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Covariation among vowel height effects on acoustic measures

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Abstract: Covariation among vowel height effects on vowel intrinsic fundamental frequency (IF_0), voice onset time (VOT), and voiceless interval duration (VID) is analyzed to assess the plausibility of a common physiological mechanism underlying variation in these measures. Phrases spoken by 20 young adults, containing words composed of initial voiceless stops or /s/ and high or low vowels, were produced in habitual and voluntarily increased F_0 conditions. High vowels were associated with increased IF_0 and longer VIDs. VOT and VID exhibited significant covariation with IF_0 only for males at habitual F_0. The lack of covariation for females and at increased F_0 is discussed.

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1. Introduction

The current work examines covariation among intrinsic vowel fundamental frequency (IF_0), voice onset time (VOT), and voiceless interval duration (VID) as a function of vowel height. Issues regarding the association between laryngeal and extralaryngeal function of the speech mechanism have been addressed by many researchers. The preponderance of existing work has focused on one or two of these measures, treating issues such as IF_0 independently of other segmental variability (cf., Higgins *et al.*, 1998). Consequently, while independent association between each of these three measures of laryngeal function and vowel height has been demonstrated in the existing literature, no work has examined covariation among these three measures in a single data set.

Extralaryngeal mechanical influences on laryngeal function have been proposed to influence fundamental frequency (F_0) (Honda, 2004, 1995, 1983; Vilkman *et al.*, 1996; Sapir, 1989), VOT (Weismer, 1979; Klatt, 1975), and VID (Weismer, 1979). The magnitude of each of these acoustic measures increases for high vowel compared to low vowel contexts. Honda (1983) describes a purported mechanical relationship between vowel articulation and IF_0. In short, contraction of the genioglossus muscle causes forward movement of the hyoid bone that rotates the thyroid cartilage, resulting in increased longitudinal tension along the vocal folds.

Such an explanation could reasonably be extended to account for variation in VID and VOT. Specifically, an increase in vocal fold tension resulting from contraction of the extrinsic laryngeal and lingual musculature may exert a common influence that delays voicing by increasing phonation threshold pressure. The implication of this hypothesis is that these segmental effects may automatically co-vary. The possibility of universality of the IF_0 effect has been considered to lend further evidence toward such an explanation (Whalen and Levitt, 1995). A contrasting explanation subscribes to active control, purportedly motivated by a need to enhance spectral or durational contrast (Kingston, 2007; Diehl *et al.*, 1990). The debate over passive versus active accounts of IF_0 has received considerable attention (cf., Hoole and Honda, 2011;

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Hoole *et al.*, 2006) due in part to the observation that lax German vowels pose particular problems for a passive, mechanical account for IF_0 (Fischer-Jørgenson, 1990). Hoole *et al.* (2006) suggest that a passive, mechanical explanation is viable but that talkers may also learn to enact an active enhancement strategy. Covariation among IF_0, VOT, and VID during voluntarily increased F_0 speech would suggest that these effects are automatic, not learned (Holt *et al.*, 2001) because this is an atypical mode of speech, unfamiliar to participants. Moreover, if covariation among segmental measures reflects common, passive extralaryngeal influences that increase vocal fold tension, then increased F_0 speech should further increase the magnitude of all effects by further sensitizing the vocal folds to tension increases.

2. Methods

Participants were 20 adults (10 males, 10 females), 23-35 years old, free of any speech, language, or hearing impairments. Speech was recorded in a sound-insulated booth. Talkers read CVC sequences in the carrier phrase "Say ______ instead." Each sequence was repeated five times in random order at a subject's habitual F_0, and five additional times at an F_0 approximately one-quarter octave above the habitual F_0. For example, a male with habitual F_0 of 120 Hz was required to speak at 150 Hz or above. This behavior was practiced by each participant and then monitored by the experimenter. CVCs included voiceless initial stops (/p, t, k/) and the voiceless initial fricative /s/ with vowels /i/, /u/, /a/, and /ae/ and the final consonant /d/.

CSPEECH (Milenkovic, 1988) was used to measure: *F_0*—measured from the average F_0 across 5 middle cycles of the vowel duration; *VOT*—measured from the release of the stop burst, to the first glottal pulse of the following vowel; *VID*—measured from the last glottal pulse of the preceding vowel to the first glottal pulse of the following vowel.

3. Results

A total of 11 946 measures were viable and contributed to the results.

For females, the mean F_0 difference between high and low vowels was greater in the increased F_0 (~27 Hz) compared to the habitual F_0 (~23 Hz) conditions with high vowels produced at a higher average frequency. This pattern was also observed for males with high-low vowel differences greater in the increased F_0 condition (~17 Hz) compared to habitual F_0 (~11 Hz; Table 1).

For females, vowel height contrasts resulted in mean VOT differences that were small and non-significant for /p/ and /t/ at both habitual and increased F_0. High vowel contexts did result in significantly longer VOT durations (~10 ms) for /k/ at the habitual F_0 and longer VOTs (~12 ms) at the increased F_0.

For males, vowel height contrasts resulted in longer VOT durations for high versus low vowels for every consonant at each F_0 with the exception of /p/ (~5 ms) at the habitual F_0. At habitual F_0, mean VOT differences were significant and slightly larger for /t/ (~7 ms) and larger yet for /k/ (~14 ms). At increased F_0, a similar pattern emerged with significant VOT differences that were smallest for /p/ (~6 ms), larger for /t/ (~9 ms), and largest for /k/ (~18 ms).

Vowel height contrasts on VOT durations were always greater at the increased F_0 for every consonant, for both males and females (Table 2).

Table 1. IF_0 (Hz) mean (s.d.) and comparisons between vowel heights (across consonant).

Gender	Condition	High vowels	Low vowels	*t*-Test
Female	Habitual F_0	229.6 (22.8)	207.1 (16.7)	$t\,(731) = -15.90$, $P < 0.001$
	Raised F_0	329.5 (39.2)	302.1 (39.6)	$t\,(795) = -9.85$, $P < 0.001$
Male	Habitual F_0	128.5 (14.4)	117.8 (13.2)	$t\,(791) = -10.94$, $P < 0.001$
	Raised F_0	194.2 (26.2)	177.2 (35.0)	$t\,(738) = -7.79$, $P < 0.001$

Table 2. VOT (ms) mean (s.d.) and comparisons between vowel heights (within consonant).

Gender	Condition		High vowels	Low vowels	*t*-Test
Female	Habitual F_0	/p/	98.9 (17.3)	96.8 (23.1)	NS
		/t/	108.3 (19.0)	107.9 (21.2)	NS
		/k/	118.3 (20.4)	108.6 (23.8)	$t\,(192) = 3.08$, $P = 0.0024$
	Raised F_0	/p/	82.1 (29.1)	73.3 (29.6)	NS
		/t/	91.3 (28.2)	85.9 (30.9)	NS
		/k/	97.4 (23.7)	85.1 (39.9)	$t\,(162) = 2.64$, $P = 0.0091$
Male	Habitual F_0	/p/	77.5 (16.6)	72.5 (14.6)	NS
		/t/	88.1 (15.3)	81.6 (15.8)	$t\,(197) = 2.99$, $P = 0.0032$
		/k/	96.9 (16.0)	83.1 (15.3)	$t\,(197) = 6.21$, $P < 0.001$
	Raised F_0	/p/	64.1 (16.0)	58.0 (17.9)	$t\,(195) = 2.54$, $P = 0.012$
		/t/	78.4 (15.5)	69.8 (20.4)	$t\,(184) = 3.39$, $P < 0.001$
		/k/	90.1 (15.1)	72.3 (20.1)	$t\,(183) = 7.09$, $P < 0.001$

For females, average VIDs were significantly longer for all consonants preceding high versus low vowels at each F_0. At habitual F_0, /p/ showed the smallest average difference (~11 ms), followed by /t/ (~19 ms) and /k/ (~19 ms) with /s/ having the largest average difference (~29 ms). At the increased F_0, /p/ and /s/ had similar average VID differences (~15 ms) with larger /t/ and /k/ differences (~22 ms).

For males, average VIDs were significantly longer for all consonants preceding high versus low vowels in each F_0 condition. At habitual F_0, /p/ showed the smallest average difference (~13 ms), followed by /t/ (~18 ms), /s/ (~20 ms), and /k/ (~23 ms). At the increased F_0, /p/ again showed the smallest average VID difference (~14 ms), followed by /s/ (~27 ms), /t/ (~18 ms), and /k/ (~28 ms).

Vowel height contrasts on VID were greater at the increased F_0 for every stop consonant for both males and females (except for males, where /t/ showed equal average VID differences in both F_0 conditions). However, /s/ showed a different pattern for both males and females with vowel height contrasts on VID greater at habitual F_0 (Table 3).

Covariance was analyzed pairwise by calculating the correlation coefficients and corresponding *t*-values to evaluate significance. The square of the correlation coefficient (r^2) was calculated to quantify the variance accounted for in each analysis.

For females, there were no significant covariances between VOT durations and IF_0 in either F_0 condition for any consonant. For males, covariances were significant for all consonants at habitual F_0 (/p/, $r^2 = 0.171$, $t\ (38) = 2.79971$, $P = 0.01$; /t/, $r^2 = 0.287$, $t\ (38) = 3.911$, $P = 0.001$; /k/, $r^2 = 0.407$, $t\ (38) = 5.10695$, $P = 0.001$). No significant covariances were found in the increased F_0 condition. When data were pooled across consonants, no significant covariances were found between VOT durations and F_0 across either subject group.

For females, there were no significant covariances between VIDs and IF_0 in either F_0 condition, in any consonant context. For males, covariances were significant for all consonants at habitual F_0 (/p/, $r^2 = 0.403$, $t\ (38) = 5.06474$, $P = 0.001$; /t/, $r^2 = 0.51$, $t\ (38) = 6.28896$, $P = 0.001$; /k/, $r^2 = 0.329$, $t\ (38) = 4.31647$, $P = 0.001$; /s/, $r^2 = 0.602$, $t\ (38) = 7.58138$, $P = 0.001$). No significant covariances were found in increased F_0. When data were pooled across consonant, statistically significant covariances were found for females at both the habitual F_0 and increased F_0 across subjects (habitual F_0, $r^2 = 0.788$, $t\ (14) = 7.21372$, $P = 0.001$; increased F_0, $r^2 = 0.731$, $t\ (14) = 6.16803$, $P = 0.001$). The same was true for males (habitual F_0, $r^2 = 0.717$, $t\ (14) = 5.95567$, $P = 0.001$; increased F_0, $r^2 = 0.672$, $t\ (14) = 5.35564$, $P = 0.001$).

4. Discussion

Mean differences in IFO between high and low vowels were significant for both women and men, and in both habitual and increased F_0 conditions. In addition, the

Table 3. VID (ms) means (s.d.) and comparisons between vowel heights (within consonant).

Gender	Condition		High vowels	Low vowels	*t*-Test
Female	Habitual F_0	/p/	208.4 (28.9)	197.6 (32.3)	$t\,(194) = 2.50$, $P = 0.013$
		/t/	210.6 (30.2)	191.2 (32.2)	$t\,(195) = 4.36$, $P < 0.001$
		/k/	216.9 (27.7)	197.8 (34.9)	$t\,(188) = 4.29$, $P < 0.001$
		/s/	213.6 (34.5)	185.0 (31.3)	$t\,(195) = 6.12$, $P < 0.001$
	Raised F_0	/p/	178.9 (37.8)	163.5 (37.9)	$t\,(194) = 2.85$, $P = 0.0048$
		/t/	184.4 (37.6)	162.1 (37.1)	$t\,(193) = 4.17$, $P < 0.001$
		/k/	185.5 (30.0)	163.6 (33.0)	$t\,(194) = 4.89$, $P < 0.001$
		/s/	177.4 (34.4)	162.0 (26.3)	$t\,(189) = 3.66$, $P < 0.001$
Male	Habitual F_0	/p/	182.6 (23.1)	169.7 (21.1)	$t\,(196) = 4.12$, $P < 0.001$
		/t/	184.6 (30.2)	166.9 (24.1)	$t\,(179) = 4.48$, $P < 0.001$
		/k/	188.8 (27.7)	166.3 (24.1)	$t\,(194) = 6.14$, $P < 0.001$
		/s/	194.7 (25.3)	171.7 (23.3)	$t\,(196) = 5.13$, $P < 0.001$
	Raised F_0	/p/	164.9 (27.8)	151.3 (28.4)	$t\,(194) = 3.42$, $P < 0.001$
		/t/	167.3 (27.6)	149.3 (30.1)	$t\,(196) = 4.41$, $P < 0.001$
		/k/	179.2 (27.8)	151.5 (27.3)	$t\,(195) = 7.07$, $P < 0.001$
		/s/	173.1 (24.8)	155.8 (22.8)	$t\,(196) = 5.13$, $P < 0.001$

differences between the means of high and low vowels were exaggerated in the increased F_0 condition.

Vowel height effects on VOT were observed for males in both F_0 conditions with significantly longer VOT before high vowels (except for /p/ at habitual F_0). For females, vowel height effects on VOT were observed for /k/ in both F_0 conditions. At increased F_0, slight, non-significant vowel height effects were observed for /p/ ($\sim$9 ms), and /t/ ($\sim$5 ms).

More consistent effects of vowel height were observed for VID with durations for all consonants significantly longer before high vowels for both men and women and in both F_0 conditions. For stop consonants, the effects of vowel height on mean durations of both VOT and VID were exaggerated in the increased F_0 condition. Data with /s/ did not follow this pattern.

The finding of significant vowel effects on VOT durations for only the female /k/ productions may reflect the confluence of place and gender effects on VOT. Several researchers have demonstrated an effect of place of articulation on VOT durations (Volaitis and Miller, 1992; Klatt, 1975; Lisker and Abramson, 1964). Specifically, VOT durations for stop consonants increase from bilabial to alveolar to velar place of articulations. Differences in the time-varying cross-sectional area of the constriction release, conditioned by place of articulation, could contribute an aerodynamic influence on place-conditioned differences in VOT. This aerodynamic influence could interact with the raising of the tongue for /k/, which could indirectly increase tension in the vocal folds, further increasing phonation threshold pressure (Solomon *et al.*, 2007; Titze, 1992) and delaying voicing.

Females tend to produce longer VOTs than males (Swartz, 1992; Whiteside and Irving, 1997; Ryalls *et al.*, 1997; Koenig, 2000; Robb *et al.*, 2005). Voiceless stop contexts appear to reveal this effect most consistently. Results for voiced consonants are equivocal, with some studies reporting a comparable effect (Swartz, 1992; Whiteside and Irving, 1997; Ryalls *et al.*, 1997), and others reporting a tendency for male VOTs to be longer than female VOTs (Smith, 1978; Whiteside and Irving, 1998).

Two studies suggest that gender differences in VOT are eliminated by correcting for (Allen *et al.*, 2003), or controlling (Morris *et al.*, 2008) gender differences in speaking rate. In the current data, average vowel durations for females were longer than for males ($\sim$25 ms for habitual F_0 and $\sim$8 ms for increased F_0), indicating that females tended to assume a slower speaking rate. Moreover, vowel duration changed significantly with F_0 condition only for females, with shorter vowel durations (∼14 ms) for increased F_0 compared to habitual F_0. Thus females spoke faster in the increased F_0 condition (compared to habitual F_0), whereas males did not. VOT durations can decrease with increasing speaking rate (Volaitis and Miller, 1992; Wayland *et al.*, 1994) and with increasing F_0 (McCrea and Morris, 2005). VOT durations may also increase in clear speech conditions with or without accompanying decreases in speaking rate (Picheny *et al.*, 1986; Krause and Braida, 2004). Taken together, the relationship between F_0 condition and speaking rate and the overall slower rate assumed by female participants suggests that females may have been more apt to assume a clear mode of speech, despite receiving no instructions regarding speech clarity. This possibility could account for the lack of covariation among female measures due to competing demands on laryngeal control.

The increased F_0 condition was assumed to eliminate learning influences on possible covariation and provide a further test for a strictly passive, mechanical account of segmental variability. The lack of covariation exhibited within this condition could suggest that covariation observed for the male speakers' habitual F_0 speech is, in fact, reflective of a learned, active covariation. Another explanation is that the increased F_0 condition increased the influence of reflexive neural coupling on laryngeal control (Liu and Larson, 2007; Sapir, 1989). High F_0 phonation is characterized by a reduction in F_0 jitter (Gelfer, 1995). An increased sensitivity to mechanical and auditory perturbation during increased F_0 speech (increased "pitch shift reflex"), presumably to achieve this increased vocal stability, could involve a general increase in laryngeal and extralaryngeal muscular contraction (Larson *et al.*, 2008; Liu and Larson, 2007; Loucks *et al.*, 2005; Sapir *et al.*, 2000). Such a mechanism could conceivably disrupt passive, mechanical covariation among segmental measures by stiffening the laryngeal and extralaryngeal mechanism and reducing the motor system tolerance for passive variation. While much of the research addressing this issue has looked at sustained phonation, pitch reflex sensitivity has been show to vary as a function of F_0 during speech (Liu *et al.*, 2010).

In summary, the present study demonstrates covariation among IF_0, VOT, and VID for male participants speaking at a habitual F_0. Covariation among these three acoustic measures has not been previously demonstrated. While differences between high and low vowel conditions were quite small, and significant covariation among measures was confined to the male, habitual F_0 data, the finding of covariation is consistent with a common passive, mechanical account for variability of these segmental measures. Data acquired from females and during voluntarily increased F_0 speech were not consistent with the passive, mechanical account. A lack of covariation in the female data may have reflected a group tendency toward a clear speech mode during data acquisition. Increased F_0 speech may invoke an increase in reflexive neural coupling that confounds passive, mechanical mechanisms of covariation among IF_0, VOT, and VID. Overall, the results of the current work suggest that a common passive, mechanical explanation for the acoustic effects of vowel height variation may only be plausible for certain talkers and speaking conditions. Thus while some variation in these acoustic measures may derive automatically from extralaryngeal influences, talkers can actively modify laryngeal behavior to enhance specific acoustic cues (Hoole and Honda, 2011).

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