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Changes in Articulatory Contact Pressure as a Function of Vocal Loudness

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Abstract: This study evaluated the impact of vocal loudness on the articulatory contact pressure (ACP) between the tongue and palate during the production of lingua-alveolar consonants. Fourteen adults with typical speech produced phrases with the phonemes /t, d, s/ embedded while ACP was sensed with a miniature pressure transducer attached to a palatal appliance. Stimuli were produced at four loudness levels: habitual, twice as loud (loud), half as loud (soft), and whisper. There was a statistically significant difference in ACP as a function of loudness for all three phonemes ($p < 0.001$ for each). Post hoc comparisons indicated that ACP during loud speech was significantly greater than habitual for each phoneme. ACP during soft speech was significantly less than habitual for /t/ and /d/, but not /s/. Whispered speech ACP values were significantly lower than soft for /t/ and /d/, but not /s/. The results indicate that changes in vocal loudness cause changes in ACP that are most evident for stop consonants /t, d/, and, to a lesser extent, the fricative /s/. A louder voice was associated with higher ACP. Elevated ACP may have implications for oral aerodynamics that could help explain why loud-focused clinical treatments improve articulation, although this remains to be empirically confirmed.

Keywords: loud; loudness; articulation; contact pressure; speech; tongue; palate

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1. Introduction

Tongue contact with the palate is critical for the articulation of several sounds in languages spoken around the world. Such contact is necessary to create an obstruction to the airstream, resulting in intraoral air pressure (P_O) build-up which, when released, results in a burst that is characteristic of lingua-alveolar, lingua-palatal, and velar stop consonants [1]. Likewise, contact between the tongue and palate is important to create constrictions, but not complete obstruction, within the oral cavity to create a narrowing within the oral cavity that results in turbulent airflow for the production of various fricative sounds such as /s/ and /ʃ/. Despite the importance of tongue-to-palate contact across multiple speech sounds, features of this contact pressure during speech, such as its amplitude, duration, and variation across sounds and speaking conditions, have received limited attention.

Although contact between the tongue and palate is important, speech is a low force task that does not require substantial tongue strength [2]. When instructed to speak using a person's 'typical' or 'habitual' speech, the articulatory contact pressures (ACPs) between the tongue and palate range from approximately 1 to 4 kPa [3,4], although even higher pressure up to a mean of 8 kPa has been reported [5]. Although the data are sparse, differences in ACP as a function of the specific phoneme have been reported with lingua-alveolar stop consonants having higher ACP than alveolar fricatives, affricates, nasals, and glides [3,6]. Additionally, the position of the consonant within a syllable can influence the maximum amplitude of the ACP [7].

In addition to variations as a function of stimulus features (i.e., phoneme type, syllable shape), there is evidence of altered ACP in individuals with speech disorders. Adults diagnosed with amyotrophic lateral sclerosis have been found to produce lingua-alveolar phonemes with significantly lower maximum ACP than age- and gender-matched adults without a speech disorder [8]. In contrast, higher ACP has been reported after the complete removal of the larynx (i.e., total laryngectomy), with the increased sense of speaking effort significantly correlated with ACP [9]. Elevated ACP has also been reported for bilabial plosives after total laryngectomy [10]. The findings from individuals without a larynx have been interpreted as most likely resulting from the person's attempt to overexaggerate their articulation to maximize speech intelligibility. Research has also shown that patients with a glossectomy produced the phonemes /t/, /tʃ/, and /ʃ/ with ACP that did not differ, which was in contrast to a non-glossectomy control group for whom ACP did differ across phonemes [3]. The fact that ACP does change in some patient populations relative to those with typical speech sound production highlights the potential use of ACP for diagnosing speech issues and potentially tracking change in speech status as a function of time, disease, recovery, or intervention (e.g., speech therapy, medication, surgery, etc.).

One aspect of ACP production that has received almost no attention is the set of parameters that might alter the tongue–palate pressure. Changes to speech in terms of the rate, pitch, loudness, and articulatory precision are known to be influenced by a variety of factors such as the competing environmental noise [11], hearing status of the listener [12], distance between communication partners [13], language spoken by bilingual individuals [14,15] (Nevo et al., 2015; Ryabov et al., 2016), and differing language backgrounds of communication partners [16], among other factors. In clinical settings where the goal may be to rehabilitate or optimize speech, parameters such as the rate of speech [17,18], loudness [19,20], and articulatory precision [21,22] may be the target of the intervention approach. Changing certain aspects of the speech production process such as the rate, loudness, or precision seems likely to cause changes in aspects of articulatory contact, including ACP. For example, healthy adults without communication disorders have been shown to significantly increase ACP when instructed to use 'clear speech' [23].

Nothing has been reported in the literature regarding how ACP might change under instruction to increase or decrease the loudness of speech. Loudness is a parameter that is often targeted in the therapeutic setting for various purposes. In some instances, the focus is to reduce habitual loudness (or at least to limit the use of loud speech) to avoid vocal fold tissue trauma [24]. In other situations, the goal is to increase vocal loudness and vocal effort. Increases in these parameters are emphasized in therapeutic approaches with individuals who have Parkinson's disease (PD), such as through the application of the Lee Silverman Voice Treatment (LSVT LOUD®) [25] or SPEAKOUT! [26]. The outcome data regarding the LSVT LOUD indicate that it is an effective means of increasing vocal loudness in this patient population [27–29]. Of relevance here, this therapy intervention has been shown to also create positive changes to articulation, such as increased vowel formant triangle area, perceived vowel goodness [25], increased articulator displacements and velocities [30], and improved speech intelligibility [29], in people with PD, highlighting the interaction between behaviors of the phonatory and oral articulatory systems. Such interaction has been noted for measures such as articulator movement velocity and the maximum distance moved in adults with typical [31–34] and disordered speech [35,36] as well as in children [37].

The purpose of this study was to evaluate the impact of vocal loudness on the ACP of lingua-alveolar consonants. The four loudness conditions evaluated were self-determined habitual loudness (habitual), half as loud as habitual (soft), twice as loud as habitual (loud), and whispered speech (whisper). The hypothesis was that the ACP on the consonants would increase from soft, to habitual, to loud speech. Different individuals produce the whispered voice differently, at least in terms of glottal configuration and aerodynamics [38], and inter- and intra-individual variation has been large in some studies [39]. As such, there was not a firm hypothesis about where ACP during whispering would be relative to the other loudness conditions.

2. Materials and Methods

2.1. Participants

Fourteen adults (9 females and 5 males) ranging from 28 to 48 years old (mean = 36 years, standard deviation = 6 years) provided the speech samples for the study. They were a convenience sample who all spoke standard American English as their primary language and all were participating in a larger study looking at typical ACP values for the lips and tongue [40]. All were screened and found to have a negative history of speech, language, hearing, neurological disease, head and neck cancer, or other conditions that are known to impact speech. Two certified speech-language pathologists evaluated their oromotor function and speech production which were determined to be typical in all cases.

2.2. Speech Stimuli

The stimuli sampled in this study were three lingua-alveolar phonemes (/t, d, s/) in the syllable-initiating position of the monosyllable words /tɪp/, /dɪp/, and /sɪp/ that were placed in the carrier phrase "you CVC here", which was produced using a person's habitual speaking rate, loudness, and articulation. These stimuli were also sampled in three other loudness modes, namely, whisper, soft, and loud. This set of consonants provided the opportunity to sample ACP across phonemes that varied in terms of their voicing feature (/t/ vs. /d/) and manner of production (/t/ vs. /s/). The CVC vowel was held constant, as was the vowel preceding and following the CVC word. The consonant chosen to end the CVC stimulus allowed for a meaningful American English word and avoided tongue contact on the alveolar ridge to make it easier to identify the tongue–palate pressure peak for the CVC-initiating consonant.

The stimuli were presented on a computer screen with instructions to say the phrase using a specific loudness level, as depicted in Figure 1. A direct magnitude estimation (DME) procedure was utilized to elicit the soft and loud conditions. This procedure allows individuals to perceptually judge their loudness level relative to a "standard" (i.e., a modulus), which in this case was the loudness level they typically use during daily communication (i.e., termed habitual for this study). An arbitrary value of 100 is assigned to this loudness and then they are asked to vary their loudness based on their auditory perception of their voice (i.e., their loudness) relative to this modulus. DME procedures have been utilized for other tasks requiring auditory perceptual judgements such as voice quality, speech intelligibility, and stuttering severity [41–43]. For the loud condition, participants were prompted to double their loudness and produce the stimulus at a value of 200. Likewise, for the soft condition, they were instructed to use a loudness level that was half of their habitual level, or a value of 50. The whisper condition was represented on the DME scale as a value of 0 and participants were also verbally instructed to whisper as if they were telling a secret in a quiet room. The target loudness level for a given production was indicated by altering the displayed text to show the intended loudness condition presented in red font with a double circle around it. Although it was not necessary for participants to precisely double the perceived loudness (roughly considered to be about 10 dB) or halve their loudness (roughly 10 dB less than usual) in the loud and soft conditions, as a group they did consistently adjust in the expected directions and magnitude, as reflected in the sound level meter recordings that were obtained. The mean habitual loudness for the group summed across all three sentences and repetitions was measured at 63.2 dB (sd: 1.61) compared to 71.8 db (sd: 2.67) in the loud condition and 55.3 dB (sd: 3.1) in the soft condition; the whisper condition was measured at 51.9 dB (sd: 1.0).

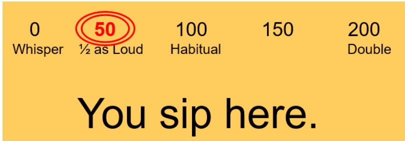


Figure 1. Example of a stimulus presentation to elicit the carrier phrase at differing loudness levels using a direct magnitude estimation approach. In this example, the phrase is to be produced in the "half-as-loud" or soft condition.

Each CVC stimulus was produced five times for each phoneme in a block in each of the four loudness conditions (whisper, soft, habitual, and loud) for a total of 60 productions per participant and 840 samples in total across the 14 participants. The order of the sentences was randomized within each loudness condition, and the loudness conditions were randomized across participants. The pace of the stimulus presentation was controlled by a researcher and allowed for taking a breath and taking a drink of water if needed.

2.3. Instrumentation

The instrumentation has been described previously [6]. Briefly, an Entran EPI-BO transducer was mounted on a 0.5 mm thick palatal mold that was custom made for each participant from a dental casting of the maxillary arch. The transducer diameter is 2 mm and has a pressure range from 0 to 68 kPa. The transducer was placed on the alveolar ridge at a known point of articulatory contact between the tongue and palate, as determined ahead of time by electropalatography. For the /t/ and /d/ phonemes in this study, the placement for all the participants varied slightly but was approximately 2–6 mm posterior to the central incisors in the midline. For /s/, most speakers had contacts off midline on the left and the right side, which is consistent with the typical production of this fricative that involves the elevation of the tongue to the palate, but with a central groove to create a turbulent airflow.

The transducer signal was amplified and routed to a PowerLab 8 SP digital converting system for recording using LabChart 8.1.28 software (20 kHz digitization, 16-bit precision). To optimize the identification and measurement of the maximum ACP, the signal was low-pass filtered at 50 Hz. A peak-picking routine in LabChart was used to identify the maximum ACP signal excursion from baseline corresponding to the consonant phoneme of interest. To confirm that measurements were taken from the consonant, a headset microphone (AKG C410) was in place on the participant throughout the data collection, with the signal routed through an amplifier (Shure SCM262) and into a second channel of the PowerLab system. The audio signal was displayed simultaneously with the ACP signal and could be played back by the researchers to confirm what was being said and to confirm the location of the target phoneme in the phrase.

2.4. Procedures

Data collection was completed in one visit lasting approximately 60 min in a quiet research lab. The palatal mold was placed in the mouth with the transducer attached. The participant wore the appliance for 15 min while engaging in conversation with the researcher and reading various reading passages to allow accommodation to the device. Then, they were seated in front of a computer monitor that displayed the instructions and the stimuli. The monitor for the computer that was used for the ACP and audio recording was turned away from the view of the participant. Data collection proceeded under the control of the researcher who advanced the stimulus display with a 3 s pause between stimuli. If a misreading of a stimulus occurred, the trial was repeated.

2.5. Analysis

To address the study aim, a mean ACP was calculated for each consonant (/t/, /d/, /s/) for each participant. Preliminary assessment revealed a violation of the assumptions regarding homogeneity of variance for the planned comparisons and normality of the distributions of ACP values for some phonemes and loudness conditions, which prompted the use of the nonparametric statistical procedure, the Friedman's test. Three Friedman's tests were applied, one for each phoneme with ACP as the dependent variable that was compared within subject across the four loudness conditions. An alpha level of 0.05 was shared across these three tests, such that a $p < 0.017$ was considered statistically significant. In the event of a statistically significant Friedman's test, subsequent Wilcoxon signed-rank tests were planned for all pairwise comparisons of the loudness conditions. A Bonferroni correction was applied for the 18 possible post hoc tests (i.e., 6 paired comparisons × 3 phonemes), such that a $p < 0.003$ was considered statistically significant. The effect size estimates for each Wilcoxon test were computed as r = Z value divided by the square root of N (number of observations over two loudness conditions being compared) based on procedures from [44]. The interpretation of the effect sizes used Cohen [45] criteria of 0.1 for small effect, 0.3 for medium effect, and 0.5 for large effect. Individual differences in patterns of ACP change across the loudness conditions were also informally considered through the plotting of values per participant. All statistical procedures were completed using IBM SPSS Statistics software (version 28.0.0.0).

3. Results

Figure 2 displays the ACP group data in each loudness condition. There was a statistically significant difference in ACP for the phoneme /t/ as a function of loudness, $\chi^2(3) = 40.886$, $p < 0.001$. In the post hoc testing (Table 1), all paired comparisons of ACP for /t/ were statistically significant and indicated the highest values for loud, followed by habitual, whisper, and then soft. For each pairwise comparison, the effect sizes were large (0.58–0.62) using Cohen's (1988) [45] criteria. ACP also differed significantly across the loudness conditions for the phoneme /d/, $\chi^2(3) = 36.429$, $p < 0.001$. For the post hoc tests, all paired comparisons except one were statistically significant (Table 1) and had large effect sizes (0.60–0.62). The habitual and whisper conditions did not differ significantly for /d/ (medium effect of 0.46), but in all other cases, ACP descended from the highest values for loud, followed by habitual, whisper, and soft. Lastly, there was a statistically significant difference in ACP for the phoneme /s/, $\chi^2(3) = 33.000$, $p < 0.001$. The post hoc testing indicated that ACP was significantly greater in the loud condition compared to the habitual, soft, and whisper conditions (large effect of 0.62 for each compared to loud). However, the habitual, soft, and whisper conditions did not differ from one another, although the effect sizes were medium to large (habitual–soft = 0.55, habitual–whisper = 0.44, soft–whisper = 0.53).

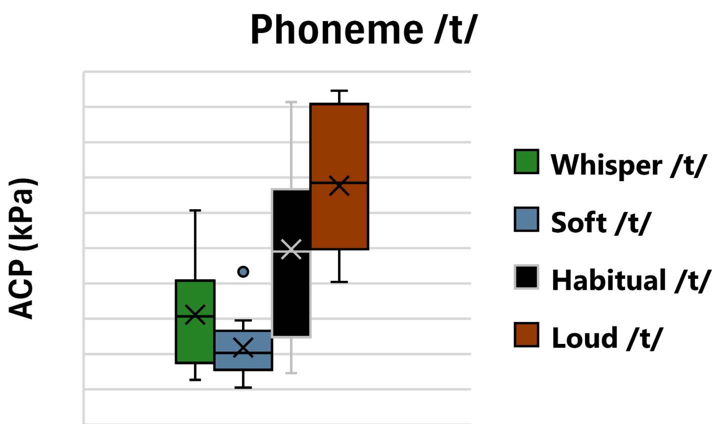


Figure 2. *Cont.*

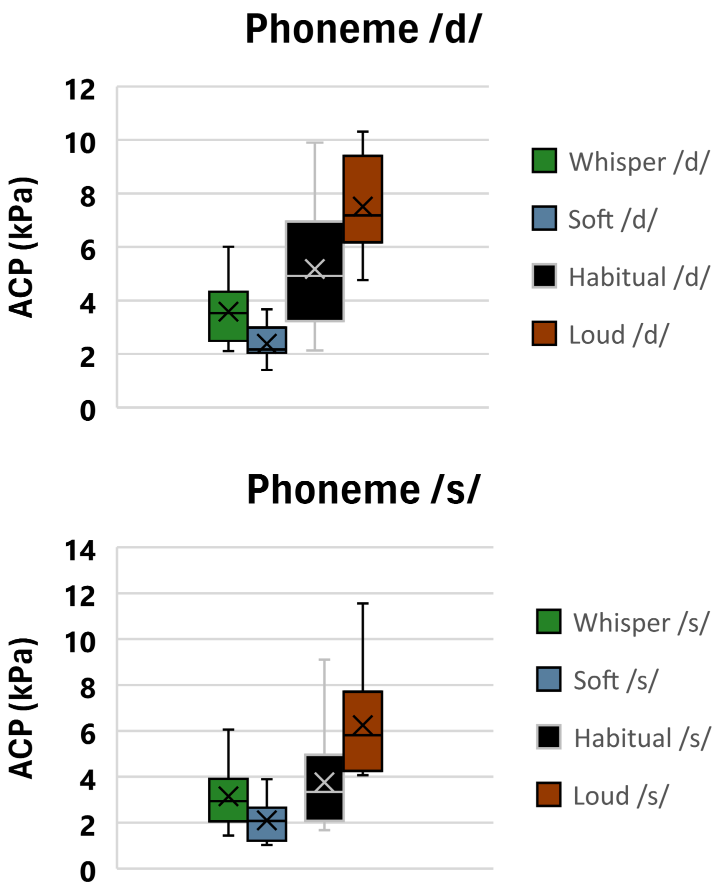
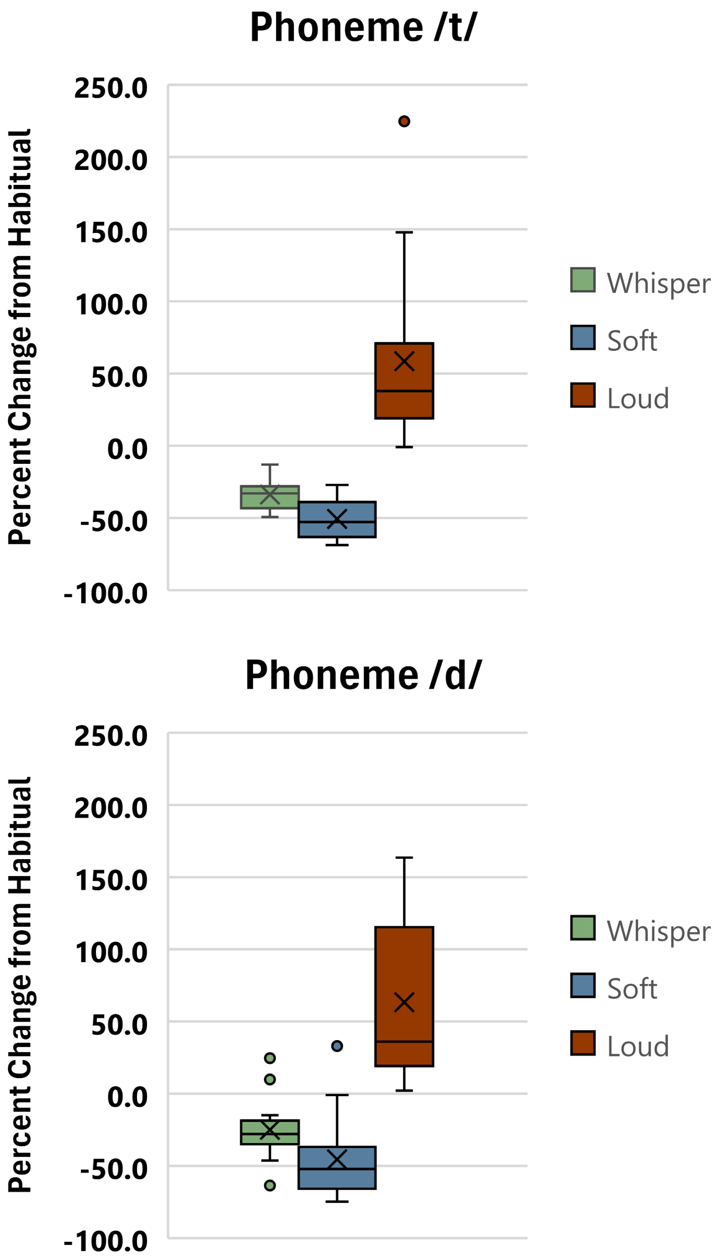


Figure 2. Box-and-whisker plots for articulatory contact pressure (ACP) for each phoneme in the four loudness conditions.

Table 1. Wilcoxon signed-rank test results for all paired comparisons of the articulatory contact pressure (ACP) mean across loudness conditions for /t/, /d/, and /s/. Probability values < 0.00278 (*p*) were considered statistically significant. *Z* = statistic for the Wilcoxon signed-rank test.

Phoneme	Loudness Condition	Statistic	Loudness Condition		
			Soft	**Habitual**	**Loud**
/t/	Whisper	Z	−3.296	−3.297	−3.296
		p	<0.001	<0.001	<0.001
	Soft	Z	--	−3.297	−3.297
		p	--	<0.001	<0.001
	Habitual	Z	--	--	−3.233
		p	--	--	0.001
/d/	Whisper	Z	−3.297	−2.417	−3.296
		p	<0.001	0.016	<0.001
	Soft	Z	--	−3.170	−3.297
		p	--	0.002	<0.001
	Habitual	Z	--	--	−3.170
		p	--	--	0.002
/s/	Whisper	Z	−2.794	−2.323	−3.297
		p	0.005	0.020	<0.001
	Soft	Z	--	−2.88	−3.296
		p	--	0.004	<0.001
	Habitual	Z	--	--	−3.297
		p	--	--	<0.001

In order to capture the magnitude of change in ACP as a function of loudness, the percentage change in the loud, soft, and whisper conditions relative to an individual participant's habitual condition was calculated. Group data for the percent differences are presented in Figure 3. Based on the median percent differences, ACP in the loud condition was approximately 38% higher than the habitual condition for /t/, 36% higher for /d/, and 90% higher for /s/. In contrast, ACP in the soft condition was 53% lower than the habitual condition for /t/, 52% lower for/d/, and 37% lower for /s/. Likewise, ACP was lower in the whisper condition compared to the habitual condition by 33% for /t/, 27% for/d/, and 11% for/s/.



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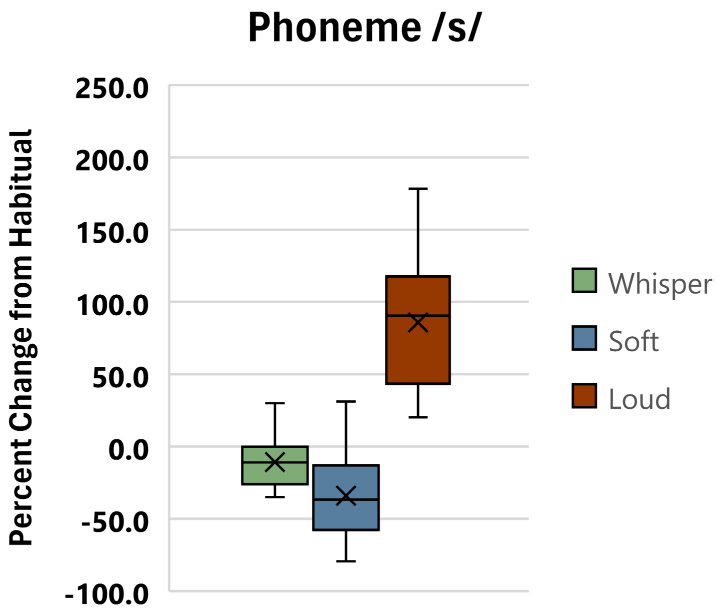
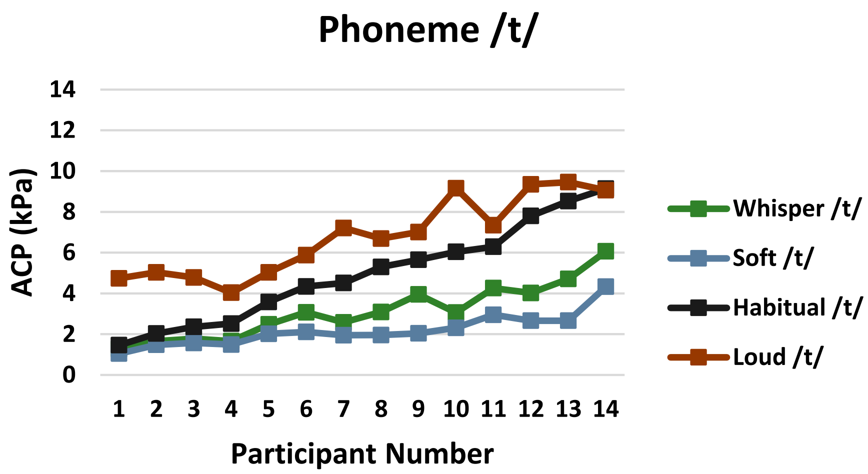


Figure 3. Box-and-whisker plots of the percent change in ACP in the whisper, soft, and loud conditions relative to the habitual condition for each of the experimental phonemes. Bars = interquartile range; line within bars = median; X within bars = mean; whiskers = minimum and maximum; dots = outliers.

To gain insight regarding the changes in ACP at the level of the individual, the ACP values for each participant are plotted in Figure 4 by the phoneme and loudness condition. In this case, the participants were ordered on the *x*-axis from those with the lowest to the highest ACP in the habitual condition. In general, these plots indicate that individuals who tend to produce higher ACP in their habitual productions than others also tend to produce higher ACP than others in their loud and whisper productions. For the soft condition, the pattern is less pronounced and only present for the phoneme /t/.



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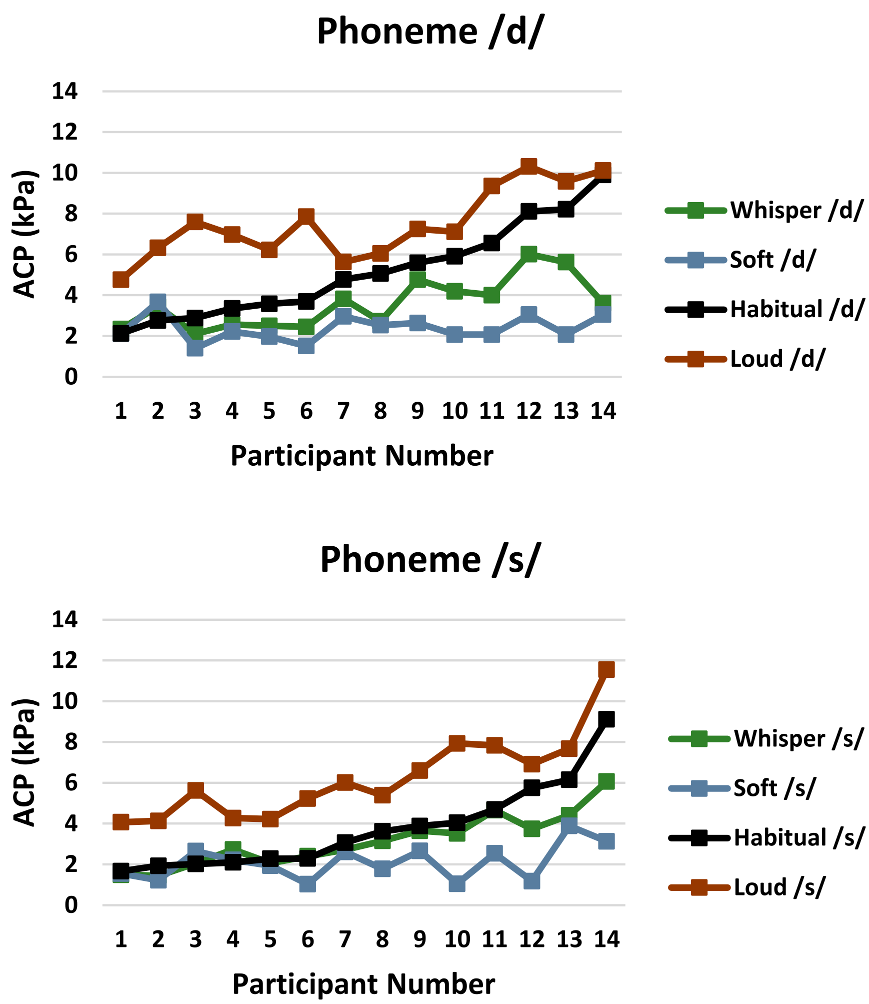

Figure 4. Articulatory contact pressure (ACP) for each phoneme produced in the four loudness conditions plotted for individual participants ordered from the least to the greatest ACP in the habitual condition.

4. Discussion

This study evaluated the influence of vocal loudness on the tongue-to-palate contact pressure generated during speech. Overall, the findings supported the hypothesis that ACP differs as a function of loudness with significantly greater values in the loud condition compared to the others for all three phonemes. The habitual condition tended to have higher ACP than the soft and whisper conditions, although these differences were not all statistically significant, depending on the phoneme.

The novel finding from this study is that altering vocal loudness is associated with articulatory changes reflected in ACP measures. The magnitude of the change in ACP was large, with it being at least 36% greater in the loud condition compared to the habitual condition. Conversely, the ACP values for the three phonemes were at least 37% smaller in the soft compared to the habitual condition. There are no other benchmark data in the literature for comparison, but the current results indicate that the alterations to tongue–palate pressure are substantial when a person either increases or decreases their loudness.

Previous studies have identified other influences besides loudness on ACP, such as the phoneme class [3] and syllable structure [7]. The fact that ACP varies across loudness conditions is consistent with other studies documenting changes in oral articulatory activity when adjustments are made in the phonatory system. For example, loudness manipulation has been shown to result in associated changes in speech-related movement strokes and spatial variation of the trajectory of articulator movements [34]. Others have reported that increasing loudness resulted in increased articulatory displacement and velocity of the upper and lower lips during bilabial stop consonants [46]. The current ACP results are congruent with these studies, and together, the literature highlights that the phonatory and articulatory subsystems influence one another.

In a clinical context, increasing a person's vocal loudness may increase their ACP, although this remains to be determined in future studies that include individuals with speech disorders from conditions such as PD. High values of ACP have been associated with increased oral air pressure during stop consonant production [47]. One outcome of an increase in oral air pressure is likely to be a more intense burst or frication on phonemes, which could have a positive impact on the clarity of speech [23]. Although this needs to be confirmed empirically, one reason that loud-focused interventions often help people with PD and those with non-progressive dysarthria may be the concomitant increase in ACP with associated increases in oral air pressure on stops and fricatives. In turn, more perceptually salient bursts and frication might result in perceptions of greater speech precision and intelligibility that have been reported when such therapy is applied to these patient populations [26,48,49].

Future research about the relationship between ACP and vocal loudness is needed on several fronts. Because this is the first reporting of the impact of loudness on ACP, confirmation of the results is needed with a larger subject pool and with a broader set of speech stimuli, in particular, speech that more closely reflects typical daily conversation. Second, a multiparameter assessment of speech produced in the four loudness conditions is needed to more robustly characterize the articulatory parameters that change and how these parameters relate to one another. For example, including measures of oral air pressure during obstruent phoneme production and kinematic measures from articulography along with ACP would allow better understanding of how tongue movements relate to force of contact and the build-up of air pressure that ultimately results in the burst release or frication of obstruent phonemes. A third area of future work moves toward the clinical applications of loud-focused therapeutic interventions such as those for people with PD. Although positive changes to articulation and speech intelligibility have been reported in PD patients undergoing such treatment, little is known mechanistically about how or why this occurs. Future studies that include PD (and perhaps other patients with dysarthria) will be important to learn if ACP is altered from the loud-focused intervention and if it is related to articulatory changes that might support improved intelligibility (e.g., stronger burst releases on stops, increased intensity of consonants, fewer instances of omitting or slighting consonants during connected speech, etc.).

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data supporting the conclusions of this article will be made available by the corresponding author on request.

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