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Effect of Speaking Rate Manipulations on Acoustic and Perceptual Aspects of the Dysarthria in Amyotrophic Lateral Sclerosis

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Key Words

Dysarthria · Vowel space · Acoustics · Intelligibility · Speaking rate

Abstract

The current study explored the acoustic and perceptual effects of speaking rate adjustments in persons with amyotrophic lateral sclerosis (ALS) and in neurologically normal individuals. Sentence utterances were obtained from the participants at two self-selected speaking rates: habitual and fast. Total utterance durations, segment durations, and vowel formant frequencies comprised the acoustic measures, whereas magnitude estimates of speech intelligibility and severity of speech involvement were the perceptual measures. Results showed that participants in both the neurologically normal and ALS groups were able to increase their speaking rate when asked to do so, but that the participants with ALS were significantly slower than the neurologically normal participants at both rates. Both groups of participants also showed compression of the acoustic vowel space with increased speaking rate, with the vowel spaces of participants with ALS generally being more compressed than the vowel spaces of neurologically normal participants, at either rate. Most importantly, the perceptual measures failed to show any effect of the speaking rate adjustment on scaled intelligibility or severity, for either group. These findings are discussed relative to the general issue of slow habitual speaking rates among many speakers with dysarthria, and possible explanations for the slowness. The lack of an effect of increased rate on the perception of the speech deficit among speakers with ALS argues against the idea that the habitually slow rates are a form of compensation to reduce the complexity of speech production.

Wirkung von Sprechgeschwindigkeitsänderungen auf akustische und wahrnehmungsbedingte Aspekte der Dysarthrie bei Personen mit amyotropher Lateralsklerose (ALS)

Die Wirkung von Sprechgeschwindigkeitsänderungen auf akustische und wahrnehmungsbedingte Elemente bei Personen mit ALS wurde mit jener bei neurologisch normalen Personen verglichen. Die Veränderungen der Sprachproduktion wurden durch zwei selbstgewählte Sprechgeschwindigkeiten, normal und schnell, erzeugt. Die gesamte Sprechdauer, Abschnittlängen und die lautsprachlichen Formantlängen wurden aufgrund von akustischer Messung gewonnen, während der Grad der Spracherkennung und die Schwere der Sprachstörung auf der Basis von wahrnehmungsbezogenen Daten erhoben wurden. Die Ergebnisse zeigten, dass sowohl bei den Patienten mit

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ALS als auch bei den normalen Personen die Sprechgeschwindigkeit willkürlich erhöht werden konnte, wobei die ALS-Patienten bei beiden Geschwindigkeiten deutlich langsamer artikulierten. Beide Gruppen zeigten auch eine Verkürzung der Lautabstände mit zunehmender Sprechgeschwindigkeit, wobei die ALS-Gruppe gegenüber der Normalgruppe bei beiden Sprechtempi deutlich stärker verkürzte. Die bedeutendste Erkenntnis besteht darin, dass bei beiden Gruppen weder die Spracherkennbarkeit noch die Schwere der Sprachstörung durch die unterschiedlichen Sprechgeschwindigkeiten Veränderungen zeigten. Diese Ergebnisse werden in Bezug auf bekannte Phänomene bei normalen Sprechgeschwindigkeiten von dysarthrischen Sprechern als mögliche Erklärung für die Verlangsamung diskutiert. Die fehlende Auswirkung der schnellen Rede in Bezug auf die Wahrnehmung eines Sprechdefizits bei ALS-Patienten spricht gegen das Argument, dass die Verlangsamung als Kompensation eingesetzt wird, um die Komplexität der Sprachproduktion zu reduzieren.

Effet des variations du débit oral sur les aspects acoustiques et perceptifs de la dysarthrie dans la sclérose latérale amyotrophique

Ce travail étudie les effets acoustiques et perceptifs des variations du débit oral de patients atteints de sclérose latérale amyotrophique (ALS) et de témoins sans troubles neurologiques. Les sujets émettaient des phrases à un débit normal et rapide. Les mesures acoustiques comprenaient la durée totale d'émission, les durées segmentaires et les fréquences des formants des voyelles, alors que les mesures perceptives évaluaient l'intelligibilité et la sévérité de l'atteinte du langage. Les résultats ont fait apparaître que les sujets des deux groupes étaient capables d'augmenter leur débit oral à la demande, mais que les sujets ALS étaient significativement plus lents dans les deux cas. Il est important de noter que les mesures perceptives n'ont pas révélé d'effet d'adaptation du débit sur l'intelligibilité ou la sévérité du trouble, ceci pour les deux groupes. Ces données sont discutées par rapport au débit oral habituellement lent chez nombre de sujets dysarthriques et elles ouvrent la voie à une explication possible. Le manque d'effet sur l'amélioration de la perception du trouble du langage chez les sujets ALS contredit la thèse selon laquelle le débit oral habituellement lent de ces patients constitue une compensation destinée à réduire la complexité de la production langagière.

The speech associated with amyotrophic lateral sclerosis (ALS) is characterized perceptually as having a slower than normal speaking rate, prolonged phonemes, distorted vowels and shortened phrases [1]. It has been shown that ALS speakers, at self-selected conversational rates, produce longer segment durations than neurologically normal individuals and speakers with Parkinson's disease [2]. In addition, studies of the spectrotemporal properties of vowels produced by speakers with ALS show that in comparison to neurologically normal speakers, formant transition extents are reduced, formant transition slopes are shallower, and the vowel space is relatively collapsed [3–7]. The latter feature may be especially important in the development of acoustically based models of speech intelligibility as the size of the vowel space appears to explain a significant proportion of the variance in speech intelligibility scores [8].

Acoustic vowel reduction resulting from increased speaking rate has been observed in the speech of neurologically normal individuals [8–10]. Fourakis [11] found that both tempo and stress have an impact on the size of the acoustic vowel space. The vowel space was largest in the slow stressed condition and smallest in the fast unstressed condition. The reduction of the vowel space was primarily due to the low vowels and partially due to the nonfront vowels. Increased speaking rate may also affect other aspects of normal speech production. For example, consonants appear to be more resistant than vowels to change in duration as rate increases [12]. Part of the rate-induced changes in formant frequencies may be tied in a systematic way to the effect of rate on vowel durations, which absorb most of the temporal adjustments when speaking rate is modified [13].

Little is known about the influence of speaking rate on the speech intelligibility of individuals with ALS [14], although it is clear that rate manipulations are possible in this population. For example, Turner and Weismer [15] found that ALS speakers were able to alter their rate by both increasing and decreasing their habitual rates, even though the rates were substantially slower than the habitual rates of neurologically normal speakers. Turner et al. [8] investigated the effect of speaking rate on vowel space and intelligibility in ALS speakers. Compared to neurologically normal speakers, the dysarthric speakers were found to have a more compact vowel space area (see also Lehiste [16]) and less change in vowel space during speaking rate manipulations. Larger acoustic vowel spaces were associated with higher speech intelligibility in this population. There is also evidence that speakers with hypokinetic dysarthria can manipulate rate [17] and that these rate changes may be associated with improved speech intelligibility [18, 19].

The purpose of the current study is to explore further the effect of speaking rate manipulation on the acoustic and perceptual characteristics of speech production in persons with ALS. Because manipulation of speaking rate is a common management approach in dysarthria [20, 21], it is important to understand the relation between rate change and acoustic and perceptual measures. Moreover, because rate manipulations have predictable acoustic effects in neurologically normal speakers, the study of rate effects in dysarthria may provide some insight into the nature of the speech production deficit and its effect on intelligibility. In the current study, participants produced sentences at habitual and *fast* speaking rates. Although it is often assumed that slowing of speaking rate in motor speech disorders will be beneficial to speech production and hence speech intelligibility, there are good reasons to explore the effects of increased rate as well. Primary, among these, is the possibility that additional slowing of speaking rate, especially when the neurological disease has already produced an abnormally slow rate, may force the speech mechanism to operate under conditions poorly suited to the highly coordinative behavior typically associated with normal speech production [22]. On the other hand, if slowed speaking rate is a beneficial manipulation for dysarthric speakers, perhaps because it reduces the complexity of these coordination demands, then increased rate might be expected to produce negative effects on speech production and intelligibility. In this sense, an evaluation of fast rate effects on the dysarthria associated with ALS is a test of the compensation explanation and rationale for the habitually slow rate among certain speakers with dysarthria, and the further slowing of that rate to obtain a therapeutic effect.

The current study thus addresses the following three questions: First, what is the influence of increased speaking rate on segment durations and vowel formant frequencies derived from sentence level material among ALS speakers? Secondly, what is the relation between this rate manipulation and the speech intelligibility of ALS speakers? And finally, what is the relation between rate manipulations and the perceived severity of speech impairment among the ALS speakers?

Method

Speakers

The speech samples were collected from 10 speakers exhibiting the dysarthria associated with ALS and 19 speakers with no known neurological disease. The participant groups consisted of 10 males (mean age = 72.2 years) and 9 females (mean age = 69.9 years) in the group of neurologically normal speakers and 5 males (mean age = 54.6 years) and 5 females (mean age = 56.8 years) in the ALS group. All were native speakers of English. Single-word intelligibility scores were acquired for the ALS participants as described in Kent et al. [4]. Scores ranged from 78.5 to 99.67%. The perceptual judgments of three of the authors character-

Table 1. Mean TUDs across groups and speaking rates (ms)

	Normal			ALS		
	habitual	fast	percent change	habitual	fast	percent change
'Buy Bobby a puppy'	1,173 (118)	882 (104)	24.8	1,649 (396)	1,317 (308)	20.1
'The high stack of cards is on the table'	2.119 (199)	1,573 (148)	25.7	3,104 (774)	2,465 (592)	20.6
'The potato stew is in the pot'	1,847 (195)	1,317 (146)	28.6	2,489 (576)	1,978 (520)	20.5

The column labeled 'Percent change' shows the relative increase in TUD from habitual to fast rate. Values in parentheses represent standard deviations.

ized the speakers as mildly to moderately dysarthric during spontaneous and sentence length speech; however, the speaker with the highest word intelligibility score was perceived as within normal limits of intelligibility.

Listeners

The perceptual portion of the study included 8 female and 2 male listeners. All were undergraduate or graduate students at the University of Wisconsin-Madison and reported English as their native language. Although all of the listeners had been exposed to dysarthria as a speech disorder, none had extensive research or clinical experience with the relevant clinical populations.

Procedure and Materials

Speech Samples. Each speaker was presented three different prerecorded stimulus sentences ('Buy Bobby a puppy', 'The high stack of cards is on the table', 'The potato stew is in the pot') via a loudspeaker. Each sentence was presented six times at an habitual rate and six times at a fast rate. Speakers repeated each sentence immediately following the model at the appropriate rate. The two rates were produced in separate blocks, and within the blocks the order of the 18 sentences was randomized. A total of 36 sentence utterances (3 sentences × 6 repetitions × 2 rates) were produced. All speech samples were recorded on tape using high-quality equipment.

Acoustic Analysis. Acoustic analysis was performed with Cspeech [23]. Measurements of total utterance durations (TUDs), segment durations, and F1 and F2 of selected vowels were gathered from the stimulus sentences. TUDs were obtained by measuring for each utterance all consonant and vowel intervals sequentially from combined waveform and spectrographic displays, using well-known criteria [24–26]. These intervals were then summed across the utterance to yield a TUD, which was used here as an estimate of speaking rate.

Formant frequencies were measured by centering a 30-ms window at the temporal midpoint of each vowel, and constructing overlaid FFT and LPC spectra for that window. These spectra were displayed along with a digital spectrogram, and final determination of the formant frequencies was made by comparing the LPC peaks with the center of the formant bands via ganged cursors. In the case of mismatches between the cursors, the spectrograph display was used to make the final measurement. The vowels selected for this analysis were the /æ/in 'stack', the /ɑ/'s in 'Bobby' and 'pot', and the /u/ in 'stew'. The fourth corner of the vowel space, /i/, was not included in this investigation because it was not represented in the set of sentences available for analysis. The measurement of the /u/ duration and formant frequencies required special operational definitions because the right-hand boundary was not an obstruent ('stew is'). Accordingly, /u/ durations were measured from the /t/ release in 'stew' to the point in time at which the falling F2 reversed its downward course and began to rise for /I/. The /u/ formant frequencies were measured using a 30-ms window extending leftward from the right-hand boundary of the /u/ interval.

Listening Task. Sentences were presented via a loudspeaker, within a sound-treated booth. Perceptual judgments of speech intelligibility and severity were obtained utilizing a magnitude estimation paradigm. Listeners were instructed to scale intelligibility according to perceived articulatory precision; overall severity was scaled based on the combination of articulation, speaking rate, and respiratory, nasal, and vocal characteristics. A modulus utterance, produced by a member of the ALS group and reflecting moderate severity of dysarthria as judged by the authors, was presented first, followed by 11 sentences randomized by rate and speaker. The 11th sentence was a repeated sentence from the first 10 and was used to measure intrarater reliability. The scale value for the modulus was set at 100. Listeners made magnitude estimates of the subsequent sentences relative to this modulus. The sentences were presented in 24 blocks of 11 sentences each, for a total of 264 sentences within both of the perceptual scaling tasks. Each block consisted of sentences randomized by rate and group.

Results

Total Utterance Durations

Two of the experimenters remeasured all of the utterance durations of a randomly selected subject with ALS. The interjudge agreement coefficient for this set of remeasurements was 0.99, and the average absolute difference between the first and second measurements was 51 ms. This figure is well below the group and rate differences reported in table 1.

Figure 1 displays the mean TUDs across sentences for each group and speaking rate; the means and standard deviations, as well as the percent change from habitual to fast rates are reported in table 1. The mean TUDs were always greater for the speakers with ALS, compared to the neurologically normal speakers. Both groups of speakers reduced TUD from the habitual to fast rate by approximately the same amount; because the TUDs of the ALS group were substantially greater than those for the normal group, the percentage reduction from the habitual to fast rate was

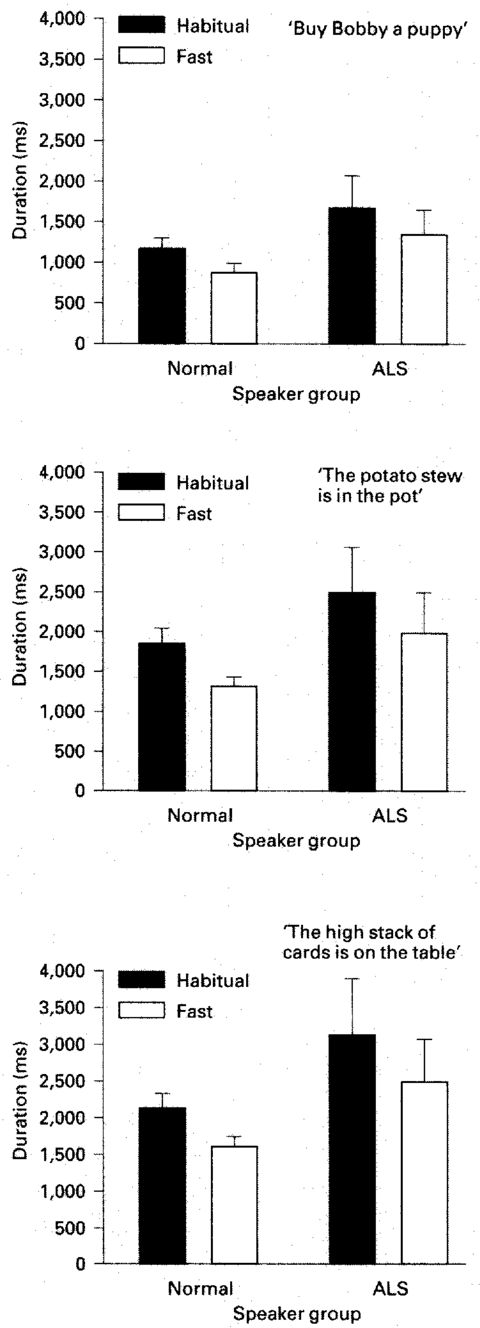
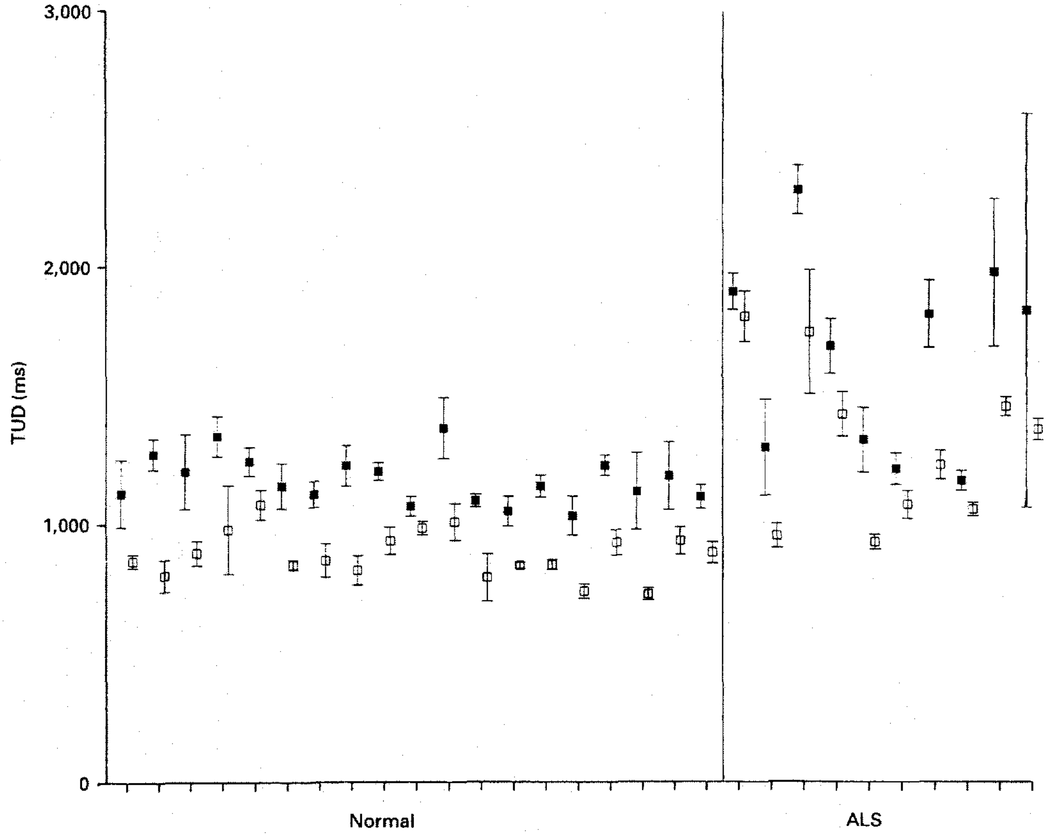


Fig. 1. Mean total utterance durations across sentences for each group and speaking rate. Error bars show 1 SD.

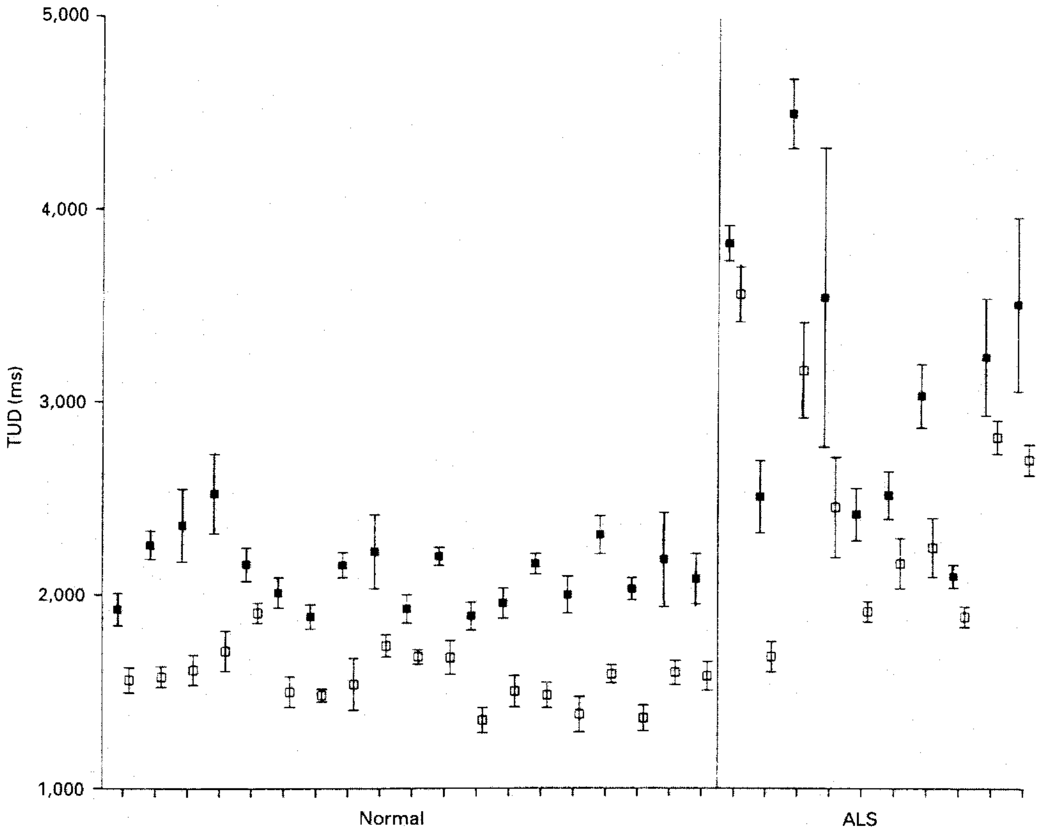


2a

Fig. 2. Mean total utterance durations at habitual (■) and fast (□) speaking rates shown for individual subjects in both groups. The data are arranged in pairs of symbols, one pair to a speaker as explained in text. The error bars extending from each symbol show ± 1 SD about the mean of six repetitions of a given utterance by an individual speaker. Data are shown separately for 'Buy Bobby a puppy' (**a**), 'The high stack of cards is on the table' (**b**) and 'The potato stew is in the pot' (**c**).

about 5–8% greater for the normal group (table 1). Inspection of the error bars shows that the interspeaker variation was much greater among the group of ALS speakers, as compared to the normal speakers.

The group and rate effects shown in figure 1 appear to be the same for each of the three sentences, but there were some statistical differences. The sentence 'Buy Bobby a puppy' had significant main effects for group [$F(1, 27) = 5.46$, $p < 0.05$] and rate [$F(1, 312) = 642.92$, $p < 0.05$], as well as the interaction between group and rate [$F(1, 312) = 4.07$, $p < 0.05$]; the same effects were significant for 'The high stack of cards is on the table' (group [$F(1, 27) = 5.97$, $p < 0.05$], rate [$F(1, 313) = 751$, $p < 0.05$] interaction between group and rate [$F(1, 313) = 5.97$, $p < 0.05$]). However,

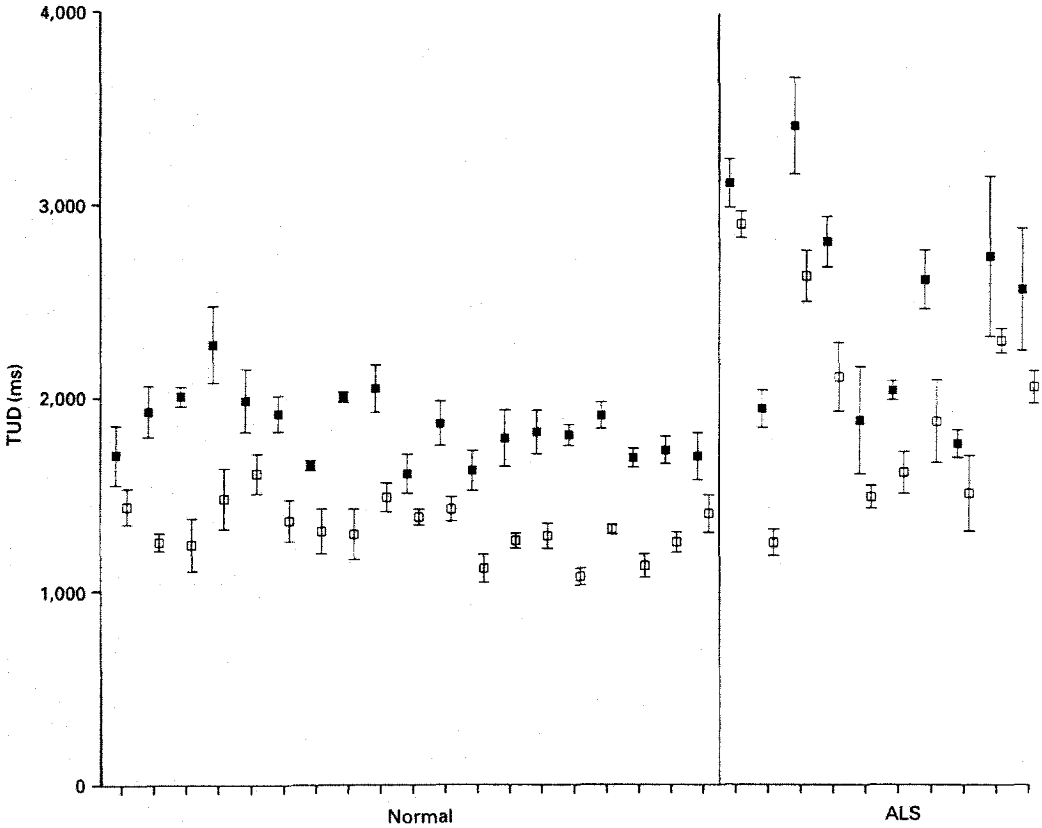


2b

(For fig. 2c see next page.)

the sentence 'The potato stew is in the pot' was significant for rate only [$F(1, 307) = 924$, $p < 0.05$]. The lack of a significant group effect for this sentence appears to be related to the smaller mean TUD difference between the normal and ALS groups (as compared to differences for the other sentences) combined with the large variability within the ALS group. The significant group by rate interactions for 'Buy Bobby a puppy' and 'The high stack of cards is on the table' reflects the slightly larger reduction in absolute TUD from habitual to fast rate for the speakers with ALS. These differences (41 ms for 'Buy Bobby a puppy' and 93 ms for 'The high stack of cards') are sufficiently small to rule out any substantial basis for the statistical interaction.

Figure 2 displays individual speaker TUDs at both rates. In these panels, the data for each subject are shown as a pair of adjacent symbols, with filled and unfilled boxes plotting mean TUD for the habitual and fast rates, respectively. There are 19 pairs of symbols for the normal subjects and 10 pairs for the subjects with ALS. The error bars show ± 1 SD



2c

about the mean of the 6 repetitions per speaker. Examination of these graphs suggests that the group results are a good representation of individual subject effects. Normal subjects appear to be quite consistent in the degree to which they reduce their TUDs from habitual to fast rate; across speakers and sentences, the percentage reductions range from 8 to 59, with a mean of 26.5 and a standard deviation of 7.97. The corresponding range, mean, and standard deviation for speakers with ALS is 5–38, 21.13, and 8.97. Two of the speakers with ALS produced very small percentage reductions for all three sentences. It should also be noted that several of the speakers with ALS produced absolute changes in TUD from habitual to fast rate that were substantially larger than the greatest changes produced by any of the neurologically normal speakers. Also, the fast TUDs for several of the speakers with ALS were very similar to the habitual TUDs of the normal speakers.

Formant Frequencies

Interjudge reliability for measures of F1 ($r = 0.963$, $p < 0.05$) and F2 ($r = 0.684$, $p < 0.05$) was significant. The average measurement error (difference between the original and second measurements) for F1 and F2 combined was 45 Hz, with somewhat lower measurement errors for F1, and higher errors for F2. This is just what would be expected

Table 2. Average formant frequencies (Hz) of selected vowels across sentences as a function of speaking rate, gender and speaking group

	Habitual		Fast	
	F1	F2	F1	F2
Normal females (n = 9)				
/æ/ 'stack'	731	2,055	697	2,071
/u/ 'stew'	394	1,091	434	1,364
/ɑ/ 'Bobby'	868	1,471	865	1,500
/ɑ/ 'pot'	913	1,477	897	1,512
ALS females (n = 5)				
/æ/ 'stack'	703	2,087	683	2,134
/u/ 'stew'	399	1,392	423	1,560
/ɑ/ 'Bobby'	881	1,644	870	1,684
/ɑ/ 'pot'	898	1,587	960	1,597
Normal males (n = 10)				
/æ/ 'stack'	641	1,667	631	1,658
/u/ 'stew'	378	1,102	393	1,173
/ɑ/ 'Bobby'	734	1,281	698	1,306
/ɑ/ 'pot'	766	1,310	739	1,300
ALS males (n = 5)				
/æ/ 'stack'	611	1,657	602	1,665
/u/ 'stew'	390	1,189	404	1,328
/ɑ/ 'Bobby'	684	1,379	671	1,365
/ɑ/ 'pot'	707	1,334	706	1,361

Table 3. Pattern of significance of the main effects of rate, group and their interaction for F1 and F2 across gender and vowels

	Female				Male			
	æ	u	ɑ1	ɑ2	æ	u	ɑ1	ɑ2
Rate								
F1	*	*		*	*	*	*	*
F2	*	*	*	*		*		
Groups								
F1								
F2		*				*		
Rate by group								
F1				*		*		*
F2		*				*	*	

* indicates significance at $p < 0.05$. æ = 'stack', u = 'stew', ɑ1 = 'Bobby', ɑ2 = 'pot'.

from previous studies of formant frequency measurement errors [27, 28].

In general, formant frequency changes with changes in speaking rate appear to be highly variable across both neurologically normal speakers and speakers with ALS. Previous research would lead to an expectation of reduction in formant frequencies from habitual to fast rates in the direction of the F1-F2 coordinates for /ə/. Examination of the group measures reported in table 2 shows that in many cases this expectation was confirmed, but the absolute magnitude of these effects was often small. A MANOVA with F1 and F2 as the dependent variables indicated variable significance for the main effects of rate and group and their interactions; table 3 shows the significant effects for F1 and F2. The vowel /u/ had the most consistent effects, with all cases showing the expected increases in both F1 and F2 with the change from habitual to fast rate. The significant interactions reflect different magnitudes of these effects for different groups, rather than different directions of effects.

When the rate effects on formant frequencies were examined by individual subject, it was clear that in some cases large intersubject variability complicated the interpretation of the group data. In the case of the vowels /æ/ and /ɑ/, for example, the F1 and F2 values were approximately equally likely to increase as decrease from the habitual to fast rate, for both groups of subjects. Individual subject data for /u/, shown in figure 3, were more orderly. In figure 3, F1 and F2 changes are shown. Figure 3 shows that 15 of the 19 neurologically normal subjects and 6 of the 10 subjects with ALS showed a rate-induced in-

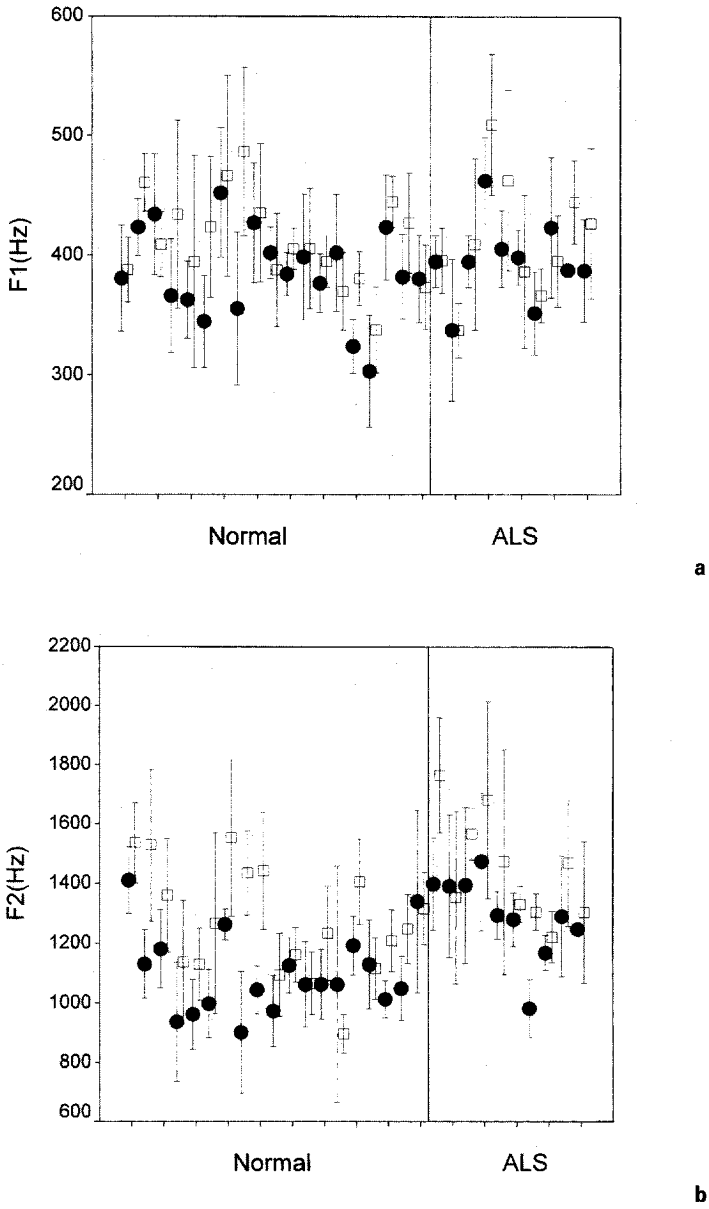
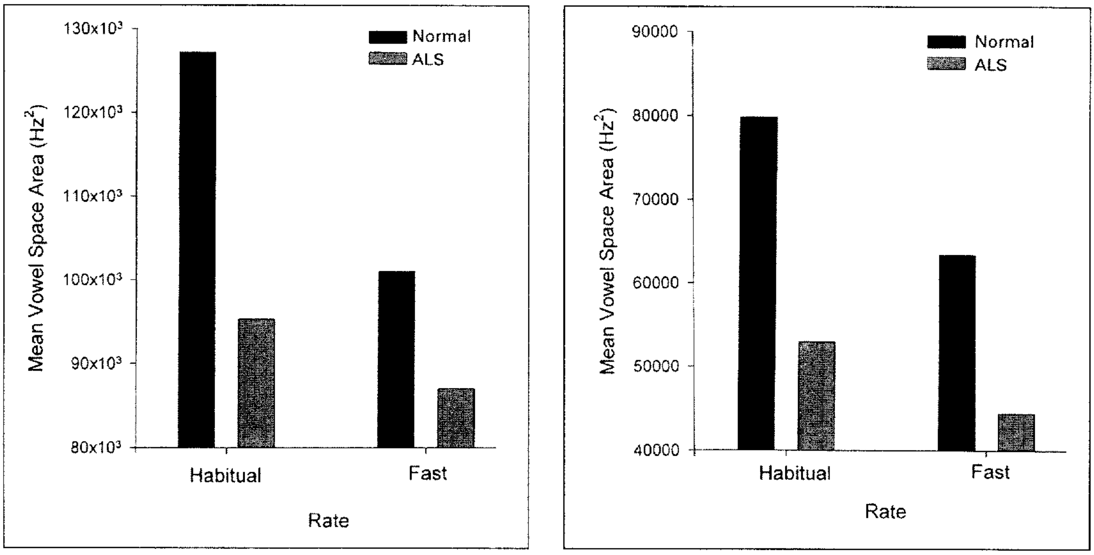


Fig. 3. Mean F1 (**a**) and F2 (**b**) values for the vowel /u/ at habitual (●) and fast (□) speaking rates, shown for individual subjects in both groups. The error bars show ± 2 SD about the mean of six repetitions of the vowel (in the utterance, 'The potato st**ew** is ...'). Subjects are shown along the abscissa, and within each group the females and males are separated by plotting the females first (from left to right) and then the males.

crease in F1. For F2, 16 of 19 neurologically normal speakers and 9 of 10 speakers with ALS had higher values at the fast, as compared to habitual rate. The rate effects for individual subjects tended to be small for F1 (on average, about 30–50 Hz for the subjects who showed the expected change toward the schwa coordinates), but somewhat larger for F2 (on average, about 130–300 Hz). There were no obvious between-group differences



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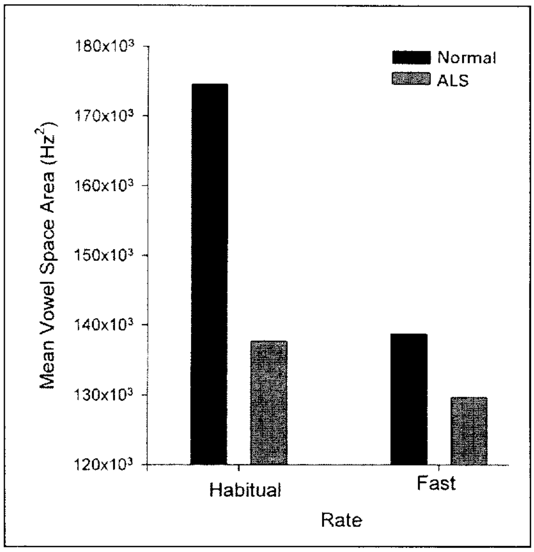

c

Fig. 4. Mean vowel space areas (in Hz^2) for both groups and speaking rates. **a** Participants pooled across gender. **b** Male participants. **c** Female participants.

when the individual subject data were examined. It is possible that the systematic effects seen for /u/, as compared to the other vowels, may be related to the greater change in duration for /u/ across rate. /u/ durations were reduced by between 34–54% from the habitual to fast rate, whereas the other vowels tended to have reductions of 9–30%.

Vowel Space

The vowel space area computed from three of the four corner vowels is plotted as a function of rate in figure 4. Vowel space areas are cleraly smaller for the ALS speakers, as compared to normal speakers, in all cases. This is similar to previous findings suggesting a reduced vowel space area for ALS speakers dur-

Table 4. Geometric means derived from magnitude estimates of speech intelligibility

	Normal		ALS	
	habitual	fast	habitual	fast
'Buy Bobby a puppy'	209 (96)	209 (122)	140 (60)	136 (64)
'The high stack of cards is on the table'	228 (129)	207 (98)	141 (67)	145 (69)
'The potato stew is in the pot'	229 (137)	222 (140)	150 (83)	142 (74)

Values in parentheses represent standard deviations.

Table 5. Geometric means derived from magnitude estimates of speech severity

	Normal		ALS	
	habitual	fast	habitual	fast
'Buy Bobby a puppy'	217 (120)	213 (114)	149 (77)	146 (67)
'The high stack of cards is on the table'	228 (121)	213 (115)	149 (83)	156 (90)
'The potato stew is in the pot'	225 (137)	223 (131)	155 (82)	149 (85)

Values in parentheses represent standard deviations.

ing habitual and fast speaking rates [8]. In the current study, however, rate change appeared to affect vowel space differently in females with ALS, as compared to the other gender/group combinations. Both groups of males showed the expected compression of vowel space at the faster rate (fig. 4b: percentage change from habitual to fast rate: normal males, 21%; ALS males 16%), as did neurologically normal females (fig. 4c: 21%). Females with ALS did show compression of the vowel space, but with a substantially smaller magnitude (fig. 4c: 6%).

Scaled Intelligibility and Severity

Table 4 reports the geometric means for intelligibility ratings for each sentence across groups for the two speaking rates. The scale values are very similar within groups, across rate; as expected, the scale values are consistently different across groups. The group differences appear to be about the same for each of the three sentences. These impressions were confirmed by an analysis of variance, which indicated significant main effects only for group [$F(1, 19) = 20.82$, $p < 0.05$]. The absence of a rate effect on scaled intelligibility is treated in some detail in the discussion.

The scale values for severity are reported in table 5. These data mirror the intelligibility findings, with significant main effects for group classification only [$F(1, 19) = 17.14$, $p < 0.05$].

Individual listener, mean scale values for intelligibility are plotted in figure 5. Each point plots the mean scale value from a single listener for one of the three sentences; this yields 30 points in each column of the graph

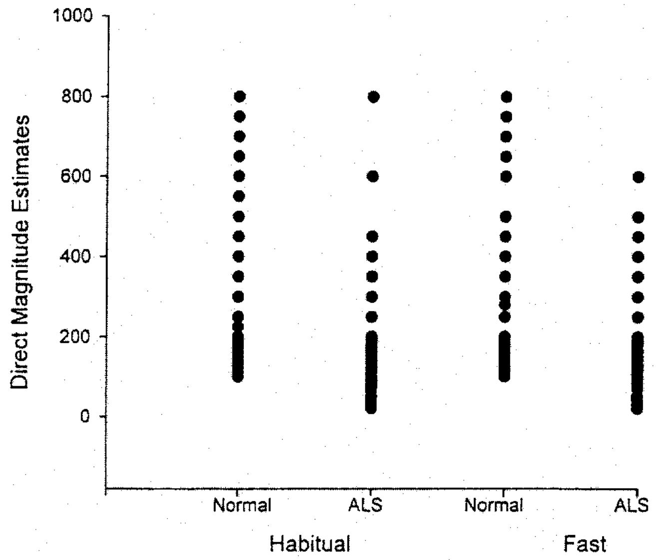

Fig. 5. Distribution of mean magnitude estimates of intelligibility from individual listeners, across the three sentences. Each column of data contains 30 points (10 listeners × 3 sentences).

(3 sentences × 10 listeners). These data show the clustering of points in the vicinity of the modulus value of 100, the tendency of some scale values for the ALS utterances to be less than 100 (more severe than the modulus), and the nearly complete overlap of the scale value distributions across rate and within groups. The distributions for the severity scale values were just like those shown in figure 5.

Scaling Reliability

A matrix of concordant pairs using Kendall's tau-b for the 10 raters produced significant correlations ($p < 0.05$) ranging from 0.570 to 0.762, suggesting a reasonable degree of agreement across utterances and ratings of intelligibility. Intrarater reliability for ratings of severity was correlated significantly ($r = 0.729$, $p < 0.05$). A matrix of concordant pairs from 0.115 to 0.800. Additionally, ratings of severity and intelligibility were correlated ($r = 0.659$, $p < 0.05$).

Discussion

The present investigation examined the effects of speaking rate adjustments on utterance durations, vowel formant frequencies, speech intelligibility and perceived severity of the speech impairment among ALS speakers. Speakers in the present investigation were asked to increase, rather than decrease, their speaking rate relative to their habitual rates; the latter is the more typical manipulation for clinical purposes [20, 21; but cf. 29, p. 317]. In general, speakers in both groups did increase their rates and reduce their formant frequencies when asked to speak more rapidly, but there were some between-group differences. On the other hand, the rate manipulation did not affect the perceptual scale values for speech intelligibility or severity. These findings are considered in more detail, below.

Total Utterance Duration

The question of why so many speakers with dysarthria have slow speaking rates has not been discussed much in the literature. It is often true that neuromotor diseases are characterized by reductions in velocity, amplitude and force-generating capabilities, one or all of which might be expected to produce slowness. In individuals with ALS, these reduced muscular capabilities have been said to be characteristic of the speech mechanism [30–32]. The typically slower-than-normal speaking rates in individuals with ALS, demonstrated again in the current study, may therefore reflect the abnormalities in muscular contraction and movement known to occur when muscles are weakened by lower (flaccid) and upper (spastic) motor neuron damage.

The explanation of slower-than-normal speaking rates resulting from these neuromotor deficits, however, is probably not quite so simple. First, some speakers with ALS do have the capability to modify (increase) their speaking rates in the direction of 'normal'. In agreement with Turner and Weismer [15], the present investigation found that most of the ALS speakers were able to increase speaking rate from their habitual (slower than normal) rate. Some of the ALS speakers within the present study, and in Turner and Weismer, were even able to increase their rate into the range of habitual rates observed among neurologically normal speakers. Thus, the neuromotor factors that might predispose a speaker with ALS to produce slower-than-normal rates do not necessarily preclude him or her from producing speech at near-normal rates.

Second, among normal speakers there is no straightforward relationship between factors such as velocity and amplitude of articulatory movements, and rate of produced syllables. Westbury and Dembowski [33], in a study of articulatory kinematics of diadochokinetic sequences, failed to find strong predictive relationships between measures such as tongue velocity and displacement on the one hand, and syllable rate on the other. Speakers who showed very small movements of limited velocity also showed high syllable rates. Limited range and velocity of movement, even when caused by neurological disease, may not map in a direct way onto measures such as speaking rate.

Third, there are neurological diseases other than ALS where the same neuromotor factors may be observed (e.g., limited range and velocity of movement, reduced force control) in the absence of slower-than-normal speaking rates. The articulatory bradykinesia in Parkinson disease, for example, may be accompanied by faster-than-normal speaking rates [34–36].

What then, are other possible explanations for the typically slower rates among ALS patients? It has been proposed that slowing of speaking rate might help to reduce kinematic interactions and coarticulatory influences, thereby making the task of speaking 'easier' [37]. Consistent with this view is a recent finding [38] suggesting that slow-rate movements appear to be less effortful than normal and fast-rate movements. On the other hand, articulatory movements produced at slow speaking rates are 'choppy', and not as smoothly executed as they are at normal and fast speaking rates [22, 38]. Thus, even though the present study and one other [15] suggest that some speakers with ALS can speak at near-normal rates, the more typical slower-than-normal rates may serve as an effective compensatory strategy. Perhaps ALS speakers are unable to maintain the effort required to speak within a normal range of speaking rates, or the cost of doing so (in terms of effort) is too high. This 'compensation-based-on-effort' speculation, however, still must contend with the opposing observation of non-smooth movements at slow speaking rates. Perhaps the effort reduction is more important than operating the speech mechanism at rates where the movements are not decomposed (i.e. not smooth), or perhaps the movements in neurological disease are decomposed already, and further decomposition does not result in substantial negative effects.

An issue that is suggested by the current data, but cannot be resolved adequately by them, is why there is so much variability among speakers with ALS in the degree to which their rate can be modified. One obvious possibility is that the more severely involved speakers were not as capable of modifying their speaking rate, when compared to less severely involved speakers. In the present investigation, however, single-word intelligibility scores and percentage increase in speaking rate (from the habitual to fast condition) were not significantly correlated across speakers in a post hoc evaluation of this hypothesis. Of course, this analysis depends on the assumption that the single-word intelligibility scores are a reasonable estimate of severity of speech involvement.

It is interesting to consider the notions of compensation and/or effort expenditure relative to the *increased* speaking rate manipulation of the current investigation. If there is an effort continuum and speakers with ALS slow their rates as a compensatory and/or effort reduction strategy, an increased speaking rate may be expected to tax the mechanism and affect the output of the vocal tract. More specifically, it might be expected that utterances spoken at faster rates by persons with ALS would somehow suffer from loss of compensatory benefit and increased effort involved in their production (for a similar argument, see Yorkston [21, p. 45]). As shown in the present investigation and discussed further below, this was not the case.

Effects on Rate Manipulation of the Vowel Space

The reduced vowel space area observed for the ALS speakers in the present investigation is broadly consistent with the findings of previous studies [6–8]. The average vowel space areas at the habitual rate for men and women with ALS were approximately 23 and 21% smaller than the areas for neurologically normal men and women, respectively. The similarity of these reductions suggests that the effect of the disease on the habitual-rate vowel space is comparable for men and women. The comparison of these group differences to previous findings [8] is not entirely straightforward, because the vowel space in the current study was constructed from only three of the four corner vowels (/i/ excepted) extracted from sentence productions. In Turner et al. [8], where all four corner vowels were used and embedded in a reading passage, there was a 64% difference in the habitual-rate vowel space area of neurologically normal individuals and individuals with ALS (pooled across gender). It seems safe to conclude that the dysarthria associated with ALS is typically characterized by a compression of the acoustic vowel space, but the degree to which this occurs is almost certainly going to depend on the nature of the speech material, the vowels used to obtain the measurements, and the particular speakers used in the study. For example, the vowel /u/ obviously played a large role in the reduction of the vowel space for all speakers in the current investigation. A vowel space constructed from /i/, /æ/, and /ɑ/ may have produced somewhat different results from those reported above.

The current findings also suggest a gender effect for the additional reduction of the vowel space consequent to an increased speaking rate; neurologically normal men and men with ALS had 21 and 16% reductions, respectively, whereas the corresponding percentage reductions for neurologically normal women and women with ALS were 21 and 6% (pooled across gender, the rate-induced reductions in vowel space in [8] were 11% for neurologically normal speakers, and only 2% for speakers with ALS). Because of the small number of subjects in the current study, it is impossible to know if this unusually small percentage reduction among women with ALS is a real gender/disease effect, or simply reflects sampling error. For example, it is possible that members of this group of women with ALS were more severely involved than the group of men with ALS, but the post hoc correlation analysis described above does not support this view. More specifically, perhaps the women with ALS had less-reduced vowel space areas because they did not reduce the vowel durations across rate to the same extent as men with ALS. Because there tends to be a relationship between extent of vowel duration reduction and reduction of formant frequencies [8, 9], differential rate effects across the ALS groups could have produced an apparent difference in reduction of the vowel space with rate manipulation. When the relative reductions in durations of the vowels from which the formant frequencies were obtained are compared across groups, however, there is no evidence that the women with ALS had a smaller reduction of vowel duration. In fact, for each one of the four vowels, the women with ALS had equal or *greater* reduction of vowel duration across rate, as compared to the men with ALS. The percentage reductions across rate for the four vowel durations and groups, in the order normal females, normal males, women with ALS, men with ALS, were /æ/, 25, 24, 21, 9; /ɑ1/, 22, 30, 23, 15; /ɑ2/, 14, 11, 9, 10; and /u/, 37,54, 41, 34. This suggests that the differential reduction of the vowel space across the male and female ALS groups cannot be explained by differential reduction of vowel durations.

Gender effects in speech production characteristics have been demonstrated for patients with ALS [39, 40]. A comparison of the results of these studies showed that the perceptual error rates for certain phonetic distinctions differed between males and females, most notably for the initial-consonant voicing and the initial glottal vs. null contrasts. One conclusion was that the errors of males appeared to be related to laryngeal function, whereas females exhibited minimal impairment of laryngeal function [41]. The female participants primarily showed contrast errors related to lingual articulation, velopharyngeal function and syllable structure. Such differences may indicate that neurologic disease affects the speech mechanism differentially depending on gender, and perhaps the lack of rate-induced change in the vowel space among women with ALS is another index of this phenomenon.

Rate Manipulation and Perception of Intelligibility and Severity

It has been hypothesized that slowed speaking rate is a compensatory mechanism with the goal of facilitating articulatory behavior, and thus increasing intelligibility [21]. This notion has been advanced not only to explain the habitually slowed rate of speakers with many forms of dysarthria (including the one associated with ALS [21]) but also the therapeutic approach of slowing patients even further to facilitate articulatory behavior. Presumably, increasing speaking rate among these patients would reduce or eliminate these compensatory strategies, and have a measurable effect on the perception of the speech disorder. In the present study, however, the increased speaking rate had no impact on either of two perceptual measures of the speech disorder, including scaled intelligibility and scaled severity.

The failure of the present investigation to demonstrate reductions in scaled intelligibility and severity with increased speaking rate raises several important theoretical and clinical questions. One obvious question concerns the validity of the compensation explanation of typically slow speaking rates in motor speech disorders. The slower-than-normal rates may have nothing to do with compensation, and in fact this would seem to be suggested by the current findings. What is needed are additional formal tests of the relationship between voluntary modifications of speaking rate, and measures of speech production and speech intelligibility, at both slower-than-habitual and faster-than-habitual rates. The available demonstrations of increased intelligibility with decreased speaking rate are generally for the cases of speakers with hypokinetic dysarthria and relatively faster-than-normal, habitual speaking rates [18, 42] and with ataxic speakers with slower-than-normal speaking rates [43, 44]. For the larger majority of dysarthric speakers with slow speaking rates, similar demonstrations have not been published. If, for example, there are differential effects of decreased vs. increased speaking rate on speech intelligibility, these kinds of manipulations should reveal their magnitude and consistency. The present results showing a great deal of production variability across patients in their response to rate change would suggest that the results of these intelligibility tests would be patient specific. The clinical implication of this would be that the application of a standard rate manipulation (i.e., based on an assumption about compensation, or reduced effort) might give way to systematic manipulation up or down the rate continuum to find a 'best' rate (in terms of speech intelligibility), if it exists, or to discard rate manipulation as a therapeutic strategy (if rate change does not modify speech intelligibility). Moreover, these same studies would allow an examination of the rate-dependent speech production factors that might be tied to potential changes in speech intelligibility. For example, the argument noted above that slowing of speaking rate reduces coarticulatory influences [37] is basically unproven but has an obvious link to compensation issues in dysarthria. The few studies of coarticulation in motor speech disorders [45–47] have produced conflicting results, and should be supplemented by within-speaker observations across different speaking rates.

It is also possible that we did not see any perceptual changes with modifications in speaking rate because the magnitude of rate change was not sufficient, or because the perceptual measures we used were not sufficiently sensitive. The relationship between speaking rate and speech intelligibility, if it exists, is not likely to be linear. If the rate changes produced by patients in the present investigation did not reach some threshold for loss of compensatory effect, the absence of perceptual effects would not be surprising. This is an unlikely explanation for the current results, however, because many of the rate increases were substantial. The sensitivity of the perceptual measures concerns our exclusive use of scaling techniques, which certainly do not tap into all potential levels of an intelligibility deficit. For example, it is possible that the rate increases achieved in the current investigation did cause selected sound segments to deteriorate, even though the general scaling of intelligibility was not affected. Even though the hypothesized deterioration of sound segment quality did not affect these global estimates of speech intelligibility, it would still serve as some evidence of a loss of compensatory effect. For this reason, the rate studies suggested above should probably include some form of segmental analysis, perhaps like the one reported for cerebral-palsied speakers [48].

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