Phase relations between the tongue body and the jaw across rate modifications in younger and older speakers

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ABSTRACT

The present study investigated the effects of age and speech rate on intergestural phasing patterns of oral articulators in younger and older speakers across three speech rates. 12 younger and 16 older speakers produced the target word ‘Kaia’ at a fast, typical and slow speech rate. Phase angles were used to quantify the spatiotemporal relations between the tongue body and the jaw. The timing of the jaw movement was referenced to the tongue body’s movement cycle during ‘Kai’. The results replicated previous studies on rate effects and showed that younger speakers systematically increased phase angles from fast to typical and further to slow speech. However, in older speakers such increased phase angles were only observed for comparisons of typical and slow speech as phase angles did not differ between fast and typical speech. The findings suggest that intergestural timing patterns may become less flexible with advancing age.

Keywords: phase angle, articulatory timing, aging effects, speech kinematics

1. INTRODUCTION

Speech production is a complex motor task that requires multiple articulators to reach their target positions in a well-timed sequence. Such sequential timing relations are described as patterns of stability and have previously been investigated between the upper lip and the jaw [1]–[4] or the tongue tip and the jaw [5], [6] and described by phase angles on the phase plane. One major goal of these investigations was to identify invariance within speech motor control, as phase angles provide insights into intergestural coordination in the spatiotemporal dimension.

Most studies investigated vowel-consonant-vowel (VCV) sequences with intervocalic labial or alveolar stops or nasals, so that the onset of the consonant with respect to the vocalic jaw cycle was determined. One jaw cycle is defined from the onset of the first vowel to the onset of the second in vowel. Tuller and Kelso investigated regularities in kinematic patterns and reported that the occurrence of lip movement was stable across rate conditions within speakers but variable across speakers [1]. In contrast, Nittrouer and colleagues showed that the phase angle of labial and alveolar movements to the jaw cycle changed due to stress, speech rate and phonetic contrast [3], [5], [6]. As a temporal regularity they observed that the shorter the jaw cycle, the smaller the phase angle and vice versa. They also pointed out that the tongue tip coordination with the jaw exhibited greater variability than the upper lip coordination with the jaw. Shaiman et al. [2] reported rate effects between the upper lip and the jaw in five out of eight speakers and highlighted speaker-specific strategies. In a later study, Shaiman investigated CVC sequences with labial consonants and provided converging evidence that phase angles vary in response to speech rate manipulations [4].

However, so far, tongue tip and lip movements have always been studied with reference to the jaw cycle in symmetrical sound sequences (pseudowords). It remains to be determined if previously reported rate effects on timing patterns can also be observed a) during asymmetrical sound sequences elicited in a sentence repetition task, b) when the tongue body cycle serves as the reference for the jaw, and c) when speakers are of older age. Such knowledge is important to understand the organization of timing patterns between articulators in general and to specify age-related changes on speech motor control.

The present study aims to investigate the intergestural timing between the jaw and tongue body with respect to variation in speech rate (typical, slow, and fast speech). We test whether phasing relations are similar in younger and older speakers, since there is some evidence in the literature that speech motor control is affected by aging [7]–[9]. Phase angles were used to quantify the phasing relations between the tongue body and the jaw. Tongue body cycles were taken as reference movement for the jaw timing.

As shown in most of the previous studies, timing differences due to speech rate changes are expected.

Relative to the typical speech rate, the phase angle is expected to increase during slow speech and decrease during fast speech. No predictions were made for potential aging effects because previous studies have not included age as factor in their analysis (cf. [2]).

2. METHODS

2.1. Participants

12 younger (4 females, 8 males) and 16 older speakers (5 females, 11 males) of American English participated in the study. The mean age was 24 (± 2) years in the younger and 67 (± 8) years in the older group. All participants passed the Mini-Mental State Examination [10] and a pure tone hearing screening to rule out cognitive decline and hearing impairment.

2.2. Speech Material

As part of a larger research project, all participants were asked to produce ten repetitions of the sentence: *Buy Kaia a kite*. For the purpose of the study, we specifically focused on the $C_1V.C_2$ sequence [kaj] of the word *Kaia*, consisting of a stop consonant, a vowel, and an approximant. C_1V is the first stressed syllable, while C_2 is part of the second unstressed syllable. All participants produced the sentence in three conditions: typical, fast, and slow. The typical condition was always elicited first. The fast and slow condition were elicited in a pseudo-randomized order. For fast speech, participants were asked to produce the sentence as fast as possible. For slow speech, participants were asked to produce the sentence at half their typical speaking rate by stretching out the words.

2.3. Data collection

The speech material was recorded with an electromagnetic articulograph (AG 501, Carstens). Small sensors were attached to the articulators to track their movements. One sensor was placed with dental adhesive (Periacryl 90, GluStitch, Inc.) to the sagittal midline of the tongue (approx. 4 cm posterior to the tongue tip) to track the tongue body movement. Another sensor was attached on the central part of the gumline of the lower teeth to track the jaw movement. Three additional sensors were placed on plastic googles that functioned as reference sensors for head correction. The raw data were converted into positional data first using CalcPos software and then head-corrected and rotated into a head-based coordinate system using a biteplane recording and the respective NormPos software provided by Carstens. Data were further processed in SMASH, a MATLAB-based software program [11].

2.4. Data processing

Although the calculation of phase angles in the current study followed closely procedures described in previous studies [1, 8], the tongue body cycle was used as the reference to quantify changes in the spatiotemporal timing of the jaw reaching the first vowel /a/ in the word *Kaia*. Traditionally, the jaw cycle had been used as a reference to quantify timing patterns with the upper lip or tongue tip [2]–[5]. This means that the consonantal closure of the tongue tip or the lip were related to the jaw motions associated with the flanking vowels. In contrast to previous studies, we used the jaw opening motion associated with the vowel and related it to the tongue body motions associated with the flanking consonants in CV.C sequences. We chose this approach because the tongue body exhibited a well-defined lowering and raising movement cycle during the CV.C sequence with reliable landmarks for its onset and offset across all rate conditions.

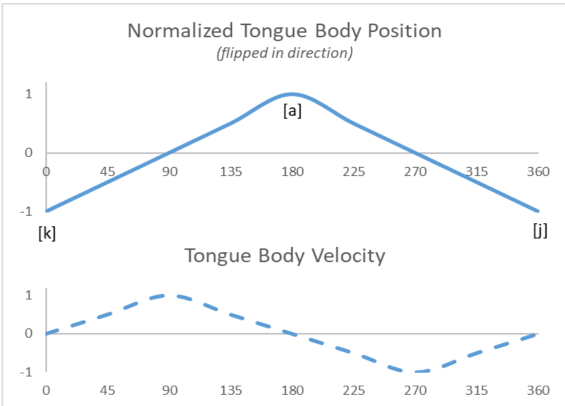

Figure 1: Schematized relationship between tongue body position and related velocity signal along a 360° cycle.

The tongue cycle was defined as the tongue body movement from the constriction [k] to the constriction [j] as it represents a full movement cycle in the closed – open – closed dimension. Positions and associated velocities of the tongue body and jaw movements were taken from the vertical dimension (y-axis). Local maximum and minimum positions were defined by zero crossings of the velocity signal (Figure 1). Please note that movement directions were flipped in their direction as it was necessary for the calculation of normalized tongue body positions and velocities.

Tongue body positions ($TB\ pos_N$) and velocities ($TB\ vel_N$) were normalized across each cycle as described by Kelso and colleagues [12, p. 43,44], so that the tongue cycle was displayed with values ranging from 1 to -1 as in a unit cycle (Figure 2). In Figure 2, the tongue position (pos) is depicted on the vertical axis, and the tongue movement velocity (vel) on the horizontal axis. Point P (vel, pos) describes landmarks of the tongue body along the phase plane within the unit cycle. The tongue body lowering from [k] to [a] in the word *Kaia* is reflected in the movement from A to C via B. The velocity is zero at A and C, as the tongue body has reached its highest and lowest point. At the midpoint of this movement (point B), the tongue body reaches its local peak velocity. The tongue body raising from [a] to [j] in the word *Kaia* is associated with the movement from point C to point A via point D. Again, at midpoint (point D), the peak velocity is reached.

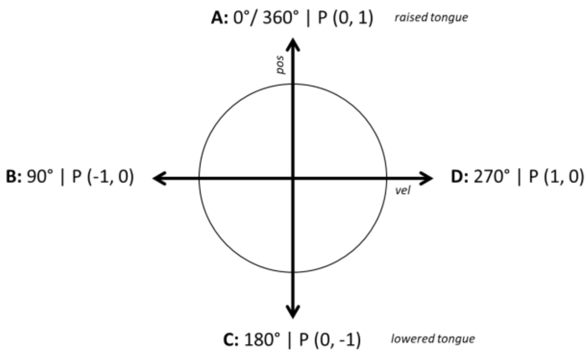

Figure 2: Tongue cycle on a phase plane.

The timing of the jaw reaching its maximum opening position for /a/ in relation to the tongue body cycle was specifically of interest in the current study. Within the tongue body cycle the occurrence of the jaw target for [a] can be defined as an angle on the phase plane, as coordinates within the phase plane can be converted into a phase angle (φ). This allows to determine the timing in degrees of the maximum jaw opening relative to the tongue body cycle.

2.5. Measurements and Statistics

To determine speech rate effects, the tongue body cycle duration was measured. The *cycle duration* refers to the time interval (in ms) between the onset of tongue body lowering from [k] for [a] to the offset of tongue body raising for [j] (both defined as the maximum position in the y-dimension, Figure 1). The phase angle (φ) at the time of the maximum jaw opening was then calculated with the following formula:

$$(1)\ \ Phase\ angle\ (\varphi) = arctan\ \left(\frac{TB\ vel_N}{TB\ pos_N}\right)$$

Values smaller than 180° indicate that the jaw reached the target position for [a] earlier than the tongue body. Angles larger than 180° indicate that the jaw reached the target position for [a] after the tongue body. Values equal to 180° indicate simultaneous arrival of the jaw and tongue body at the target position for the vowel [a].

To verify that participants significantly modulated their speech rate and to determine potential aging effects on speech rate performance, tongue body cycle durations of each participant's 10 productions at each rate condition were submitted to a linear mixed model with task and group as fixed factors and subject as a random factor. Furthermore, to determine rate effects and aging effects on spatiotemporal timing relations of the tongue body and jaw, phase angles for each participant's 10 productions in each speech rate condition were submitted to a linear mixed model. If the main effects or the interaction term were found significant at $p < .05$, pairwise post-hoc analyses with Bonferroni adjustments were completed. Statistical analyses were performed in SPSS (Version 28.0).

3. RESULTS

3.1. Speech Rate

A significant main effect of rate [$F(2,328.6) = 1276.09$, $p < .001$] and group [$F(1,68.93) = 9.63$, $p = .003$] was found. The rate *x* group interaction was not significant. In both groups, the tongue body cycle duration was shortest during fast speech, and longest during slow speech (Table 1). However, the average cycle duration regardless of rate was significantly shorter in younger speakers compared to older speakers (mean difference = 37.18 ms). Although the rate *x* group interaction was not significant, the elicited modifications in cycle duration across all rate conditions tended to be greater in the younger speakers than in the older speakers (Table 1).

	younger	older
fast	200 (7.1)	251 (6.1)
typical	275 (7.2)	322 (6.2)
slow	625 (18.7)	638 (16.4)

Table 1: Mean tongue body cycle duration *(SE)* in ms.

3.2. Timing Relation of the Tongue Body and the Jaw

Averaged jaw phase angles relative to the tongue body cycle are presented in Table 2. While the main effect of group was not significant, the main effect of rate [$F(2, 415.17) = 30.14$, $p < .001$] and the rate *x* group interaction [$F(2, 415.17) = 7.18$, $p < .001$] were significant. Pairwise comparisons of rate revealed that in younger speakers, fast speech was associated with significantly smaller phase angles relative to typical speech (mean difference = -7.47, $p < .001$) and relative to slow speech (mean difference = -11.52, $p < .001$). In addition, slow speech was associated with significantly greater phase angles than typical speech (mean difference = 4.05, $p = .007$).

	younger	older
fast	171 (2.9)	179 (2.0)
typical	178 (2.6)	178 (1.8)
slow	182 (2.5)	185 (2.0)

Table 2: Mean phase angles of the jaw (*SE*) relative to tongue body cycle in degrees.

In older speakers, greater phase angles were elicited in slow speech relative to typical speech (mean difference = 6.32, $p < .001$) and relative to fast speech (mean difference = 5.79, $p < .001$). Fast speech was not associated with significantly different jaw phase angles relative to typical speech in older speakers. No significant between-group comparisons were found at any of the three rate conditions.

3.3. Associations between Tongue Cycle Duration and Jaw Phase Angle across Speech Tasks

No significant correlations were observed between tongue body cycle durations and jaw phase angles across all speakers as well as within each age group (Figure 3). However, fast and typical speech elicited more variable jaw phase angles than slow speech within both groups. In slow speech jaw phase angles hovered around 180°, particularly in older speakers.

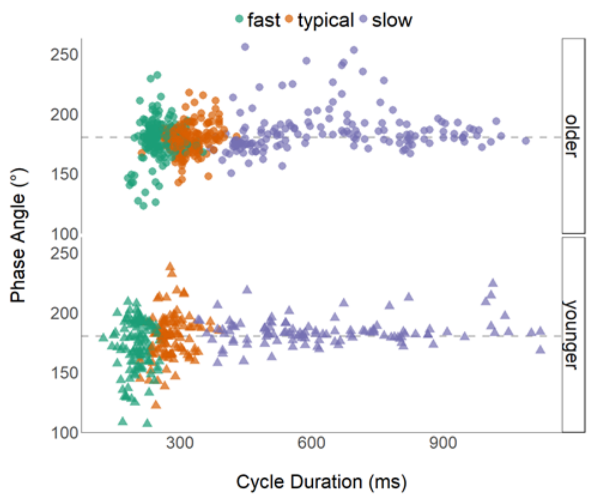

Figure 3: Jaw phase angles as a function of tongue body cycle duration for older speakers (top panel) and younger speakers (bottom panel), speech tasks are color-coded. Grey dashed lines indicate a jaw phase angle of 180°.

4. DISCUSSION

As reported in previous studies [2]–[6], rate effects on phase angles were observed in younger speakers. Phase angles were smaller during fast speech and larger during slow speech relative to typical speech. The significant changes in phase angles from typical speech to fast and slow speech suggest that younger speakers change intergestural timing patterns with task demands. Younger speakers appear to have a lot of articulatory flexibility to accomplish such changes. However, the absence of a significant correlation between cycle duration and phase angles suggests that these changes in intergestural timing are not purely duration-driven in terms of intrinsic consequences of the speech system's dynamical organization. Instead, speakers appear to switch into a different control mode when cued to speak faster or slower.

In older speakers, phase angles changed significantly in response to slow speech but not in response to fast speech relative to typical speech. Nevertheless, cycle durations differed significantly between fast, typical, and slow rates. Older speakers appear to maintain the same timing mode they use for typical speech when being cued to speak faster, although they manage to successfully shorten their cycle durations (Table 1). As phase angles tended to be larger in older adults than younger adults during fast speech (Table 2), older speakers are perhaps not able to move the articulators as independently of each other as younger speakers. This may indicate a less economical articulatory strategy, as the jaw does not move on to the next sound as quickly after it has reached the vocalic target. In addition, significant group differences were found for tongue body cycle durations with older speakers producing longer cycle durations than younger speakers across all speech rates. This finding is in line with previous studies and may suggest a slowing down of the speech system with advancing age [7], [8], [13].

Both age groups change intergestural timing for slow speech. Although the absolute durations during slow speech vary greatly in both age groups (Figure 3), the phase angles are stable [12]. This highlights the task-specific effect, as the variability in phase angles decreases. The observed rate effects on phase angles, particularly in slow speech, could provide a better context to examine intergestural timing in speakers with motor speech disorders as their speaking rate is often abnormally slow [12, 13]. Therefore, the findings of this study are an important first step to understand intergestural timing patterns in speakers with motor speech disorders.

5. CONCLUSION

Although previously reported rate effects on intergestural timing patterns were replicated, the current study showed that younger speakers are more flexible in their intergestural timing responses than older speakers. Furthermore, findings suggest that the cued speech task, but not duration itself, determines the intergestural timing patterns.

6. FUNDING

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