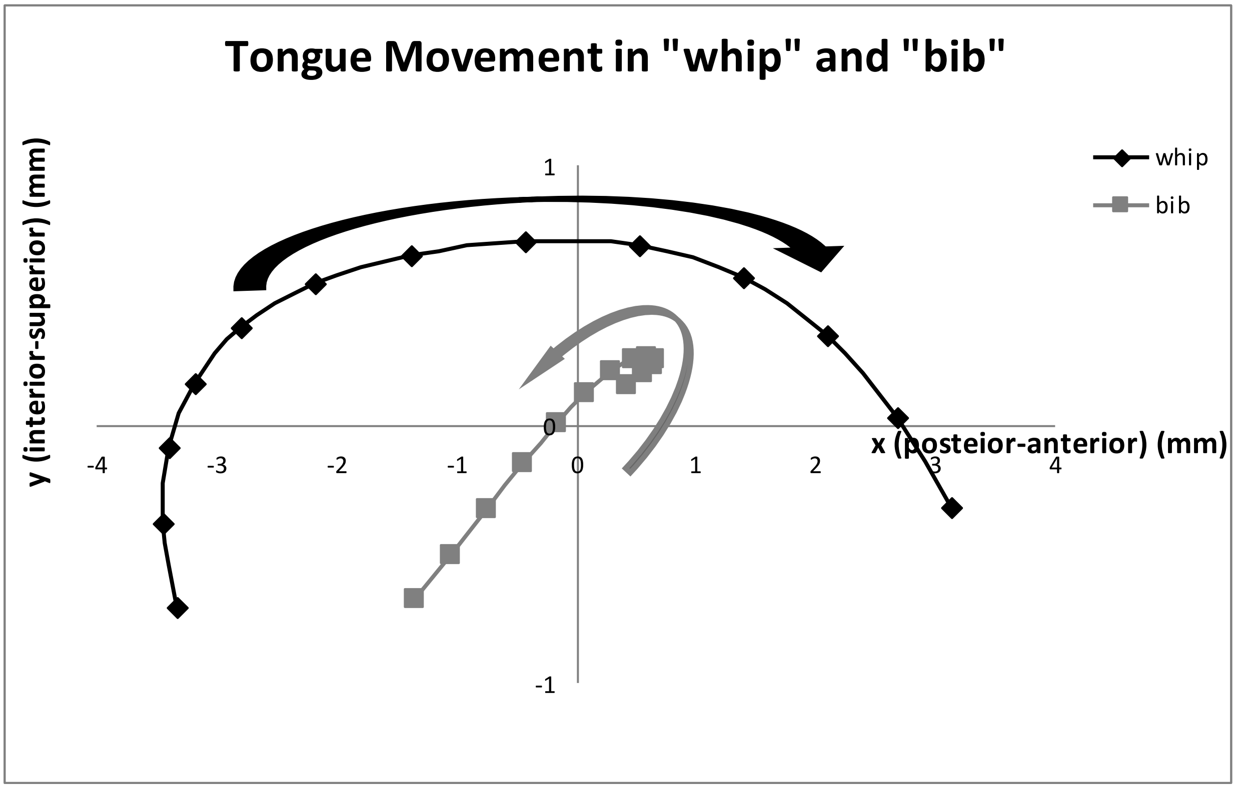

Figure 5. This figure displays different tongue movements for both ‘whip” and “bib”. “Whip” production showed a greater overall tongue movement and greater X distance changes.

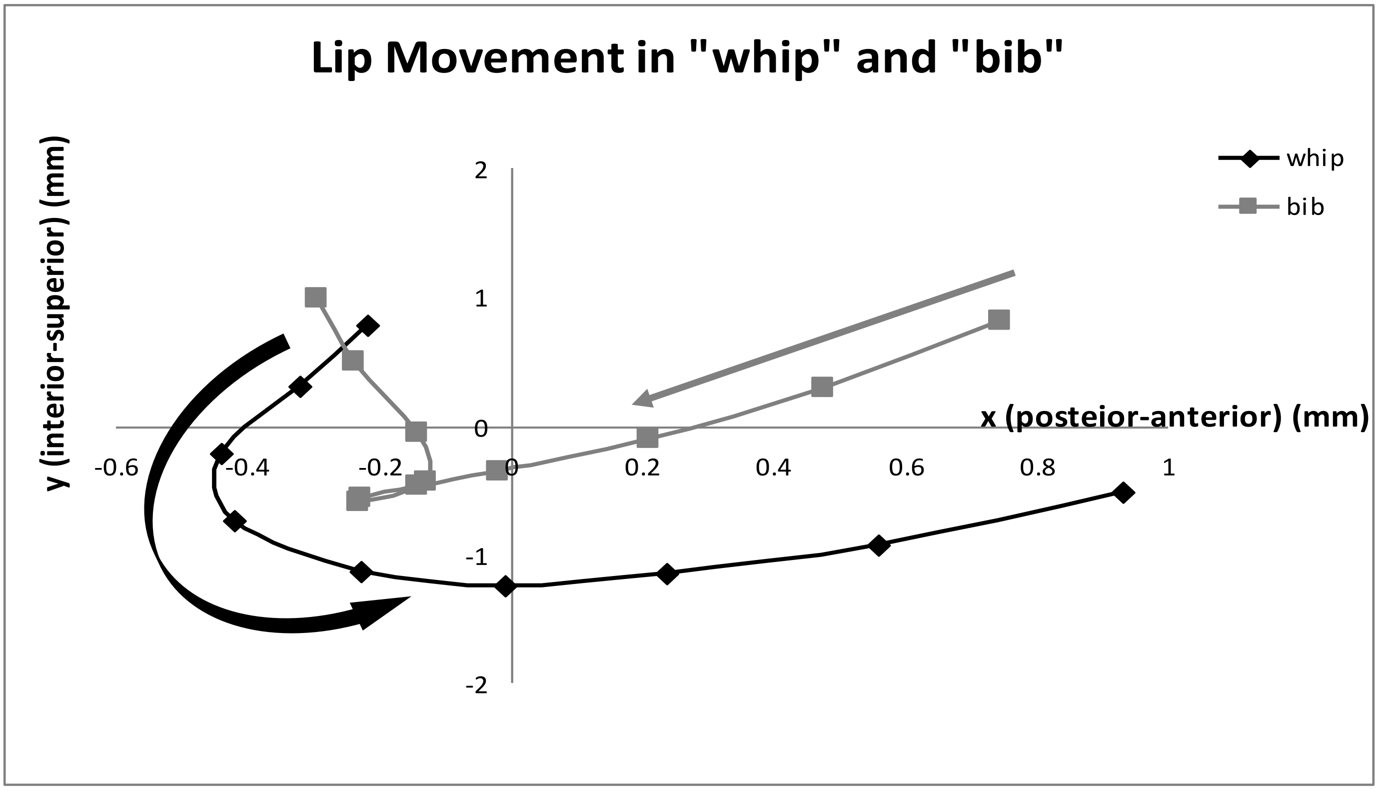

Figure 6. This figure displays lip movement patterns in both “whip” and “bib”. More downward lip movement (Y axis) was observed in “whip” when compared to ‘bib”. There was not a significant difference in X distance changes between both tokens.

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