TONGUE- AND JAW-SPECIFIC RESPONSE PATTERNS TO SPEAKING RATE MANIPULATIONS

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ABSTRACT

Economy of effort is a principle of speech motor control that is thought to underlie rate-related changes in articulatory behavior. In this current study we aimed to determine the extent to which economy of effort is reflected in the response patterns of individual articulators that form a functional unit (synergy) during speech production. We examined slow and fast speech effects on jaw and independent tongue displacements associated with vocal tract shape changes during the production of the diphthong /aɪ/. Group findings suggest that speakers increase jaw and independent tongue displacements in response to slow speech but decrease only the independent tongue displacements in response to fast speech. Jaw contribution to overall tongue displacement was lowest during typical speech and increased during fast and slow speech. Inspection of each speaker's response pattern to rate changes, however, suggests great inter-speaker variability in articulatory strategies. Theoretical and clinical implications are discussed.

Keywords: speaking rate manipulation, speech kinematics, tongue – jaw interactions

1. INTRODUCTION

Speech production requires coordinated movements of multiple articulators to achieve vocal tract shapes that produce the intended speech acoustic signal. Perturbation studies have demonstrated that speakers are quite flexible with regards to the amount to which each articulator contributes to the overall vocal tract shape changes [1-3]. Trading relations between articulators have also been observed during natural (unperturbed) speech, for example reciprocal covariation between tongue body raising and lip round during the production of /u/ [16]. This flexibility is thought to accommodate 'ease of movement' and optimize the biomechanical effort during speech production [13,17].

Economy of effort is also thought to drive changes in articulatory behavior that occur in response to speaking rate modifications. For example, it has been shown that speech is generally hyperarticulated when speaking rate is slow and hypoarticulated when speaking rate is fast [4,5, 10,12,18]. However, little is currently known about how individual articulators that form a synergy during sound production (e.g., tongue and jaw) respond to these speaking rate changes.

Findings of previous studies on diadochokinetic movements suggest a reorganization of articulatory behavior due to articulator-specific response patterns to rate changes. For example, when accelerating syllable repetition rates, it has been shown that some speakers reduce jaw contribution to vocal tract shape changes by limiting jaw displacements and relying more on independent tongue and lower lip displacements [7,21]. However, a variety of other articulatory strategies were also observed [7, 14, 18, 21]. It was speculated that articulatory strategies may depend on the speaker's skill level to perform diadochokinetic tasks [18].

Systematic investigations of articulator-specific response patterns to rate changes in connected speech are surprisingly rare. Further, although commonly assumed, to our knowledge a rate-induced reorganization of articulatory behavior has not been documented for connected speech. Therefore, the current study sought to determine rate effects on jaw and independent tongue displacements associated with vocal tract shape changes during the production of the diphthong /aɪ/ embedded in connected speech. The study also aimed to determine how speakers reorganize their articulatory behavior in response to rate changes by examining jaw contribution to overall tongue displacement during slow, typical, and fast speech.

2. METHOD

2.1. Participants

30 native English speakers (16 males,14 females) participated in this study. Speakers were recruited as controls for a larger project on speech performance in speakers with dysarthria. The mean age of the speakers was 64.5 years (*SD* = 10.1 years).

Participants reported no history of speech, language, or hearing impairment and passed a cognitive screening.

2.2. Experimental Tasks

As part of a larger experimental protocol, all participants were asked to produce five repetitions of the sentence "*She saw a boy with a kite hiding behind the house*" at their typical speaking rate. Then, participants were asked to produce the same sentence five times with approximately half their typical speaking rate, and five times as fast as possible. The order of the two rate conditions varied across participants.

2.3. Kinematic Data Acquisition and Processing

In this study, the diphthong /aɪ/ in the word "kite" was of specific interest. This speech segment was chosen because it elicits rapid vocal tract changes that are evoked by tongue and jaw displacements. Further, segment boundaries were well-defined in the tongue kinematic signal across all rate conditions. Tongue and jaw movements were recorded using three-dimensional electromagnetic articulography (Medizinelektronik Carstens AG501). Specifically, posterior tongue movements were recorded by attaching a small sensor coil to the midline of the tongue approximately 4cm from tongue tip using dental glue. Jaw movements were recorded by placing a small sensor coil on the gumline of the front central incisors using a small amount of putty (Stomahesive). Further, a sensor coil was attached to the tip of the tongue, the upper lip and the lower lip.

Participants wore a pair of goggles which had three head reference sensors attached. A resting recording was completed during which participants held a small biteplane with sensors between their teeth. Head reference sensors and biteplane sensors were used to correct for head movements and re-express the data relative to an anatomically-based coordinate system using Normpos [15]. Finally, kinematic data were smoothed in SMASH [6] using a 15 Hz low pass filter.

2.4. Kinematic Data Analysis

The steps for kinematic data analysis paralleled those described in [11]. That is, first kinematic onset and offset positions of the diphthong /aɪ/ were determined based on the positional extrema of the posterior tongue in the vertical dimension. Then, 3D positions of the jaw sensor and posterior tongue sensor were extracted at the defined onset and offset and the 3D Euclidean distance between onset and offset was calculated for each articulator. Jaw displacements at the location of the posterior tongue sensor were estimated taking into account jaw rotation [20]. Independent tongue displacement was calculated by subtracting the estimated posterior jaw displacement from the measured posterior tongue displacement [11]. Finally, diphthong durations were based on the tongue kinematic signal with described onsets and offsets for the diphthong /aɪ/.

2.5. Statistical Analysis

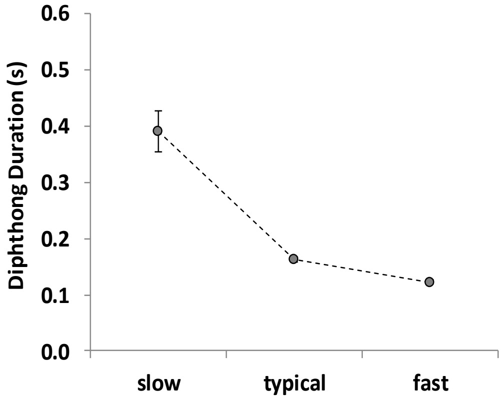
Speaking rate effects were evaluated using linear mixed effects models. To control for within-subject effects participants were entered as random effects. Dependent variables were diphthong duration, jaw displacement, independent tongue displacement, overall tongue displacement, and percent jaw contribution to overall tongue displacement. In addition to group findings, speaker-specific response patterns to rate manipulations were analyzed.

3. RESULTS

3.1. Diphthong Durations

Instructions to speak faster and slower elicited significant changes in diphthong duration [$F(2, 147.5) = 204.8$, $p < .001$]. As can be seen in Figure 1, diphthong durations associated with fast speech were significantly shorter than those associated with typical speech and slow speech ($p < .001$). Further diphthong durations associated with slow speech were significantly longer than those associated with typical speech ($p < .001$) and fast speech ($p < .001$).

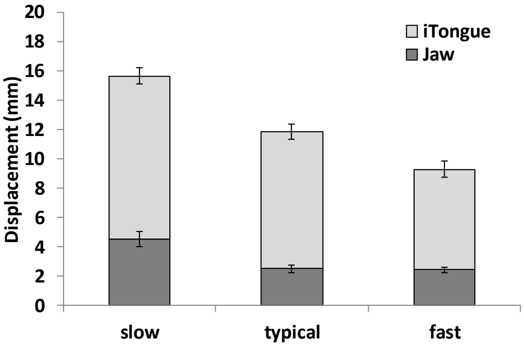
Figure 1. Mean diphthong durations (+/- *SE*) across rate conditions.



3.2. Displacement

Speaking rate had a significant effect on independent tongue displacement [$F(2,218.8) = 55.4$, $p < .001$] (Figure 2). Relative to typical speech independent tongue displacements decreased during fast speech ($p < .001$) and increased during slow speech ($p < .001$). Speaking rate effects were also significant for jaw displacement [$F(2,172.4) = 50.0$, $p < .001$] (Figure 2). Although jaw displacements did not significantly differ between typical and fast speech, jaw displacements were significantly larger during slow speech than during typical and fast speech ($p < .001$). Finally, overall tongue displacements varied predictably with speaking rate [$F(2, 275.2) = 118.0$, $p < .001$]. Relative to typical speech overall tongue displacements decreased during fast speech ($p < .001$) and increased during slow speech ($p < .001$).

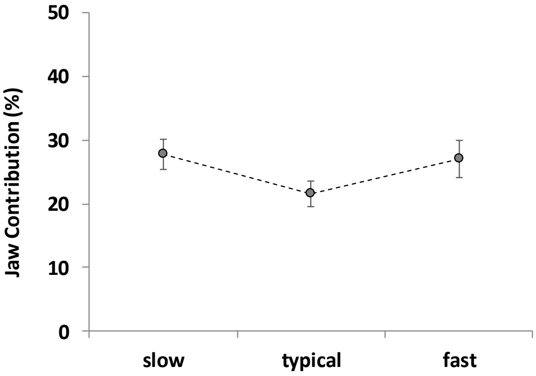
Figure 2. Mean independent tongue and jaw displacements (+/- *SE*) across rate conditions



3.3. Jaw Contribution to Tongue Displacement

Speaking rate had a significant effect on the relative contribution of the jaw to overall tongue displacement [$F(2,175.0) = 30.0$, $p < .001$]. Jaw contributions increased during slow and fast speech relative to typical speech ($p < .001$) (Figure 3).

Figure 3. Jaw contribution to overall tongue displacement (+/- *SE*) across rate conditions



3.4. Speaker-Specific Speaking Rate Effects

Figure 4 shows the three most common response patterns of independent tongue and jaw to speaking rate change and how these articulator-specific changes impacted the synergistic tongue-jaw relation during the diphthong productions. Finally, Figure 5 displays the diphthong durations for these three subgroups.

Figure 4. Three common articulator-specific response patterns to rate changes (left panels) and the resulting changes in jaw contribution to overall tongue displacement (right panels)

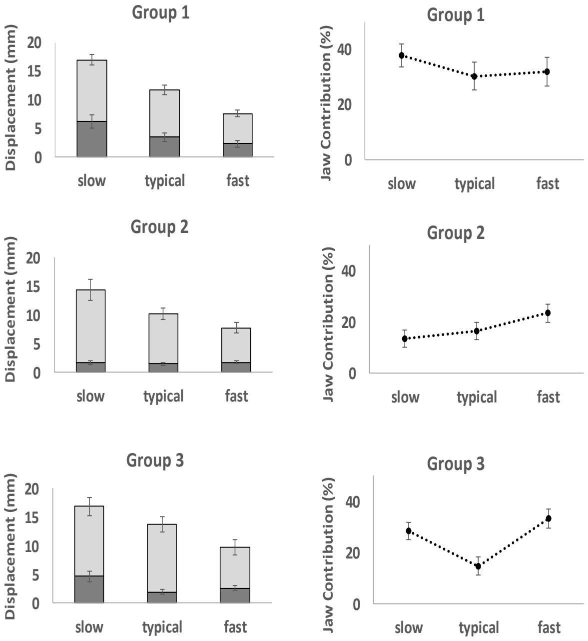
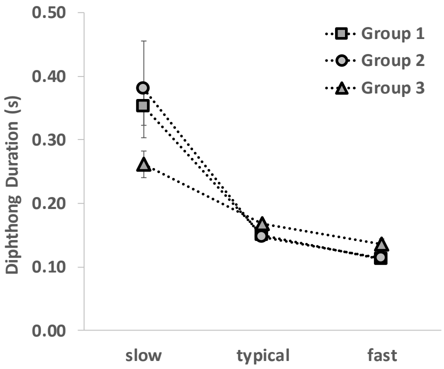


Figure 5. Mean diphthong duration for three subgroups across rate conditions



Speakers in group 1 (3M, 5F; median age: 67) reduced both jaw and independent tongue displacements as they accelerated their speaking rate. During slow speech jaw contributions to overall tongue displacements tended to be greater than during typical speech in this group; however, no changes in jaw contribution were observed when switching from a typical to a fast speech rate.

In group 2 (3M, 2F; median age: 68) jaw displacements did not vary with rate; however, independent tongue displacement decreased from slow to fast speech. These articulator-specific changes resulted in gradual increases in jaw contribution to overall tongue displacement with increase in rate. Diphthong durations were comparable between group 1 and 2 across all rate conditions (Figure 5) despite differences in the relative contribution of the jaw to overall tongue displacement and differences in the underlying articulator-specific response patterns to rate change.

In group 3 (3M, 3F; median age: 56) jaw displacement increased in response to slow and fast speech; however, the magnitude of change was greater for slow speech than for fast speech. Independent tongue displacement did not change in response to slow speech but decreased during fast speech. In this group jaw contributions tended to be greater during slow and fast speech relative to typical speech. Finally, diphthong durations tended to be longer during fast speech and shorter during slow speech relative to those of group 1 and group 2.

In three cases jaw response patterns were similar to those in group 3; however, independent tongue displacements did not vary with rate. The jaw contributions to overall tongue displacement were also greater during slow and fast speech compared to typical speech. These three speakers produced relatively long diphthong durations during typical and slow speech whereas diphthong durations during fast speech were comparable to those produced by speakers in group 1 and 2. Two speakers showed minimal changes in jaw and independent tongue displacement while successfully shortening and prolonging diphthong durations. Finally, seven speakers exhibited unique patterns of jaw and independent tongue displacement changes for fast and slow speech. In five of these seven speakers rate manipulations altered jaw contributions to overall tongue displacements.

4. DISCUSSION

The current study aimed to determine articulator-specific response patterns to speaking rate manipulation and how such changes impacted relative contribution of the jaw to overall tongue displacements during the production of the diphthong /aɪ/. Findings support the common assumption that rate manipulation can induce a reorganization of articulatory behavior as indicated by the changes in the relative contribution of the jaw to overall tongue displacement. Although the way in which articulatory behavior was reorganized varied widely across speakers, the underlying articulator-specific changes could generally be explained by the economy of effort principle [10,13,17]. For example, the reduction in jaw displacements from slow to typical speech aligns with the goal to minimize the physical effort of moving such a massive structure at a faster rate. An additional reduction of jaw displacement during fast speech, however, was only observed in a subgroup of speakers who produced relatively large jaw displacement during typical speech (Group 1). Considering that typical speech is produced at about 75% of a speaker’s maximum rate [19] it is not surprising that most speakers appear to already move their jaw most economically during typical speech. Once speech rate was increased beyond the typical rate, many speakers only reduced their independent tongue displacements to economize effort (e.g., group 2 and 3). Although displacement reductions and acoustic undershoot have been reported frequently, particularly for vowels [4, 5, 9, 12, 19], the current study contributes new knowledge by showing that undershoot during fast speech is typically driven by reductions of independent tongue displacements, not jaw displacements, at least for the production of /aɪ/.

Some speakers, however, did not display any tongue or jaw displacement changes across the rate continuum while others even exhibited increased displacements during fast speech. All speakers varied diphthong durations successfully; however, some preferred to adjust their velocity rather than their displacement. This observation aligns with previous reports of inter-speaker differences in articulatory strategies during rate increases [9].

Finally, previous studies on diadochokinetic tasks suggested that speakers may not adjust control parameters for rate globally but rather differentially for each articulator [7]. Current findings further support this notion. However, future studies should aim to delineate factors that contribute to the wide range of articulatory strategies across speakers. Our current data suggest that age could be one factor (see median age of group 3 vs. group 1 and 2). A better understanding of such factors can improve the detection of impaired motor performance patterns in impaired speakers.

5. ACKNOWLEDGEMENTS

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