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Intentional Changes in Sound Pressure Level and Rate: Their Impact on Measures of Respiration, Phonation, and Articulation

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The purpose of the study was to compare the effects of changing sound pressure level (SPL) and rate on respiratory, phonatory, and articulatory behavior during sentence production. Ten subjects, 5 men and 5 women, repeated the sentence, "I sell a sapapple again," under 5 SPL and 5 rate conditions. From a multi-channel recording, measures were made of lung volume (LV), SPL, fundamental frequency (F_0), *semitone standard deviation (STSD), and upper and lower lip displacements* and peak velocities. Loud speech led to increases in LV initiation, LV termination, F_0, STSD, and articulatory displacements and peak velocities for both lips. Token-to-token variability in these articulatory measures generally decreased as SPL increased, whereas rate increases were associated with increased lip movement variability. LV excursion decreased as rate increased. F_0 for the men and STSD for both genders increased with rate. Lower lip displacements became smaller for faster speech. The interspeaker differences in velocity change as a function of rate contrasted with the more consistent velocity performance across speakers for changes in SPL. Because SPL and rate change are targeted in therapy for dysarthria, the present data suggest directions for future research with disordered speakers.

KEY WORDS: sound pressure level, rate, speech respiration, phonation, articulatory kinematics

Researchers often have individuals alter their speech in a particular way, and then measure the effects of these changes at various points along the vocal tract. This approach has revealed much about the physiology of speech production. Some investigators have manipulated vocal sound pressure level (SPL), in part because it varies with the communicative context of everyday speech, and also because some disorders of speech have been associated with reduced overall SPL, or limited SPL variability (Fox & Ramig, 1997; Gentil & Pollak, 1995; Kent & Rosenbek, 1982; Scott & Caird, 1981). The same rationale has been applied to studying changes in the rate of speech. Rate varies naturally within and between speakers (Tsao & Weismer, 1997), and rate abnormalities have been observed in disordered speech (Campbell & Dollaghan, 1995; Hefter, Arendt, Stremmel, & Freund, 1993; Turner & Weismer, 1993).

Modifications to SPL or rate form the basis of several treatment approaches for dysarthria. For example, the Lee Silverman Voice Treatment (LSVT; Ramig, Countryman, Thompson, & Horii, 1995) has been shown to help Parkinson patients achieve improvements in functional

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communication by training them to increase their vocal effort. Rate increases have been reported to enhance naturalness for some speakers (Hodge & Hall, 1994); however, it is more common to reduce rate as a means of improving intelligibility (Crow & Enderby, 1989; Yorkston, Beukelman & Bell, 1988).

Both SPL and rate could be termed "global" variables because their effects span the different levels of the speech production mechanism: respiration, phonation, and articulation. When an individual speaks loudly there will usually be a deeper inhalation (Russell & Stathopoulos, 1988), a greater degree of vocal fold adduction (Gauffin & Sundberg, 1989; Scherer, 1991), and larger articulatory excursions (Schulman, 1989) than for normal speech. When speech is produced more rapidly, the coordination of respiratory, phonatory, and articulatory activity must be maintained, although the precise timing relationships and the relative duration of speech segments can vary with rate (Gay, 1981). Another way in which SPL and rate modifications could be considered global changes to speech production is in the time domain. An individual can speak more loudly than usual for entire utterances, and thus, the changes in speech production span an output that extends beyond individual gestures or syllables (Allen, 1973). Similarly, a speaker can talk slowly or rapidly for extended periods, applying a rate increase to an entire utterance rather than just to individual segments.

It has been shown by acoustic as well as kinematic studies that individual speech sounds are not affected uniformly by these global changes. In loud speech, vowels increase in SPL more than consonants (Tschopp & Beckenbauer, 1991). The more sonorant sounds also show a tendency to increase in duration (Fonagy & Fonagy, 1966), whereas stop consonants become shorter in loud speech (Schulman, 1989). As rate increases, the individual speech sounds are not linearly compressed; instead, vowels are shortened more than consonants (Gay, 1981). Smith, Goffman, Zelaznik, Ying, and McGillem (1995) found that there were different kinematic templates for lower lip movement at different speech rates, further demonstrating that rate changes involve complex forms of movement reorganization. These complex changes result from relatively simple efforts on the part of the speaker, who does not need to apply unusual concentration to speak more loudly or quickly. One purpose of the present study was to examine the effects across three speech subsystems of these speaker-intended changes in vocal effort and rate.

The task-dynamic model of speech production (Kelso & Tuller, 1984) suggests that complex speech movements can arise from the dynamic properties of the system and that relatively simple changes to the command sequences originating in the central nervous system can result in more complex changes in the motoric and acoustic output (Smith, Browman, McGowan, & Kay, 1993). For example, it has been suggested that rate changes arise from a modified specification of stiffness in the articulators (Gracco, 1994) and that biomechanical properties of the moving structures give rise to the individual movement characteristics (Kelso, Saltzman, & Tuller, 1986). Similarly, it could be speculated that the differential changes in speech segment duration and amplitude arise from the dynamic properties of the speech mechanism as individuals speak more loudly, and that individual kinematic changes are not specified explicitly by the central nervous system.

If simple behavioral changes involving global variables (e.g., "be loud") are found to have consistent effects across the subsystems of speech production, there could be important implications for increasing treatment efficacy (Hardy, 1967; Netsell, 1986; Ramig, Pawlas, & Countryman, 1995). Dromey, Ramig, and Johnson (1995) reported that a Parkinson patient who was able to increase his vocal SPL also showed improvements in articulation, even though articulation was not targeted in therapy. Increased vocal effort has also been found to help speakers with traumatic brain injury to reduce velopharyngeal orifice area (McHenry, 1997), which could hold promise for reducing hypernasality. If speakers are able to achieve improvements in parameters of speech that are not directly addressed in therapy, treatment could be applied more efficiently by selecting the target that is found to lead to the most widespread and consistent effects across the speech subsystems. A global response to a simple treatment target could help reduce the cognitive/computational demands placed on a patient in therapy (Ramig, Countryman, O'Brien, Hoehn, & Thompson, 1996; Ramig et al., 1995). This could increase the likelihood for success in patients with a reduced capacity for attention. If a hypophonic, dysarthric speaker can improve both voice and articulation with a focus on loudness (Dromey et al., 1995), there might be less reason to practice articulation drills and provide a voice amplifier.

It is clear from previous studies that have examined SPL and rate change that individual speakers can differ in the way they achieve the general goal of louder or faster speech. Stathopoulos and Sapienza (1993) found that in speaking loudly, some individuals relied on deeper inhalations before speech, presumably to take advantage of the greater recoil forces available at higher LVs (Hixon, 1973). However, others adducted the vocal folds more fully to raise their SPL without significant increases in the LV at which speech began (Stathopoulos & Sapienza, 1993). Significant interspeaker differences have also been documented for fast speech. Some speakers increase the velocities of their articulatory movements while maintaining similar displacements; others reduce movement excursions but do not change their velocity; still others decrease both the amplitudes and the velocities of their articulatory movements (Kuehn & Moll, 1976). Such findings suggest that speakers have considerable freedom to control the individual components of speech production in response to a global requirement for louder or faster speech. This might be considered a form of multi-system motor equivalence, whereby different combinations of movements contribute to the same overall outcome of modified SPL or rate. It is important to learn which of these global control variables leads to the most predictable performance within and across speakers so that in clinical populations, intervention can be planned on the basis of what is known about how the speech mechanism typically responds to SPL or rate change.

In planning treatment, it is important to know whether a given approach is inherently associated with greater stability of performance than another. For example, if reducing an individual's rate of speech leads to increased variability in articulatory movements, there is less likelihood that a particular outcome (e.g., reaching a spatial target) can be reliably predicted. Smith et al. (1995) showed that the variability in kinematic activity from token to token increased as individuals spoke more slowly, which corroborated the findings of Adams, Weismer, and Kent (1993) of multiple velocity peaks in the kinematic trajectories of slow speech, which were not present at normal or faster rates. However, if a given intervention (e.g., loud speech) is found to lead to more consistent articulatory performance, it will be easier to predict the outcome of therapy. Few studies have reported the influence of SPL change on motoric stability, although Orlikoff and Kahane (1991) reported lower voice perturbation values for louder phonation, as did Dromey et al. (1995). There is, therefore, a need for articulatory kinematic data to allow SPL-related changes to be compared with those from rate adjustments.

A primary objective of the present study was to measure the effects of SPL and rate change in a multilevel experiment, to learn how these variables affect the respiratory, phonatory and articulatory subsystems during speech production. The questions to be answered were: (a) Which global adjustment, SPL or rate, has the greatest impact on respiratory, phonatory, and articulatory measures of speech? (b) Which adjustment leads to the most consistent performance across speakers? (c) Which adjustment leads to the least variability across multiple repetitions by the same speaker?

Method

Subjects

The participants were 10 native speakers of English, who were non-smokers with no history of asthma and no professional singing or acting experience. Two of the five female participants had limited amateur singing experience in the past. On the day of the study, all speakers were free from respiratory infection. The 5 men ranged in age from 26 to 34 (mean 31.0) and the 5 women from 23 to 39 (mean 32.0). All experimental participants passed a hearing screening at 20 dB HL and had no history of disordered communication.

Instrumentation

All data were collected while participants sat in a medical examining chair in an IAC sound-treated booth. Variable inductance plethysmograph bands (Respigraph; Non Invasive Monitoring Systems, PN SY03) were placed around the rib cage at the level of the nipples, and around the abdomen at the level of the umbilicus, below the level of the lowest rib to avoid sensing rib cage movements. The bands were secured to the participants' clothing (closely fitting T-shirts or thin cotton shirts) with micropore tape.

Each participant wore a head-mounted microphone (AKG C410), which was adjusted to maintain a constant 4 cm distance from the mouth. A sound level meter (Bruel and Kjaer Type 2230) was positioned 30 cm from the speaker's mouth.

A lightweight, head-mounted, strain-gauge cantilever system (Barlow, Cole, & Abbs, 1983) was used to track the movements of the upper and lower lips during speech. This equipment was calibrated prior to the experiment by displacing the beam in the upward and downward directions in measured increments and recording the output voltage to allow the analog signal to be interpreted as a displacement in mm. The cantilever beams were guided through small beads attached with an adhesive tab to the speaker's upper and lower lips at midline.

All signals from the transducers were stored on an 8-channel digital audio tape (DAT) recorder (Sony PCM 108) for subsequent off-line digitization. Signals were digitized using a WINDAQ DI-200 12-bit hardware/software data acquisition system (Dataq Instruments, Akron, OH) on a 486/66 PC. The WINDAQ/PC system allowed the on-line monitoring of signals during data collection by displaying all 8 channels on a computer screen while they were being stored on the DAT recorder. The microphone signal was also recorded on a 2-channel DAT recorder (Panasonic SV-3700), which provided a higher sampling rate (44 kHz) than the 8-channel device (10 kHz).

Subsequent analysis of the digitized signals was performed with WINDAQ EX software to extract calibrated measures of duration and amplitude from the sampled signals, as well as derived measures (e.g., velocity) following additional processing. The sampling rate for the movement, SPL, respiration, and microphone signals was 500 Hz, with a low-pass filter cut-off at 200 Hz. The microphone signal in this data set served as a temporal marker. The microphone signal from the 2-channel DAT recorder was low-pass filtered at 5 kHz and digitized at 10 kHz for fundamental frequency (F_0) analysis with CSpeech software (Milenkovic & Read, 1994).

In order to ascertain whether the respiratory data might become contaminated through nonlinearities in the Respigraph measurement system, sets of test calibrations were performed. The voltage of the Respigraph output was measured as a function of LV level as measured with the spirometer across the vital capacity (VC) range. A linear relationship was found between the Respigraph output and the spirometer volumes (0 to 100% VC in 20% increments). The R^2 values ranged from .968 to .994 for these linearity tests, and therefore the experimental data, were considered valid. However, because linearity testing was not conducted for all participants, it is possible that this result was not representative of performance in every instance. It should also be noted that the Respigraph provides estimates of LV, rather than actual volume measures.

Speech Tasks

Once all of the transducers were positioned appropriately, participants were asked to inhale and then exhale maximally. This task was performed twice, and was used to derive a measure of VC, against which the LV during the speech conditions was measured as percent vital capacity (%VC; see Russell & Stathopoulos, 1988).[1] Experimental participants performed an isovolume maneuver at end expiratory level (EEL). They were instructed to hold their breath at the end of a tidal expiration, then asked to "pull your belly in gently, then let it flop out." This allowed allow a sum channel to be computed that equally weighted the contributions of the rib cage and abdominal transducers to LV. Measures of %VC were made from this LV channel.

Following the respiratory calibration maneuvers, participants were instructed to repeat the sentence, "I sell a sapapple again," in various ways. The stimulus sentence was selected for several reasons. It allowed an examination of lip opening and closing during the /pæp/ syllable of the word "sapapple" and also permitted relatively natural production because of its normal morphologic and syntactic form. It was easy to say without placing stress on any particular part of the sentence. If a longer speech stimulus had been employed, the very slow rate condition could not have been completed easily in one breath. It cannot be assumed that a repeated stimulus will fully represent what occurs in everyday speech, but the need to compare results across two sets of five conditions necessitated sacrificing a degree of external validity in order to implement the repeated measures design. The speakers were instructed to say the sentence 10 times under each condition, with enough of a pause between each token to relax.

The specific instructions to the speakers were as follows:

Say the sentence…

1. as you normally would.
2. at a rate that feels like twice as fast as normal.
3. at a rate that feels like four times as fast as normal.
4. at what feels like half your normal speed.
5. at what feels like a quarter of your normal speed.
6. as you normally would.
7. at a level that feels like twice as loud as normal.
8. at a level that feels like four times as loud as normal.
9. at what feels like half your normal loudness.
10. at what feels like a quarter of your normal loudness.

The sequence of instructions was the same for each individual, rather than being randomized. The normal condition was always produced first to allow relative adjustments to be made incrementally in loudness or rate. Ten tokens under a given condition were produced together to improve the consistency of the way sentences were spoken. Speakers were not required to reach specific rate or SPL targets set by the experimenter, but rather to follow the verbal instructions as closely as possible. Because they were not required to match specific targets, the 2x or 4x conditions of higher- or lower-than-normal rate or SPL were simply used in order to have the speakers change their speech production in increments that were meaningful to them. The scaling by a factor of two or four did not refer to a physical change in performance, but was a goal based on the speakers' perception of rate or loudness. This offered the advantage of having individuals avoid precise target-matching paradigms, which have been found by previous researchers to have an impact on dependent measures (Hanson, Gerratt, & Berke, 1990). Before experimental tokens were produced for each set of 10 sentences, participants were encouraged to practice saying the sentence several times under each new speech condition until they felt comfortable with the new mode

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[1] Measurement of VC was not performed with a spirometer until the end of the experiment because this often dislodged the cantilevers attached to the lips.

of production. A certified speech-language pathologist, who was monitoring the signals during recording, served as a second judge of the adequacy of the speakers' performance of the requested tasks. If they did not perceptibly modify the speed or loudness of their speech, the instructions were modified until the new level (as determined by the experimenter and the second listener) was reached. For example, if the instruction was given, "Speak at twice your normal rate," but the person did not increase the speed sufficiently, then the instruction was given, "Speed the sentence up a little."

For the different rate and SPL conditions, the experimenter monitored the signals on-line from the microphone and sound-level meter to ensure that participants were achieving the goal of different rates and SPLs. At no time were the tasks modeled by the experimenter, because it was felt that this could influence the speakers' performance if they were to imitate aspects of the experimenter's speech other than the requested rate or SPL change.

Data Analysis

Respiratory Activity

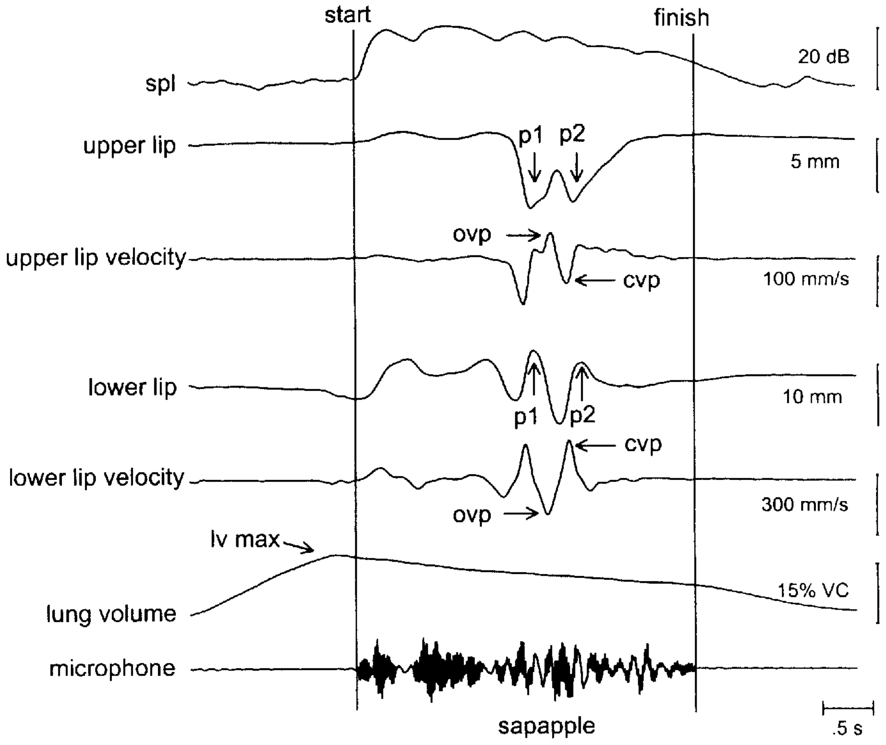
The signals from which the dependent measures were made are diagramed in Figure 1. From the computed respiratory sum channel, which represents estimated LV, measures were made of the LV at the start of the acoustic signal ("start") and the LV at its end ("finish"). These were defined as LV initiation and LV termination, respectively. The difference between LV initiation and LV termination defined the LV excursion for the speech task (Russell & Stathopoulos, 1988). All volumes were expressed as %VC, based on the VC maneuver prior to the speech tokens.

Phonatory Activity

The utterance duration was measured from the microphone signal using cursors in the WINDAQ program (Figure 1, "start" and "finish"). This corresponds to the measure of mean speech rate over the entire utterance. Previous researchers have used duration as the inverse of mean speech rate for the utterance (Adams et al., 1993). The latency between the maximum LV and the onset of phonation was also measured as a gross index of respiratory/phonatory coordination. This corresponds to the time between the points "lv max" and "start" in Figure 1.

The mean SPL during the utterance was determined from the calibrated sound level meter channel. The arithmetic mean of the data points between the cursors was taken as a measure of overall SPL.

Figure 1. Measures derived from the simultaneously acquired signals. Start and finish represent the onset and offset of phonation for the sentence "I sell a sapapple again." P1 and P2 are the lip displacements associated with the first and second bilabial closures in the word *sapapple*. OVP and CVP are opening and closing gesture velocity peaks for the bilabial gestures. LV MAX is the lung volume peak before speaking.



The mean and standard deviation of the F_0 were derived from the microphone signal from the 2-channel DAT recorder to determine the effects of SPL and rate change on the F_0 contour of the voice during the production of the sentence. This analysis was performed with CSpeech. Semitone standard deviation (STSD) was calculated from the mean and standard deviation of the F_0 in Hz as follows:

$$\text{STSD} = \left(\frac{12}{\log 2}\right) \cdot \log\left(\frac{\bar{x} + SD}{\bar{x} - SD}\right)$$

where $\bar{x}$ is the mean F_0, and sd is the standard deviation in Hz. This measure was derived as a quantitative correlate of the perception of a more varied or monotone prosodic pattern.

Articulatory Activity

The time-varying voltage signal from the strain-gauge cantilever transducers represented an analog of the upward and downward movements of the lips. From this record, measures were made for the upper and the lower lip of the displacement from /p/ to /æ/ and from /æ/ to the subsequent /p/ in the /pæp/ of "sapapple" (Figure 1, points p1, p2, and the vowel displacement between them). It is recognized that the lower lip signal represents the sum of lower lip and jaw movements. This measure was selected because it allowed data to be gathered regarding the degree of oral opening during speech. A smoothed (10-point moving average) derivative of each lip's channel was produced with the WINDAQ software to calculate the magnitude of the peak opening and closing velocities for these speech gestures.

Measurement Reliability

Twenty percent of the data for each dependent variable were randomly selected and reanalyzed by the same experimenter for the purpose of assessing measurement reliability. The mean Pearson correlation coefficient across all dependent measures for the original and the re-checked data was 0.999 and ranged from .995 to 1.00 for the individual variables. The mean percent difference between the original and re-checked measures was 0.19% and ranged from 0% to a maximum of 1.42% for the individual variables. This was calculated by subtracting the re-measured value from the original, dividing by the original, and multiplying by 100.

Statistical Analysis

The primary statistical analysis was a univariate repeated measures analysis of variance (ANOVA) for each dependent measure. Because SPL and rate were separately manipulated in the experiment, they were separately analyzed (i.e., they were not crossed as factors within an analysis). In each section below, the reported values represent the mean for all 10 speakers, except in the case of F_0, which is reported as the mean for the 5 speakers of each sex. Separate analyses were conducted for the men and the women for F_0 because of the substantial male/female differences in F_0. F_0 variability, on the other hand, was analyzed for both sexes together because STSD already accounts for the male/female differences in mean F_0. Because of the relatively small *n* and the large number of tests, an alpha level of .01 was selected to assess the significance of the results.

Table 1. Mean (and standard deviation) effects of SPL changes on all dependent measures.

Measure	Unit	4 soft	SD	2 soft	SD	norm	SD	2 loud	SD	4 loud	SD
LV initiation	%VC	57.1	(10.9)	58.9	(12.7)	62.1	(11.5)	61.7	(14.0)	68.6	(19.0)
LV termination	%VC	48.7	(10.0)	49.4	(11.7)	53.8	(10.8)	52.4	(13.0)	57.2	(17.2)
LV excursion	%VC	8.4	(2.8)	9.5	(3.2)	8.3	(2.7)	9.3	(4.0)	11.4	(6.0)
Latency[a]	ms	233	(113)	160	(74)	127	(37)	108	(69)	70	(50)
Mean SPL (30cm)	dB	57.1	(4.2)	62.1	(4.5)	65.0	(4.2)	74.7	(3.8)	81.4	(4.1)
Duration	s	1.62	(0.19)	1.65	(0.19)	1.76	(0.14)	1.72	(0.21)	1.76	(0.23)
Mean F_0 (m)	Hz	100.4	(16.2)	98.7	(11.8)	100.2	(10.0)	118.5	(12.8)	157.0	(24.5)
Mean F_0 (f)	Hz	202.2	(12.8)	198.1	(16.8)	195.0	(25.1)	215.3	(29.5)	246.1	(35.4)
STSD	ST	1.35	(0.50)	1.47	(0.50)	1.67	(0.66)	2.39	(0.43)	2.80	(0.58)
UL open disp	mm	1.28	(0.85)	1.54	(0.76)	1.88	(0.82)	2.05	(0.90)	2.39	(1.21)
UL close disp	mm	1.36	(0.82)	1.57	(0.81)	1.86	(0.82)	2.21	(0.80)	2.83	(1.39)
UL open pk vel	mm/s	28.4	(25.8)	32.4	(18.0)	40.2	(24.1)	40.8	(15.5)	46.6	(17.9)
UL close pk vel	mm/s	27.3	(16.5)	29.9	(14.1)	36.1	(16.9)	42.5	(14.8)	53.0	(22.4)
LL open disp	mm	8.48	(3.21)	9.55	(3.30)	10.35	(4.00)	11.94	(3.71)	14.81	(4.82)
LL close disp	mm	7.68	(3.03)	8.96	(3.14)	9.69	(3.58)	11.25	(3.60)	13.83	(4.91)
LL open pk vel	mm/s	127.0	(52.1)	145.8	(56.3)	149.7	(62.6)	172.6	(55.3)	209.3	(62.9)
LL close pk vel	mm/s	148.0	(60.2)	170.8	(65.4)	188.8	(73.4)	223.6	(69.8)	283.2	(97.6)

[a] *Latency* refers to the interval from the inhalatory peak to the onset of phonation.

Where significant ANOVA results were found, the data were further evaluated with a best fit regression procedure to establish whether the patterns of change could most appropriately be represented with a linear, quadratic, or cubic function. Higher order polynomial fits were not attempted because there were only five levels of each independent variable.

Results

Group Data Analysis—SPL Effects

The changes in the dependent measures associated with the speakers' adjustment of vocal SPL are summarized in Table 1. Table 2 lists the results of the repeated-measures ANOVAs that tested for change in a dependent measure across the SPL range. All the variables that were found to change significantly are plotted in Figure 2. A perusal of Table 1 reveals that the speakers increased SPL more for the loud conditions than they reduced it for the soft. Because of these asymmetric changes in SPL, it was reasoned that curve fitting would allow an examination of the patterns of change in the dependent variables as SPL changed from soft to loud. The curve fitting analysis was based on the group's mean SPL values as the regression predictor variable. This provided a more accurate fit than the equally spaced categorical targets of 4x softer, 2x louder, etc., which speakers used to produce their intended changes in the magnitude production task. Table 3 reports the results of the curve fitting analysis. In each case, the fit with the lowest probability of a type-I error was selected, even though the fit did not always result in an F-ratio with a p-value below .01. In the interest of readability, the statistical results in the tables have not been repeated in the text.

Respiratory Activity and Timing Measures

LV initiation and LV termination both increased with SPL. Figure 2 shows that except at the highest SPL, there were only modest changes in the LV measures. The latency between the time of maximum LV and the start of phonation decreased as SPL increased. This measure showed a more consistent change across the entire SPL range (Figure 2). Utterance duration increased from soft to normal, whereas for loud speech there was essentially no change (Figure 2). Whereas the linear trend provided the best fit for each of these variables, none of the fits were significant at $p < .01$.

Table 2. F ratios and probability values for repeated measures ANOVAs on all dependent measures across the SPL range.

Measure	F ratio	p value
LV initiation	5.36	.002*
LV termination	3.96	.010*
LV excursion	3.25	.024
Latency	7.70	< .001*
Mean SPL	321.13	< .001*
Duration	6.21	.001*
Mean F_0 (m)	31.05	< .001*
Mean F_0 (f)	11.51	< .001*
STSD	36.39	< .001*
UL open disp	10.46	< .001*
UL close disp	12.93	< .001*
UL open pk vel	4.11	.008*
UL close pk vel	18.72	< .001*
LL open disp	34.09	< .001*
LL close disp	28.89	< .001*
LL open pk vel	20.14	< .001*
LL close pk vel	40.63	< .001*

Note. Degrees of freedom for all tests are [4, 32] with the following exceptions: For single gender F_0 tests $df = [4, 16]$.
*$p < .01$.

Table 3. Best fit functions for measures that changed significantly (ANOVA, $p < .01$) with SPL.

Variable	Best fit	R Squared	df	F	p value
LV initiation	Linear	0.842	3	15.99	0.028
LV termination	Linear	0.761	3	9.57	0.054
Latency	Linear	0.861	3	18.56	0.023
Duration	Linear	0.603	3	4.56	0.122
F_0 (m)	Cubic	0.996	2	249.83	0.004*
F_0 (f)	Cubic	0.997	2	381.23	0.003*
STSD	Linear	0.984	3	182.15	0.001*
UL open disp	Linear	0.942	3	48.84	0.006*
UL close disp	Linear	0.972	3	103.6	0.002*
UL open pk vel	Linear	0.865	3	19.2	0.022
UL close pk vel	Linear	0.971	3	99.2	0.002*
LL open disp	Linear	0.967	3	87.84	0.003*
LL close disp	Linear	0.975	3	118.92	0.002*
LL open pk vel	Linear	0.965	3	81.95	0.003*
LL close pk vel	Linear	0.972	3	102.31	0.002*

*Denotes curve fit significance at $p < .01$.

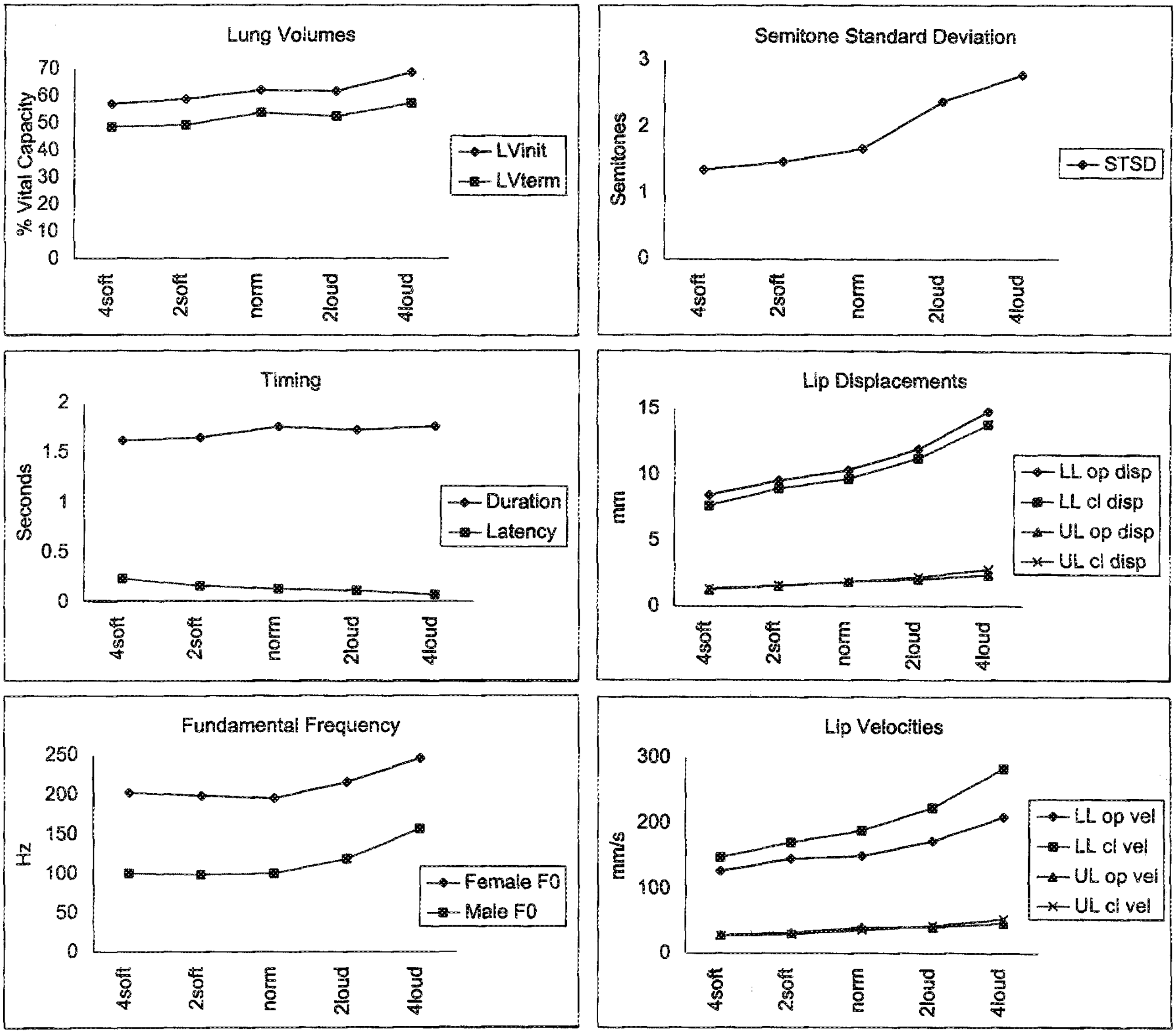
Phonatory Activity

For both male and female speakers, F_0 increased with SPL. A cubic fit was significant for these measures. Inspection of the results indicates that F_0 increased for loud speech but changed minimally for soft speech (Figure 2). F_0 variability, measured as STSD, increased with SPL. The best fit was achieved with a linear function, although Figure 2 shows that greater change occurred for loud than for soft speech.

Articulatory Activity

The opening and closing displacements and velocities for the upper lip increased with SPL. Each measure

Figure 2. Mean values across speakers for all dependent variables that changed significantly (ANOVA, $p < .01$) with SPL.



best matched a linear trend, which was significant at $p < .01$ for all of the upper lip variables except for opening peak velocity ($p = .022$). Figure 2 shows that the upper lip measures increased gradually across the entire SPL range.

Lower lip displacements and velocities increased with SPL, and all measures demonstrated a significant linear trend. The slightly steeper increase in these variables with SPL for the loudest speech condition can be seen in Figure 2.

Group Data Analysis—Rate Effects

The changes in the dependent measures associated with the adjustment of speech rate are summarized in Table 4. The results of the ANOVA for each measure as a function of rate are listed in Table 5. Table 6 reports the best fit functions for the variables found in the ANOVA to be significant at $p < .01$. The predictor values in the curve-fitting regression were the mean durations for the group, rather than the equally spaced rate targets from the magnitude production task. Duration increased more for the slow conditions than it decreased for the fast (see Table 4).

Respiratory Activity and Timing Measures

LV excursion decreased significantly as rate increased. A linear trend was significant for this measure. The latency between the maximal inhalation and the start of phonation decreased as rate increased, and also displayed a significant linear pattern of change. Figure 3

Table 4. Mean (and standard deviation) effects of rate changes on all dependent measures.

Measure	Unit	4slow	*SD*	2slow	*SD*	norm	*SD*	2fast	*SD*	4fast	*SD*
LV initiation	%VC	57.1	(13.1)	56.0	(10.0)	61.1	(14.4)	56.1	(12.5)	54.3	(7.8)
LV termination	%VC	41.2	(14.2)	46.1	(11.5)	53.8	(13.4)	49.7	(11.6)	48.0	(8.6)
LV excursion	%VC	15.8	(7.4)	9.9	(5.3)	7.4	(2.2)	6.4	(2.3)	6.3	(3.0)
Latency	ms	284	(220)	161	(77)	128	(76)	95	(95)	71	(61)
Mean SPL (30cm)	dB	64.1	(4.4)	64.4	(4.3)	65.2	(3.8)	66.4	(4.8)	68.1	(4.3)
Duration	s	3.63	(1.03)	2.28	(0.51)	1.68	(0.18)	1.33	(0.14)	1.12	(0.13)
Mean F_0 (m)	Hz	99.8	(9.3)	97.4	(9.9)	99.8	(10.3)	101.2	(10.3)	104.2	(11.0)
Mean F_0 (f)	Hz	189.4	(11.6)	190.8	(14.7)	190.6	(18.7)	202.6	(28.4)	210.7	(35.6)
STSD	ST	1.31	(0.57)	1.46	(0.63)	1.59	(0.46)	1.72	(0.56)	1.79	(0.69)
UL open disp	mm	1.98	(0.92)	1.94	(0.78)	2.01	(0.76)	1.52	(1.00)	1.22	(1.30)
UL close disp	mm	1.94	(0.77)	1.95	(0.77)	1.88	(0.61)	1.46	(0.94)	1.20	(1.28)
UL open pk vel	mm/s	33.3	(22.0)	35.7	(22.2)	47.1	(18.9)	37.6	(25.4)	32.1	(28.6)
UL close pk vel	mm/s	29.4	(12.3)	33.6	(14.1)	37.5	(14.1)	35.1	(25.1)	33.1	(34.6)
LL open disp	mm	10.95	(5.00)	10.01	(4.19)	10.21	(3.50)	9.22	(3.50)	7.63	(3.10)
LL close disp	mm	10.70	(4.54)	9.41	(3.47)	9.39	(3.27)	8.37	(3.24)	6.66	(2.88)
LL open pk vel	mm/s	119.7	(48.4)	129.7	(52.3)	156.1	(56.5)	155.9	(60.4)	137.0	(54.4)
LL close pk vel	mm/s	161.9	(79.6)	163.8	(61.4)	194.0	(73.2)	189.7	(81.8)	169.6	(85.5)

shows how these measures changed most for the slowest speech, where the change in duration was greater than for fast speech.

Phonatory Activity

Mean SPL increased with rate. A quadratic trend provided the best fit, although this was not significant at $p < .01$. Figure 3 shows that SPL change occurred across the rate range in the study, and that the change was more pronounced for rapid speech. Mean F_0 for males changed as a function of rate. As with SPL, the best fit was quadratic, but this was not significant at $p < .01$. F_0 variability in STSD increased with increasing rate (Figure 3), and this measure's quadratic fit was significant.

Table 5. *F* ratios and probability values for repeated measures ANOVAs on all dependent measures across the rate range.

Measure	*F* ratio	*p* value
LV initiation	1.29	.293
LV termination	3.00	.033
LV excursion	21.34	< .001*
Latency	7.57	< .001*
Mean SPL	13.65	< .001*
Duration	47.21	< .001*
Mean F_0 (m)	8.04	.001*
Mean F_0 (f)	3.69	.026
STSD	8.25	< .001*
UL open disp	2.52	.060
UL close disp	2.68	.050
UL open pk vel	2.02	.115
UL close pk vel	0.41	.789
LL open disp	4.17	.008*
LL close disp	6.18	.001*
LL open pk vel	4.45	.006*
LL close pk vel	1.49	.230

Note. Degrees of freedom for all tests are [4, 32] with the following exceptions: For single gender F_0 tests $df = [4, 16]$.
$^*p < .01$.

Articulatory Activity

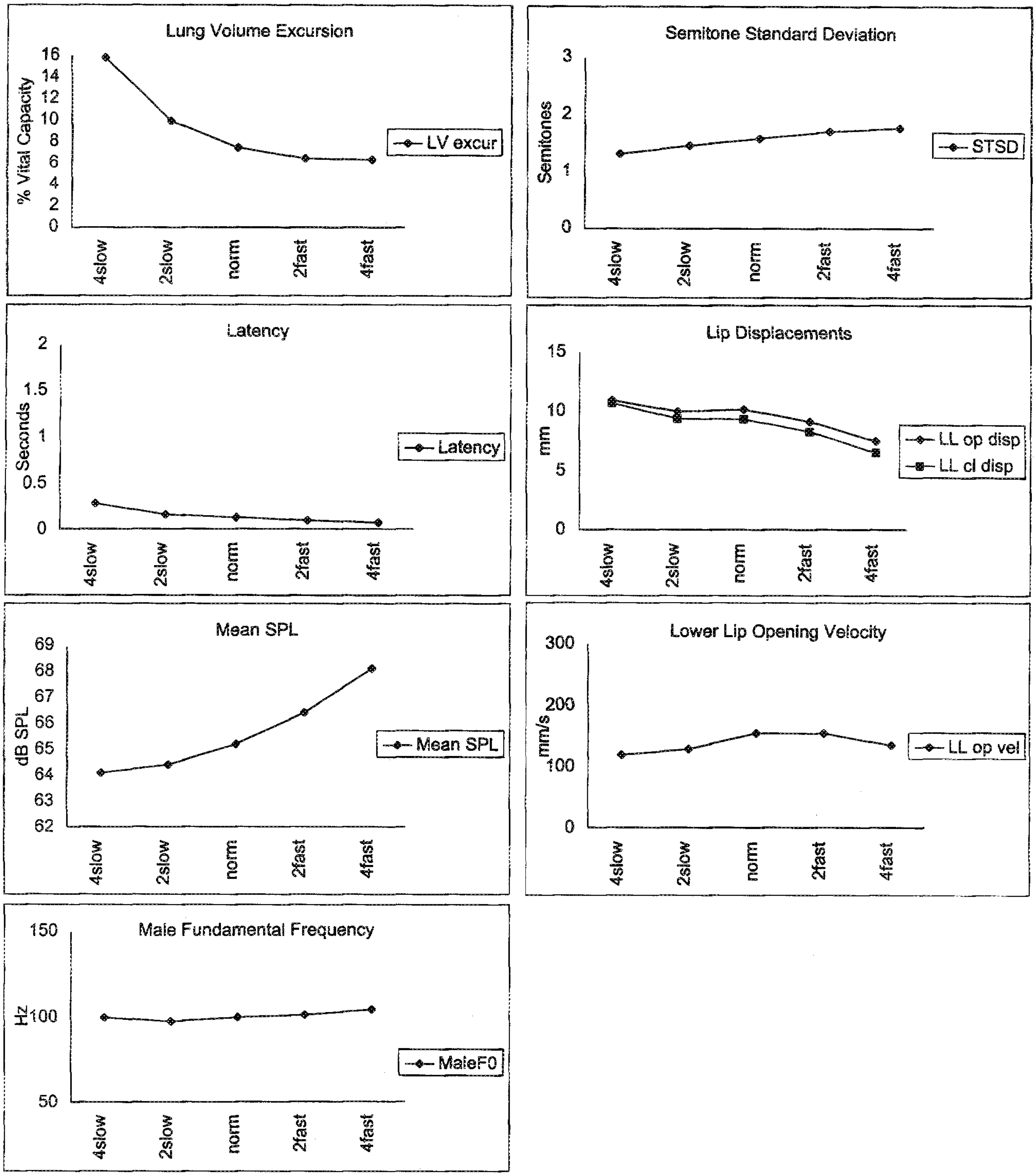
There were no significant ANOVA effects at $p < .01$ for upper lip displacements or peak velocities for the opening or closing gestures across the range of rates in the study. The opening and closing displacements of the lower lip became smaller as rate increased. Increases in displacement for slower than normal speech did not become apparent until the very slowest rate was reached (Figure 3). Lower lip opening velocity changed significantly with rate, with lower values for both faster and slower than normal speech. Although a linear fit was the closest for each of these lower lip variables, none of the fits reached significance at $p < .01$.

Table 6. Best fit functions for measures that changed significantly (ANOVA, $p < .01$) with rate.

Variable	Best fit	*R* Squared	*df*	*F*	*p* value
LV excursion	Linear	0.987	3	233.37	0.001*
Latency	Linear	0.994	3	499.06	<.001*
SPL	Quadratic	0.951	2	19.42	0.049
F_0 male	Quadratic	0.965	2	27.76	0.035
STSD	Quadratic	0.998	2	630.86	0.002*
LL open disp	Linear	0.651	3	5.59	0.099
LL close disp	Linear	0.75	3	8.99	0.058
LL open pk vel	Linear	0.572	3	4.01	0.139

*Denotes curve fit significance at $p < .01$.

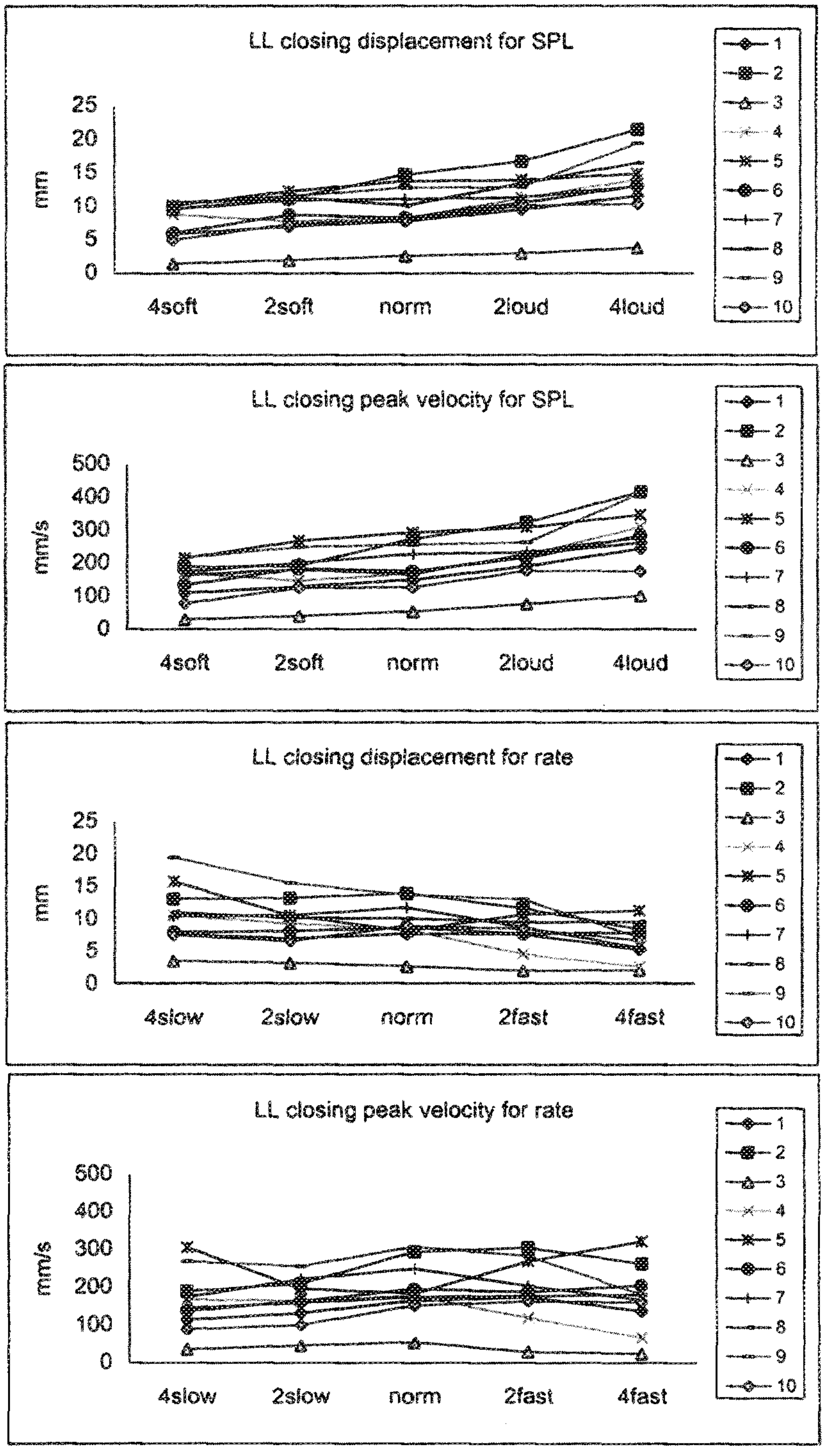
Figure 3. Mean values across speakers for all dependent variables that changed significantly (ANOVA, $p < .01$) with rate.



Interspeaker Variability

Because the opening but not the closing peak velocity for the lower lip was found to change significantly with rate, the latter measure was examined for the individual speakers, comparing the effects of SPL and rate change. Figure 4 shows the displacements and peak velocities for the lower lip closing gesture for both SPL and rate. For SPL increases, the speakers generally behaved similarly, with increased displacements and velocities across the continuum from soft to loud. On the

Figure 4. Individual speakers' lower lip displacement and peak velocity for the closing gesture, comparing changes for SPL with changes for rate.



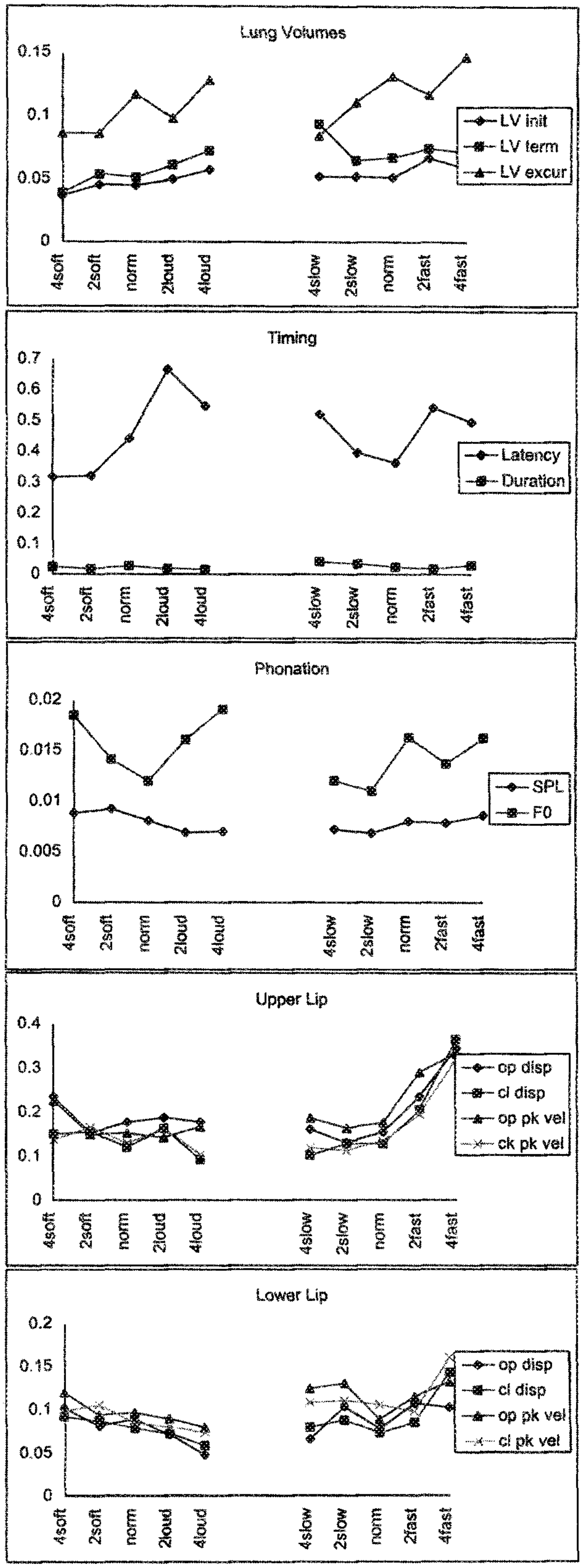
other hand, while displacements generally decreased from slow to fast, the patterns of velocity change were less uniform across individuals. This interspeaker variability likely contributed to a non-significant ANOVA for rate in the lower lip closing velocity.

Intraspeaker Variability

The participants differed in the degree to which they were consistent in their performance over the 10 repetitions under each speaking condition. For each speaker, a coefficient of variation (CV) was calculated by dividing the standard deviation by the mean for that person's tokens in each speaking condition. This allowed an assessment of token-to-token variability in the dependent measures across the levels of the independent variables. Figure 5 shows how the CVs changed across the SPL range (left side of each panel) and across rates (right side of each panel) for all of the dependent variables. In order to allow patterns of change to be seen more clearly, the y-axes differ in scale in the panels of this figure.

Visual inspection of these plots reveals that token-to-token variability increased in the respiratory measures as SPL increased, and that LV excursion generally became more variable as rate increased. The latency between maximal inhalation and speech initiation was the most variable measure across repetitions, while SPL and F$_0$ had very small values for the CV. An interesting observation for the articulatory movements was that as SPL increased, the variability mostly decreased, whereas for rate increases, intraspeaker variability generally increased for displacements and peak velocities.

Figure 5. Mean values across speakers for the coefficient of variation (CV) for all dependent variables with changes in SPL and changes in rate.



Discussion

SPL Effects

One of the goals of the present study was to determine whether SPL or rate change would have a greater impact on measures of respiratory, phonatory, and articulatory activity. An examination of Table 2 shows that for SPL, all of the variables changed significantly at $p <$ .01, with the exception of LV excursion at $p = .024$. These data suggest that SPL is indeed a global variable that has an impact across the speech subsystems.

There was a pattern of higher LVs for the initiation of speech as SPL increased. This is in agreement with Russell and Stathopoulos (1988) and likely reflects the reliance on increased expiratory recoil forces in the generation of higher pressures for loud speech (Hixon, 1973). As SPL increased, there was a decrease in the latency between maximal inhalation and the start of speech. Because this co-occurred with increasing LV, it could be speculated that speakers avoided resisting elevated expiratory recoil forces for longer than necessary in the interest of efficiency.

Sentence duration increased from soft to normal vocal effort levels, but sentences spoken at louder than normal levels did not change in overall duration, even though lip displacements increased. A possible explanation is that in louder speech, vowels tend to be prolonged and consonants shortened (Fonagy & Fonagy, 1966). This could allow the temporal changes in the vowels and consonants to effectively cancel one another. Future studies that examine segmental duration across a wide range of intensities could help support or reject this hypothesis.

SPL increased more for the loud conditions than it decreased for soft. These data would suggest that the speakers in the present study normally spoke toward the lower end of their available SPL range, and that there was more latitude for change above than below their comfortable loudness level (Awan, 1993). F_0 increased for loud speech, which is consistent with earlier research (Lieberman, Knudson, & Mead, 1969), and could reflect a passive increase in vocal fold tension as the displacement from midline increases with SPL (Titze, 1988). A recent study has shown that increases in subglottal pressure in the absence of any muscle activation differences can lead to higher F_0 (Hsiao et al., 1994). However, it cannot be determined from the present data whether cricothyroid modulation might have increased at higher SPL, thus contributing to the rise in F_0 variability (STSD). Further research to examine electromyographic activity across the SPL continuum could help to clarify this issue.

The increases in articulatory excursions and velocities with SPL are consistent with the findings of Schulman (1989), who reported larger articulatory movements and higher peak velocities for loud speech. A more open vocal tract allows a more efficient radiation of acoustic energy, thus the larger articulatory excursions can contribute to higher SPL directly. In contrast to the data for rate, which often showed dramatic interspeaker differences in velocities in fast speech, louder speech elicited more consistent effects across speakers.

Rate Effects

The ANOVA results in Table 5 show that rate change significantly affected a number of measures in all three subsystems, although the impact was less pronounced than for SPL. The increase in LV excursion with decreasing rate is likely due to the need for more air for a longer utterance. The shorter latency between maximum LV and the start of speech, as rate increased, could be linked to the more rapid speech production, with speakers preparing for faster speech and consequently starting to speak sooner.

SPL increased across the range of rates in the present study. The fastest condition was about 3 dB higher in SPL, on average, than speech at a normal rate. For faster rates, it has been hypothesized that articulator stiffness is increased (Kelso, Vatikiotis-Bateson, Saltzman, & Kay, 1985; Ostry & Munhall, 1985). It could be speculated that as more muscular effort is expended to increase stiffness in the system, greater adductory effort is applied to the vocal folds, thus leading to increased SPL. Additionally, speakers may perceive faster speech as generally more effortful (Rosenblum & Fowler, 1991), and apply increased exertion in phonation as well as in generating faster movements.

In response to the instruction to be 4x slower or 4x faster, the speakers reduced the rate of their speech more than they increased it. In theory, there would be no absolute minimum rate of speech, although speech naturalness clearly would suffer with extreme sound prolongations. Tsao and Weismer (1997) found that their speakers' habitual speech rate was about 75% of their maximal rate, which would suggest that there is greater latitude for reducing than for increasing rate. F_0 variability (STSD) increased across the range of slow to fast rates. A lower STSD value for very slow speech is consistent with perceptual observations that slow speech is more monotonous and less natural (Schiavetti & Metz, 1996).

The articulatory kinematic data for rate reveal a significant decrease in lower lip displacement with increasing rate. This finding is consistent with the work of previous researchers, who have reported reduced displacements as speakers undershoot spatial targets at high rates (Flege, 1988; Gay, 1981; Kuehn & Moll, 1976; Lindblom, 1990). However, the change in peak velocity was significant for the opening, but not the closing gesture. When individual speaker data are considered, it becomes apparent that each speaker employed different strategies in achieving higher rates of speech (Figure 4), with greater differences in peak velocity. The differences between speakers indicate that there is not a uniform mechanism across individuals for achieving faster rates of speech. Similar interspeaker differences have been reported by other researchers who have examined mechanisms of rate increase (Flege, 1988; Gay, 1981; Kuehn & Moll, 1976; Lindblom, 1990).

The lack of significant findings in the upper lip kinematics could be linked to the size of the movements. Hughes and Abbs (1976) found in their rate study that the lower lip and jaw contributed to 99% of the vertical component of oral opening, while the upper lip movement represented only 1%. Therefore, the larger component might have been more sensitive to the effects of rate change in the present study.

General Discussion

Speaker-intended SPL and rate adjustments led to different patterns of change in the articulatory movements of our speakers. It appears that loud speech involves an increase in activity across the speech mechanism. The primary requirement, in addition to stronger source, is a more open vocal tract to allow more acoustic energy to be radiated. In order to speak more rapidly, various combinations of displacement and velocity change are possible.

There could be potential clinical benefits to investigating the role of SPL and rate change in the treatment of dysarthria. The rate data show that by slowing the rate of speech, lower lip displacements increase slightly. This could potentially contribute to improvements in articulatory accuracy, assuming the dysarthria is associated with target undershoot. However, the very variable velocity performance across the rate continuum can make it difficult to predict the likelihood of improved articulation. In contrast, louder speech was associated with greater increases in lip displacement, which were also accompanied by velocity increases. The probability of articulatory improvement would seem to be greater for loud than for slow speech. We are currently planning experiments to determine whether dysarthric speakers perform similarly to the healthy speakers in the present study. Future research to examine tongue movements as a function of SPL change would be most valuable because of the tongue's role in consonant articulation. In contrast to rapid speech, where spatial targets may be compromised because of the need for rapid segment production, loud speech does not necessitate any reduction in articulatory precision. On the contrary, the larger displacements and velocities could be expected to lead to spatial targets being met more easily. This reasoning only holds for moderate SPL increases, however, considering that previous studies have reported decreases in intelligibility for shouted speech produced by healthy speakers (Dreher & O'Neill, 1957; Pickett, 1956; Rostolland, 1982).

An analysis of the relative stability of repeated productions under the different speech conditions can reveal other interesting differences between SPL and rate change (see Figure 5). The CV as used in the present context is a simple index of variability across tokens and cannot easily be compared with the more elaborate Spatiotemporal Index (STI) of Smith et al. (1995) or with the most recent non-linear time-warping methods described by Lucero, Munhall, Gracco, and Ramsay (1997). Smith et al. (1995) found more variability in the production of slower than normal speech, and also pointed to the existence of different kinematic templates for the various rate conditions. In the present study, as speech became louder, the variability in displacement and peak velocity from one token to the next became smaller, whereas for faster speech, it increased. The CV data for slower than normal speech showed slight to moderate increases in the variability of displacement and peak velocity, which is consistent with Smith et al.'s (1995) findings of higher STI values for slow speech. From a clinical perspective, the kinematic consequences of rate reduction in the treatment of dysarthria would seem more difficult to predict because of this increased variability. The smaller CVs for loud speech, on the other hand, suggest that the effects on articulation could be anticipated with greater confidence. Future studies employing similar analysis techniques to those used by Smith et al. (1995) or by Lucero et al. (1997) could help reveal important details of the differences in motor behavior for SPL and rate change.

We recognize that the findings of the present study, based on multiple repetitions of a short utterance, cannot be directly generalized to typical speech behavior. However, the findings represent a starting point from which to explore the effects of SPL and rate change under more natural conditions in clinical populations. We are currently planning additional studies to examine the representativeness of short stimuli compared to longer and more natural utterances. In spite of the present limitations, however, the data suggest that speech changes in gross and also more subtle ways as SPL and rate are adjusted. Adams et al. (1993) have suggested that rate-referenced measures of speech production are necessary in order to control for the effects of rate on such variables as voice onset time, F2 trajectories, and velocity profiles because each of these can change as a function of speech rate. Similarly, Holmberg, Hillman, Perkell, and Gress (1994) have cautioned researchers and clinicians alike against making aerodynamic measures of speech production in the absence of SPL data, since in their study, over 50% of the variance in the outcome measures could be accounted for by fluctuations in SPL. The present study lends support to the views expressed in both of these reports. Researchers need to account for the effects of SPL and rate on the variables they study. Where they are found to change without deliberate adjustment by the speaker, SPL and rate can be used as covariates in statistical analyses, so that their impact can be accounted for systematically. Researchers can then determine what proportion of their results are attributable to changes in rate and SPL and what proportion of changes are due to factors beyond these global variables.

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