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Spatiotemporal Coupling of the Jaw and Lower Lip: Comparing Talkers with Parkinson’s Disease and Amyotrophic Lateral Sclerosis

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Abstract

This study sought to determine the differences in temporal coupling between the lower lip and jaw for two gestures i.e., the vowel /ʌ/ and the labiodental fricative /f/ in the word ‘muffin.’ Because articulatory timing can be disrupted by impairments to the basal ganglia and its role in intrinsic timing and the dynamic state of the articulatory system, interarticulator timing was compared between tallkers with amyotrphic lateral sclerosis (ALS) and Parkinson’s disease (PD) relative to healthy controls. Electromagnetic articulography was used to record lower lip and jaw movements from six talkers with ALS, nine with PD, and 10 healthy controls. Lag values were obtained by subtracting the timepoint of the lower lip from the timepoint of the jaw for each gesture based on the timepoints of the positional minima for the jaw and lower lip during /ʌ/ and the positional maxima for the jaw and lower lip during /f/. Absolute lag times, percent lag (relative to total word duration), and coefficient of variation (CoV) values were compared between the three groups, as were effect sizes. Our results show a trend towards greater interarticulator timing differences (i.e., less temporal coupling) in talkers with ALS, whereas talkers with PD showed similar timing patterns to healthy controls. CoV values tended to be lower in the clinicial groups, with the ALS group showing more consistent lag times than even the PD group. Although preliminary, these results provide evidence of a mismatch between intrinsic timing and the physical state of the articulators in talkers with ALS. Despite basal ganglia pathology, the relative timing patterns among articulators appeared to be intact in talkers with PD.

Keywords: interarticulator timing, dysarthria, articulator coupling

1. Introduction

Intelligible speech requires careful timing of articulatory movements. Within the articulatory phonology framework, a high level of coupling is expected among articulators that form a gesture (Saltzman & Munhall, 1989). Within gestures, the interarticulator timing is supposed to follow a specific order. For example, for lip closing, the peak velocities of the lips are known to lead those of the jaw (e.g., Gracco, 1988). Similarly, when reaching the target position for a consonant, the jaw usually follows the tongue tip (Mooshammer et al., 2006). However, it is currently unknown if the inter-articulatory timing patterns seen in healthy, mature talkers are maintained by talkers with neurological conditions. It is also unknown to what extent disruptions to interarticulatory timing patterns may differ across talkers with different pathophysiologies within the speech motor system.

The temporal coupling among articulators is driven by a central clock linked to several cortical and subcortical areas such as the basal ganglia and cerebellum (Grahn, 2009; Konoike et al., 2012). This intrinsic clock is thought to be comprised of multiple oscillators at the gestural and suprasegmental levels that shape the motor plan to insert temporal with linguistic information (Saltzman et al., 2008; Windmann et al., 2015). Among the neural structures, there are differences in the roles of the basal ganglia and the cerebellum. The basal ganglia are engaged in the processing of attention-based, longer temporal intervals whereas the cerebellum is concerned with automatic, shorter, and event-based temporal processing (Harrington et al., 1998; Meck, 2005). The output of the central oscillators serves as input to the articulators and interacts with their physical state (e.g., stiffness) to shape the surface movement patterns. Impairments to both the central clock and dynamic state of the articulatory system can disrupt articulatory timing (Rong & Heidrick, 2022).

In individuals with amyotrophic lateral sclerosis (ALS), the articulators undergo significant morphological changes with disease progression, which alters their intrinsic properties and functional capacity as evidenced by reduced force generation, and slow and reduced movements (Lee & Bell, 2018; Shellikeri et al., 2016). Particularly the tongue is disproportionally more affected by the disease than the lips and jaw (e.g., Langmore & Lehman, 1994; DePaul et al., 1988). Therefore, the timing information generated by the central clock presumably interferes with the dynamic state of the articulators. In other words, there is likely a mismatch between the designated time determined by the linguistic event, and the physical properties of the articulators. Given the differential impairment of the articulators, the jaw is thought to become a primary articulator moving the tongue and perhaps also the lower lip more passively. This may result in more synchronized movements of the jaw and tongue or lower lip.

Evidence for the role of the basal ganglia in representing temporal information comes from multiple sources, including studies on Parkinson’s disease (PD) and Huntington’s disease. These studies report interval timing dysfunction (Malapani et al., 1998). Functional magnetic resonance imaging studies have also found that the striatum is activated by tasks that involve interval information processing durations (Tanaka et al., 2007). There is some debate about the exact role of the basal ganglia as some studies have shown that administration of dopamine agonists increases the speed of the internal clock (Maricq & Church, 1983; MacDonald & Meck, 2005); while others could not demonstrate such an effect (Balcı et al., 2008). Yet, others reported an opposite effect suggesting that increased dopamine levels might decrease the speed of timekeeping (Lake & Meck, 2013).

Despite mixed findings, there is consensus that basal ganglia disorders like PD disrupt temporal articulatory patterns. However, timing patterns between the jaw and the primary articulators (e.g., tongue, lower lip) have not been studied in these talkers. One study examined the intergestural timing patterns in talkers with essential tremor (Hermes et al., 2019), a neurological condition also associated with basal ganglia pathology. The coordination pattern between the tongue tip and

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tongue back for simple CV syllables were similar between the clinical group and healthy control speakers. However, during CCV syllables, which are thought to be phonetically more challenging, the coordination patterns of the lip, tongue tip, and tongue back significantly differed between the two groups, and these deviant patterns further degraded during deep brain stimulation. That is, participants in the clinical group activated gestures for both consonants and the vowel all at once. They also lengthened the prevocalic consonant considerably indicating their inability to adequately sequence these movements during the CCV gesture. However, it is unclear to what extent these findings translate to talkers with PD and how they relate to inter-articulatory timing patterns of the jaw and a primary articulator (e.g., tongue, lower lip) within a gesture.

To address the current gap in the literature on interarticulator timing patterns in talkers with dysarthria, the current study examined the timing between the lower lip and jaw during two gestures (open vowel /ʌ/ and labiodental fricative /f/) in talkers with ALS and PD. Specifically, as a first step, this study aimed to determine the extent to which jaw and lower lip are coupled (synchronized) in these talkers. Furthermore, we sought to determine how stable (consistent) these timing patterns were across trials. Because talkers with ALS activate the jaw more during speech than their healthy peers, and likely rely more heavily on the jaw as a primary articulator to achieve the desired vocal tract configuration, we expect more synchronized timing pattern (smaller lag times relative to controls) for the lower lip and the jaw in these talkers. Based on the consensus that their basal ganglia pathology disrupts temporal patterns in talkers PD, deviant interarticulatory pattern may be observable in these talkers; however, prediction about the specific direction (more or less synchronized than controls) could not be made. However, it should be noted that the basal ganglia pathology of talkers with PD is conceptualized to affect absolute timing patterns such as speech rate or segment durations rather than relative timing patterns. In that case, interarticulatory timing patterns of the lower lip and jaw of talker with PD may be similar to those of controls. Finally, we did not formulate specific hypotheses for the trial-to-trial variability of lag times but potential group differences will be explored.

2. Methods

This study was approved by the Institutional Review Board at the University of Missouri and Vanderbilt University Medical Center. All participants provided consent prior to data collection and were compensated for their time.

2.1. Participants

Participants belonging to three groups, namely ALS, PD, and healthy controls were included in the study. So far, we have collected data from six talkers with ALS (6 males, M_{age}=65.33, *SD*=9.63), nine with PD (5 females, 4 males, M_{age}=70.44, *SD*=5.62), and 10 controls (9 females, 1 male, M_{age}= 56.77, *SD*=5.72). Talkers with ALS and PD ranged in their dysarthria severity from mild to moderate-severe. All participants were monolingual native speakers of American English.

2.2. Kinematic Data Collection

All participants produced five repetitions of the word "muffin" embedded in the carrier phrase "Say___again". The utterance was chosen because it included a C_1VC_2 sequence that facilitated similar movements of the jaw and lower lip (lowering for the open vowel /a/ and raising for the labiodental fricative /f/). Articulatory kinematic data from all but one participant were collected using the Wave Speech Research System (NDI, Waterloo, Ontario, Canada) and data from one participant with ALS was collected with the AG501 (Carstens Medizinelektronik, GmbH, Nelkenweg, Germany). To record speech kinematics, small sensors were affixed along the mid-sagittal plane of the articulators (i.e., tongue tip, jaw, lips). The tongue tip sensor was placed at 1 cm from the tip; lower lip sensor was placed on the vermillion border, and the jaw center sensor was affixed to the lower gum below the central incisors. A head reference sensor recorded the head movements. Kinematic data were corrected for head movements and rotated into a head-based coordinate system using software provided by NDI. For recordings with the AG501, participants were asked to hold a bite plate with three additional sensors in their mouth. This recording was later used to transpose the kinematic data into a head-based coordinate system with the origin located just anterior to the jaw center sensor (Mefferd, 2017). This biteplate correction creates a head-based coordinate system that is comparable to that of the Wave system.

The sampling rate for the AG501 was 1250 Hz, further down sampled to 250 Hz, and for the Wave system, the sampling rate was 400 Hz. The audio signal was synchronized with the kinematic data and was sampled at 48,000 Hz and 22,000 Hz for the AG501 and the Wave systems, respectively. All kinematic data were low pass filtered at 15Hz. For this study, only the kinematic data of the lower lip and the jaw were used.

2.3. Data Analysis

First, the word repetitions were parsed from the carrier phrase using SMASH (Green et al., 2013). The onset was defined as the positional maxima of the lower lip at the word initial consonant /m/ and the offset was defined as the positional maxima of the tongue tip at the word final consonant /n/.

Then, a custom-written MATLAB script was used to analyze the vertical movements of the jaw and lower lip during the production of "muffin". Lower lip movements were not decoupled from the jaw because this step was not necessary given the purpose of this study and the measurement approach that was taken. Specifically, this study focused exclusively on lag times between the jaw and lower lip as they reached their positional minimum for the open vowel /ʌ/ and the positional maximum for the labiodental fricative /f/. Although this approach differs from the traditional phase angle calculations, it is well-suited to quantify the inter-articulatory timing patterns of the lower lip and jaw.

For better spatial alignment and visual inspection of the kinematic data, the parsed jaw and lower lip movements were then z-scored and plotted in one graph (see **Figure 1**). Then, an algorithm identified the timepoints of the positional minima for the jaw and lower lip during the vowel /ʌ/ and the timepoints of the positional maxima for the jaw and lower lip during the labiodental fricative /f/. Then, the timepoint of the lower lip was subtracted from the timepoint of the jaw for each target (see **Figure 1**). Finally, all lag times, which consisted of positive and negative values, were converted to absolute numbers (lag) because the study sought to determine the strength of lower lip and jaw coupling. In other words, as a first step, we merely investigated differences in the absolute lag times between the jaw and the lower lips. The order in which the lip and jaw reached the target was not of interest at this point. Because lag times may be more difficult to interpret when talkers produce the target utterance at different articulatory rates, we also calculated the percent lag time (%lag), which was the lag time relative to the total word duration. To determine the trial-to-trial variability in the lag times across five repetitions, we also calculated the coefficient of variation (CoV) based on the absolute lag values. The CoV was defined as the standard deviation across five repetitions divided by the talker's mean lag time across five repetitions.

2.4. Statistical Analysis

Linear mixed models were completed to determine between-group differences in absolute and percent lag times with group as the fixed effect, and subject as the random effect. The repeated measures variable consisted of the five repetitions of the word from each participant. For CoV, a between-group ANOVA was used to examine between-group differences. Because of the preliminary nature of the study, a critical alpha-level of $p < .05$ was selected for all test and Cohen's d effect sizes were calculated. Absolute Cohen's d < .4 and < .8 were interpretated as small and medium effects, respectively. A negative Cohen's d indicated that Group 1's mean was smaller than Group 2's mean in comparison.

3. Results

Group means (*SE*) of each dependent variable are provided in **Table 1**. The group means for the duration of the utterance "muffin" are also shown to better interpret the absolute lag durations and the %lag durations. No significant between-group differences were found for the absolute and the percent lag times as well as for the CoV of the lags for either target. Nevertheless, as can be seen in **Table 2,** medium to large effect sizes were observed for absolute lag times of both targets for ALS vs. controls. Furthermore, medium effect sizes were found for ALS vs. PD. That is, for both targets, talkers with ALS tended to have longer absolute lag times than talkers with PD and/or controls. Effect sizes for comparisons between talkers with PD and controls were small for both targets.

When considering %lag, the medium to large effects for comparisons between talkers with ALS and controls went away for both targets. Medium effects for ALS vs. PD turned in the opposite direction and only remained at a medium size for the target /f/, but diminished to a small effect for the target /ʌ/. In addition, the small effect sizes for PD vs. controls increased slightly from a small to a medium effect for /f/ while the small effect for /ʌ/ went away almost completely.

For both targets, trial-to-trial variability in lag times (CoV) tended to be lower in both clinical groups relative to those of controls. Furthermore, talkers with ALS had lower CoV values than talkers with PD. In fact, large and medium differences were observed between talkers with ALS and PD for the target /ʌ/ and /f/, respectively, while medium and small differences were observed between talkers with ALS and controls, respectively. By contrast, small differences in CoV were observed between talkers with PD and controls for both targets.

3.1. Figures and Tables

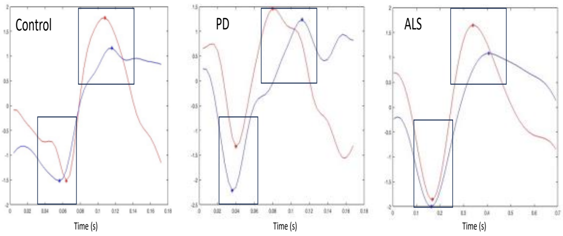

Figure 1: *Spatially normalized (z-scored) movements of the lower lip (red) and jaw (blue) during the word "muffin". Shaded areas highlight the troughs/ peaks for targets /ʌ/ and /f/, respectively.*

Table 1: *Group means (SE) for all dependent variables.*

Group	Control	PD	ALS
Lag_/ʌ/	.004 (.001)	.005 (.001)	.010 (.003)
%Lag /ʌ/	2.449 (.471)	2.730 (.560)	2.344 (.394)
CoV Lag /ʌ/	.737 (.178)	.599 (.052)	.306 (.105)
Lag_/f/	.011 (.002)	.016 (.004)	.027 (.011)
%Lag /f/	6.278 (.831)	9.049 (2.696)	5.449 (1.430)
CoV Lag /f/	.963 (.294)	.852 (.107)	.611 (.161)
Total Word Duration	.185 (.012)	.190 (.014)	.479 (.140)

Table 2: *Effect sizes (Cohen's d) for group comparisons.* Large effect sizes indicated in **bold**

Variable	ALS vs. Controls	PD vs. Controls	ALS vs. PD
Lag_/ʌ/	**1.02**	.21	.62
%Lag /ʌ/	-.06	.01	-.25
CoV Lag /ʌ/	-.73	-.24	**-1.05**
Lag_/f/	.78	.35	.40
%Lag /f/	-.23	.40	-.54
CoV Lag /f/	-.36	-.11	-.52

4. Discussion and Conclusion

The current study sought to determine potential differences in the strength of inter-articulatory coupling between talkers with ALS, PD, and controls. Furthermore, the study investigated the extent to which interarticulator coupling was consistent across five repetitions of the same utterance (i.e., CoV) and compared these findings across two clinical groups with different underlying impairments of the speech motor system (PD and ALS) relative to healthy controls. It was hypothesized that talkers with ALS would exhibit stronger interarticulator coupling than talkers with PD and controls based on the notion that their articulators are differentially affected by the disease (e.g., Langmore & Lehman, 1994) and therefore, these talkers may rely more on the jaw to move the primary articulators (i.e., tongue, lower lip). Preliminary findings for lag times did not support this hypothesis because talkers with ALS tended to have longer absolute lag times than controls and talkers with PD for both targets. Therefore, their jaw and lower lip movements appear to be less synchronized than those of the other two groups. However, there was a trend toward shorter relative lag times (%lag) in talkers with ALS when compared to the other talkers. Future studies should determine the extent speech rate differences impact lag times. Such insights would help the interpretation of the findings for talkers with ALS in this study.

With regards to trial-to-trial variability, talkers with ALS tended to show more consistent lag times than controls and talkers with PD, regardless of the target. This finding aligns with previous work showing lower spatiotemporal pattern variability in talkers with ALS (e.g., Kuruvilla-Dugdale & Mefferd, 2017) and may suggest that these talkers have less flexibility in their articulatory system to change lower lip-jaw coupling. However, given the preliminary nature due to the small sample size, further research is warranted to replicate this finding.

Given the basal ganglia pathology, we also expected deviant lag times for talkers with PD. However, effect sizes for comparisons between talkers with PD and controls were in general small and suggested only minimal differences in the lower lip-jaw interarticulatory timing patterns across these two talker groups, particularly for the target /ʌ/. This finding may provide support for the notion that articulatory movements of talkers with PD are generally merely downscaled in size while interarticulatory timing patterns are being preserved. The findings of the current study are preliminary and need to be replicated; however, they suggest that although basal ganglia pathologies can disrupt absolute temporal timing patterns (e.g., segment durations, speech rate), they may not disrupt relative timing such as lip-jaw interarticulatory timing patterns.

The trial-to-trial variability of the lag values were rather comparable between talkers with PD and controls considering the small effect sizes between these two groups. Thus, talkers with PD may have an unaffected flexibility to modify their interarticulator coupling. Larger sample sizes are needed to solidify the observed trends of the current study.

In sum, the study findings support our current conceptual understanding of timing disruptions in talkers with impaired motor speech systems. That is, this study provides preliminary evidence of a mismatch between the time designated by the central clock and the physical state of the articulators in talkers with ALS. Furthermore, our findings suggest that despite the basal ganglia pathology, the relative timing patterns among articulators appears rather intact in talkers with PD. Future studies should examine such aspects of articulatory timing behavior in talkers with other basal ganglia pathologies (i.e., Huntington’s disease) as well as contrast current findings with those of talkers with cerebellar pathologies. Such studies will help to better understand the disease-specific pathomechanisms affecting articulatory timing in talkers with dysarthria.

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