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Syllabic Timing in Dysarthria

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A new, intensity-based method of measuring syllable duration was used to assess syllabic timing in 75 patients with dysarthria of predominantly traumatic and cerebro-vascular origin and in 30 normal subjects. The applied speech tasks included repetitions of sentences containing chains of plosive-vowel-syllables. The logarithm of the duration of the syllable carrying sentence accent proved to be particularly highly correlated with perceived speech rate. Among the potential sources of temporal variability, segmental influences and the influence of sentence stress were examined. Further, the between-sentence variation of syllable duration was assessed. The resulting measures of variability were correlated with the severity of dysarthric impairment. A strengthening of normal effects was found in the consonant-related variation, whereas intrinsic vowel effects and the influence of sentence stress were largely reduced. These results are discussed from the viewpoint of timing theories in speech and limb motor control. They are considered to provide a valuable background against which the speech impairments of specific neurologic groups can be tested.

KEY WORDS: dysarthria, speech, timing, acoustics, syllable

Timing is one of the key aspects of almost any kind of motor activity and has been the subject of numerous studies of motor control in experimental psychology, functional neurophysiology, and mathematical modelling (Viviani & Laissard, 1991). Moreover, temporal parameters of motor execution have been applied successfully in investigations of the pathophysiologic nature of different neuromotor disorders (e.g., Ivry & Keele, 1989; Marsden, 1989).

In the study of speech motor control, too, rhythm and timing have been of considerable interest, in both normal (e.g., Fujimura, 1987; Ostry & Munhall, 1985) and neurologically impaired subjects. The temporal aspects of disordered speech production have been investigated on the basis of kinematic as well as of acoustic measures of articulation (e.g., Ackermann & Ziegler, 1991; Caruso & Burton, 1987; Kent, Netsell, & Abbs, 1979; Morris, 1989; Tatsumi, Sasanuma, Hirose, & Kiritani, 1979; Weismer & Fennell, 1985; Ziegler, Hoole, Hartmann, & von Cramon, 1988).

In most of the acoustic studies published so far, disordered speech timing has been described at the level of segmental or even subsegmental units. Based upon the segmentation standards applied in acoustic phonetics, the discontinuities observed at the points of voice onset/offset or of articulatory implosion/explosion were used as landmarks in the measurement of relevant intervals in the speech signal, like, for instance, vowel segments, voice onset times, or stop closure periods (e.g., Caruso & Burton, 1987; Farmer, 1980; Morris, 1989; Weismer, 1984; Weismer & Fennell, 1985).

In this article the problem of speech timing in dysarthria is addressed at the level of *syllabic* units. This syllable-based approach, which differs from most of the studies published so far, is motivated by conceptual, methodological, and technical arguments.

First, the syllabic organization of speech has a high biological significance, because it apparently reflects fundamental biomechanical constraints of the articulatory apparatus (Lindblom, 1983; Sorokin, Gay, & Ewan, 1980) and its developmental roots

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can be traced back to the babbling of infants (Kent, Mitchell, & Sancier, 1991). Moreover, the syllabic make-up of spoken language seems to be related to a very basic notion of "speechiness," that is, the attribution of speech-like quality to an utterance (Kent et al., 1991). From a functional point of view, the syllabic rhythm of speech is known to make a crucial contribution to intelligibility (e.g., Cherry & Wiley, 1967; Nooteboom, 1985) and to support attentional processes in speech perception (Pitt & Samuel, 1990).

Second, the syllable may be considered a basic unit of the rhythmic organization of speaking and as such may play a key role in comparisons of speech with other kinds of rhythmic behavior (Viviani & Laissard, 1991). For instance, cross-modal investigations of tapping and speech rhythms have typically referred to syllabic units (e.g., Klapp, 1979). Further, laboratory experiments of higher-level control mechanisms of speaking have demonstrated that the role played by syllables in the hierarchical organization of speech units compares to that of single tapping strokes in the control of tapping or keyboarding sequences (e.g., Rosenbaum, Gordon, Stillings, & Feinstein, 1987).

Third, from a methodological viewpoint the search for timing patterns in normal and neurologically impaired speech requires that, at least at some specified level of analysis, discrete speech units can be identified (Viviani & Laissard, 1991). If the effects of neuromotor impairment on speech timing are to be examined over a wide range of severity it is required that these units remain detectable even under the condition of severe dysarthria. The syllable appears to be a good candidate to fulfill these requirements: In appropriately selected speech tasks syllabic boundaries are reflected by gross discontinuities in the speech signal, and even if articulation is severely disordered there is usually no problem in identifying syllabic units. Our departure from a segment-based approach was motivated by our experience that the landmarks conventionally used in the segmentation of normal speech are often distorted or even absent in the speech signals recorded from people with severe dysarthria (cf. Morris, 1989), whereas rudiments of the syllabic structure of an utterance are still preserved in even the most severe cases (Ziegler & Hartmann, in press). This is reminiscent of arguments cited in favor of a syllable-based analysis of infant speech by Kent et al. (1991), who stressed that the syllable as a behavioral unit does not presume the existence of a fully elaborated segmental make-up.

The present study is based on sequences of plosive-vowel syllables, whose temporal structure can be considered to represent the timing of a chain of raising and lowering movements of the lips, the tongue blade, and/or the tongue back. The applied measures of syllable duration are based on speech wave envelopes rather than on oscillographic or spectrographic displays (cf. Ziegler et al., 1988). This method, which resembles an approach taken by Mermelstein (1975) (see also Rosen, 1992; Tatsumi et al., 1979), is independent of the detection of landmarks within the speech signal and allows for a fast and objective analysis of large samples of speech, even under conditions of severe articulatory distortion.

In this respect the approach chosen here differs substantially from earlier approaches, as, for instance, the one

TABLE 1. Subjects.

Group	*N*	Age*	Sex	Months since lesion*
CHI	40	21 (16–52)	33 m, 7 f	15 (3–90)
CVA	25	46 (28–70)	17 m, 8 f	6 (2–146)
Others	10	50 (21–72)	6 m, 4 f	5 (2–125)
Total	75	35 (16–72)	56 m, 19 f	10 (2–146)
Controls	30	38 (19–64)	16 m, 14 f	—

*median (min, max)

chosen by Kent et al. (1979) or Weismer & Fennell (1985), which is based on units that are critically dependent on conditions unrelated to articulatory timing, such as the onset and offset of voicing. Our analysis also differs from earlier ones in that it is based on a larger sample of control subjects ($N = 30$) and uses distribution-free and robust methods of statistical analysis.

The major questions to be answered below relate to the acoustic correlates of perceived speech rate and to the sources of temporal variability in dysarthric speech. Among the latter, the influences of consonant place of articulation, vowel height, and sentence accent are examined more closely. The reported data are based on a large sample of predominantly traumatic and cerebro-vascular dysarthric subjects ($N = 75$). The heterogeneity of this sample raises no expectations concerning the emergence of specific syndromal patterns. Because traumatic and cerbro-vascular dysarthrias may mimic the different types of speech disorders seen in the various neurologic syndromes (cf. Vogel & von Cramon, 1983; Ziegler et al., 1988), our analysis was aimed at the detection of universal, severity-dependent relations rather than on the differentiation between neurologic subgroups. The data to be reported here may provide a valuable background against which the speech dysfunctions of more specific neurologic groups can be tested.

Method

Subjects

Seventy-five patients with dysarthric impairments of different etiologies and 30 subjects with no known neurological or speech deficits were examined. An overview of the subjects is contained in Table 1. Forty patients had suffered from closed head injuries (CHI), 25 patients from cerebro-vascular accidents (CVA), and 10 patients had a variety of other etiologies. Table 1 specifies age, sex, and time since lesion for these groups.

For the CHI subgroup, cranial computed tomography revealed purely focal lesions in 7 out of 40 head-injured patients, diffuse lesions in 13 cases, and both focal and diffuse lesions in 20 cases. In 14 cases a hypoxia secondary to head trauma was suspected. In the majority of head trauma patients ($n = 29$) CT scans and/or clinical data indicated brainstem involvement. Eight patients had suffered from a transient apallic syndrome.

Among the 25 CVA patients, 7 had suffered from intracerebral hemorrhages and 18 from infarctions. Among the latter, 8 patients had multiple lesions as a consequence of subcortical arterial encephalopathy or of multiple infarctions. The remaining 10 CVA subjects had focal lesions after pontine infarctions ($n = 4$) and after infarctions in the territory of the medial cerebral artery ($n = 5$) and of the superior cerebellar arteries ($n = 1$). Among the hemorrhagic patients, bleedings of the putamen-claustrum-type ($n = 5$) and of the ponto-mesencephalic-cerebellar ($n = 1$) and the peri-aqueductal region ($n = 1$) occurred. Sixteen of the 25 CVA patients had bilateral and 9 had unilateral (5 right, 4 left) lesions. The etiologies of the remaining 10 dysarthric patients were encephalites (4), neoplasms (2), anoxic encephalopathy (1), progressive supranuclear palsy (1), pseudobulbar palsy of unknown etiology (1) and unknown neurological disease (1).

All patients received comprehensive clinical speech and language examinations at the Neuropsychological Department of the Municipal Hospital München Bogenhausen. Neurolinguistic screening tests (parts of the Aachener Aphasie-Test including spontaneous speech, reading, writing, and the Token Test; Huber, Poeck, Weniger, and Willmes, 1983) revealed residual aphasic symptoms in five patients (3 CHI, 2 CVA). Twenty-one patients reported disturbances of swallowing and mastication (9 CHI, 9 CVA, 3 others). Visual and endoscopic inspection of the speech organs (laryngoscopy, nasal endoscopy) revealed hyperkinetic movements of lips, jaw, tongue, velum, and/or larynx in 22 cases. In no case could any significant degree of muscular atrophy or muscle fasciculations be observed. Reflectory adduction of the vocal folds during coughing as well as elevation of the velum following elicitation of the gag reflex were preserved in all patients.

Materials and Examination

The acoustic data presented here were obtained from a sentence repetition task that was part of a more comprehensive speech examination (Ziegler, Hartmann, Hoole, & von Cramon, 1990). The sentences were of the form "Ich habe /gəCVC ə/ gehört" ("I have heard . . .") with C=/p,t,k/ and V=/i,y,u,a/. Each subject was asked to repeat the sentences in a quasi-randomized order upon oral presentation by the examiner. Two runs of the examination were performed within one session, yielding a total of 24 sentence productions. Speech examinations were performed in a sound-treated room. Recordings were made using a Nagra IVS tape recorder and a directional microphone (Sennheiser) at a constant mouth-to-microphone distance of 20 centimeters.

Acoustic Analysis

The recordings were digitized at a 12-bit resolution and a rate of 20kHz after low-pass filtering at 9kHz. All speech signal processing was done on an LSI 11/73 laboratory computer. The speech signal was edited and the beginning and end of a sentence was determined. For each sentence an intensity contour in dB was computed over 12.8-msec

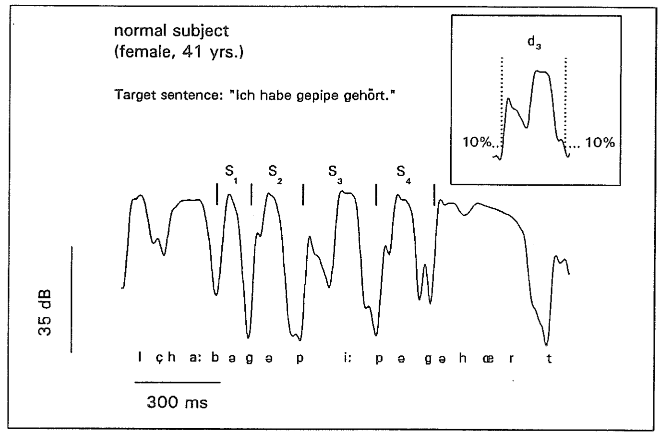

FIGURE 1. Sound pressure level contour of one of the test sentences produced by a normal subject. The four target syllables are separated by small bars. The insert illustrates how the parameter "extended nucleus duration" was determined.

windows shifted by 1.6-msec steps. The contours were smoothed by a 35-point FIR filter with a cutoff-frequency of 30 Hz (cf. Ziegler, Hoole, Hartmann, & von Cramon, 1988). The smoothed intensity contours provided the basis for duration measurements: The contour of a sentence was displayed together with the corresponding oscillogram tracing. An interactive, audio-supported routine then allowed for a rough positioning of two cursors around the intensity peak of each syllable with subsequent automatic computation of the position of the peak and of the two local minima to the left and right of it. Further, the 10% SPL thresholds to the left and right of each syllabic peak were determined. This evaluation was performed for the syllable /bə/ of "habe" as well as for each of the three syllables of the target word, the four syllables being referred to as S_1 to S_4, in the order of their occurrence (Figure 1). Intensity peaks because of inspirations or sound or syllable iterations were skipped.

The periods between the 10% rise and fall thresholds of a syllable, henceforth denoted by d_i ($i = 1, \ldots 4$), were referred to by the term "extended nucleus duration" (Ziegler et al., 1988; see Figure 1). At the sentence level a distinction was made between the "target" CV-syllable S_3, which carries sentence stress, and the "non-target" or "weak" syllables S_1, S_2, and S_4. Whereas d_{ext} denotes the mean value of the extended nucleus durations of syllables S_1 to S_4, d_w refers to the average duration of the three "weak" syllables and contrasts with d_3, that is, the duration of the target syllable.

Segmentation of the stressed vowel of a sentence and of the plosive-to-plosive-cycle of the stressed syllable S_3 was performed whenever possible, that is, whenever clear plosive bursts were detectable. The *vowel segment* S_v with duration d_v extended from the first harmonic oscillation visible in the speech signal to the point where the speech signal was critically damped. The *plosive-to-plosive cycle* S_{cv} with duration d_{cv} extended from the release burst of the plosive of the accent-carrying syllable S_3 to the release burst of the post-accent plosive of S_4. In 20 out of 75 patients (27%) these oscillogram-based segmentations could not be performed to a sufficiently reliable extent, mostly because of the presence of multiple bursts, of spirantization, or of harmonic oscillations during the closure period (cf. Weismer, 1984; Ziegler & Hartmann, in press).

Perceptual Analysis

In order to provide external criteria for the acoustic data to be reported here, the recordings of each of the 75 dysarthric patients were submitted to perceptual judgments. The listener group consisted of eight speech-language pathologists with clinical experience in the diagnosis of dysarthric patients (7 females, 1 male; 22–32 years). They were paid for their participation in the study. Listeners were asked to make judgments on a protocol of a total of 24 perceptual features including voice, articulation, and prosody, as well as more general estimates on the subject's overall speech impairment. The features that are relevant in the context of this study are *speech rate,* divided into the two subscales of "slowed" and "accelerated" speech, and *overall severity.*

Each variable was rated on a 7-point scale, with 0 denoting unimpaired performance and 6 denoting maximally impaired performance. Although it is known that, because of validity problems, interval scales are not the best instrument to assess perceptual correlates of disordered speech, such scales are nevertheless considered useful in preclassifying patient groups (Samar & Metz, 1988). The rating procedure was based on comprehensive speech recordings, including various word and sentence repetition tasks, sustained vowel tasks, and rapid syllable repetitions. The listeners were provided with forms containing the perceptual features to be rated and the corresponding rating scales. Listening sessions took between 20 and 40 minutes.

Each listener had a warm-up on three patient recordings. During this training interval listeners were allowed to ask questions about the rating criteria and the scales to be used in the procedure. For organizational reasons, it was not possible for each listener to make judgments on the whole patient sample. Instead, each listener rated a minimum of 12 recordings, each recording being judged by 4 listeners. In order to compensate for systematic between-listener differences a normalization of the perceptual data was performed for each variable independently. To this end, two listeners with ratings on a common basis of 56 recordings were chosen as "norms." For each listener the set of recordings she had in common with both norm listeners was determined and each single score on a particular variable was normalized by the difference between the listener's own average score on that variable and the grand average of the two norm listeners. By this method, the normalized scores for each listener assumed equal averages on the subset of recordings she had in common with the two norm listeners.

Inter-rater agreement was examined on the basis of deviations of individual normalized scores from their corresponding mean scores, pooled over the total sample of 300 ratings (4 [listeners] × 75 [patients]). Ninety percent of these deviations were lower than .98 for "slowed speech," lower than .44 for "accelerated speech," and lower than .93 for "overall severity," indicating that the individual ratings were fairly close to their corresponding mean scores for these variables.

TABLE 2. Perceptual data (4 listeners, averages).

Group	Perceived severity* 0: normal; 6: most severe	Perceived speech rate* −6: markedly slowed; 0: normal; +6: markedly accelerated
CHI	2.1 (0.5, 6.0)	−2.1 (−5.4, 3.2)
CVA	2.3 (0.5, 5.0)	−1.4 (−4.7, 3.2)
Others	2.6 (1.4, 5.4)	−2.5 (−4.8, 1.7)
Total	2.3 (0.5, 6.0)	−1.9 (−5.4, 3.2)

*median (min, max)

Because of the high time expenditure of the rating procedure, reratings and ratings of normal subjects were not performed.

Table 2 contains averaged normalized ratings for the three etiologic groups on the two variables "overall severity of dysarthric impairment" and "speech tempo." The two rating scales for "slowed speech" and "accelerated speech" were combined to form a single scale ranging from −6 ("markedly slowed") over 0 ("normal") to +6 ("markedly accelerated").

The "overall severity" scores demonstrate that a large range of severity was covered by the patient sample of this study, with a great number of mildly impaired patients. However, high severity ratings were also obtained. Among the three etiologic groups the mixed group ("others") was characterized by a lack of very mild cases, with an overall severity above 1.4 in all cases.

The scores given in the right column of Table 2 demonstrate that a rather skewed distribution of speech tempo ratings was obtained, with the slowest patients reaching scores up to −5.4 as compared to a maximum score of +3.2 for patients with accelerated speech. Both slowed and accelerated speech was represented in all etiologic groups, yet with a clear preponderance of the slowed type. Perceived slowness was highly correlated with the perceived degree of severity (Spearman, $r = .64$, $p < 0.01$). The severity ratings provided the basis for subdividing the patient sample into three subgroups of equal size ($n = 25$): mild dysarthrics (MID), with severity scores lower than 1.65, moderate dysarthrics (MOD), with severity ratings between 1.65 and 3.90, and severe dysarthrics (SED), with severity scores higher than 3.90.

Results and Discussion

Syllable Durations and Perceived Speech Tempo

As for the acoustic correlates of speech tempo, several measures of syllabic rate were considered (cf. *Acoustic Analysis,* above). An overview of the relevant duration parameters is contained in Table 3.

A most straightforward measure is "effective syllable duration" d_{eff}, that is, the total duration of a test sentence divided by the number of syllables (= 8). The values obtained for this parameter are reported in Table 4. Regarding underlying pathomechanisms, this measure is rather unspecific because it reflects intersyllabic pauses, hesitations,

TABLE 3. Overview of duration parameters.

Parameter	Abbreviation	Definition
extended nucleus duration of syllable S_i (i = 1, . ., 4)	d_i (i = 1, . ., 4)	period between 10% rise and fall thresholds of the SPL contour of syllable S_i (i = 1, . . 4) (see figure 1)
mean weak syllable duration	d_w	mean value of weak syllable durations d_1, d_2, and d_4
mean extended nucleus duration	d_{ext}	mean value of syllable durations d_i (i = 1, . . 4)
effective syllable duration	d_{eff}	sentence duration divided by number of syllables (=8)
duration of stressed vowel	d_v	period between first harmonic oscillation and the point of critical amplitude damping of the vowel of syllable S_3
plosive-to-plosive cycle of S_3	d_{cv}	period between the plosive bursts of syllables S_3 and S_4

inspirations, syllable or sound iterations, and prolongations of steady states and transitions.

More specific is "mean extended nucleus duration" d_{ext} (cf., Figure 1), which is presented in the second column of Table 4. This measure cancels out the influences of pausing, hesitations, inspirations, iterations, revisions, and so on, and reflects the duration of the sonority peak of an actual syllable as defined by 10% intensity thresholds, averaged over S_1 to S_4. Column 3 of Table 4 contains the extended nucleus duration of the stressed syllable of a sentence, that is, d_3 (see Figure 1). The two rightmost columns of Table 4 present the data obtained from conventional segmentations of the target vowel of a sentence (d_v) and of the plosive-to-plosive cycle of the target syllable (d_{cv}). It should be noted that these data were available only for 55 out of 75 patients, because of a failure to detect the landmarks specifying these segments in 6 moderate and in 14 patients with severe dysarthria. The figures entered in the cells of Table 4 represent group data obtained from median values of the 24 sentences spoken by each individual.

In accordance with the perceptual data of Table 2, each of the three etiologic groups, which are no longer distinguished in Table 4 and in the following, contained patients with both particularly low and particularly high duration values, with a clear preponderance of prolonged durations over shortened ones. Statistically significant deviations from the normal group (in the sense of increased durations) were found in all subgroups as well as in the whole patient sample. The slowest patients had syllable durations of the order of 500–1000 msec, whereas the shortest duration values were slightly below normal.

In the controls, the ratio between the duration d_v of the stressed vowel and the extended nucleus duration of the stressed syllable assumed a median value of .41 (range: .30–.51), and the latter occupied an average of 85% (median value) of the plosive-to-plosive cycle d_{cv}, with a range between 75 and 90%. The intermediate position of d_3 between the duration d_v of the syllabic nucleus and the plosive-to-plosive interval d_{cv} justifies the term "extended nucleus duration" chosen for this measure.

In the patients ($n = 55$), the ratios between d_3 and the two oscillogram-based measures differed from normal: The vowel segment occupied a larger proportion of the extended syllable nucleus, that is, 49% on the average (Mann-Whitney, $U = 399$, $p < 0.001$), probably due to decreased closure durations and decreased plosive aspiration periods (cf. Caruso & Burton, 1987). There was a significant correlation of this quotient with perceived severity ($r = .54$, $p < 0.001$). On the other hand, the quotient between extended nucleus durations and oscillogram-based plosive-to-plosive cycle durations was close to normal (85% on the average), but more variable in the patients than in the controls (range: .68–1.0).

The two bottom lines of Table 4 indicate the extent to which each of the five measures may be used to predict perceived speech rate by a linear regression. The r^2-values given in each of the columns may be interpreted to represent the proportion to which the variance in the perceptual data can be explained by the corresponding acoustic measure. All computations were done for both linear-scaled and logarithmically transformed durations. In all cases a logarithmic time scale yielded considerably higher prediction rates than a linear time scale did. The two parameters measured from the oscillogram had lower r^2-values than the remaining three measures, whereas among the latter, d_3 obtained the highest value. With the provision that the two oscillogram-related measures were based on a smaller sample-size ($n = 55$) it may be inferred from the data of Table 4 that the listeners' speech tempo ratings were most sensitive to the logarithm of

TABLE 4. Measures of speech tempo (median, range) in milliseconds and their relation to perceived rate.

	d_{eff}	d_{ext}	d_3	d_v	d_{cv}
Normal subjects ($n = 30$)	184 (164–256)	142 (120–193)	192 (171–248)	81 (53–119)	225 (194–302)
Patients ($n = 75$)	273 (127–1094)	215 (106–762)	257 (115–796)	146 (54–323) ($n = 55$)	347 (147–758) ($n = 55$)
r^2					
lin	0.60	0.63	0.62	.60 ($n = 55$)	.63 ($n = 55$)
log	0.72	0.73	0.74	.63 ($n = 55$)	.71 ($n = 55$)

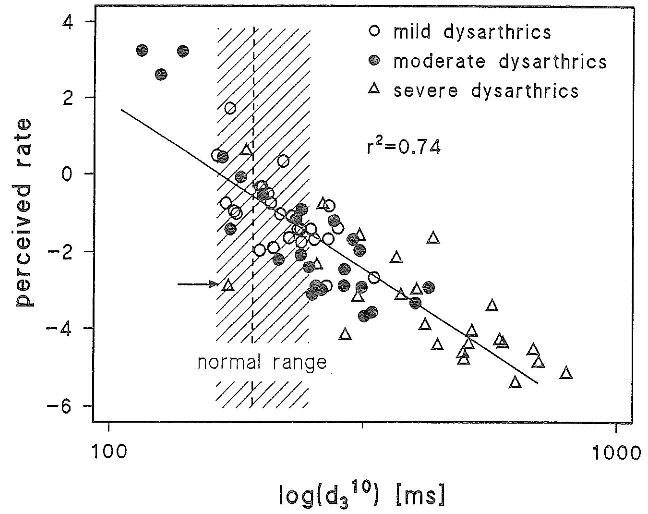

FIGURE 2. Relationship between extended nucleus durations of S_3 (logarithmic scale) and perceived speech rate. The arrow marks a patient who was rated as markedly slowed, although d_3 was considerably low (see text).

the extended nucleus duration of the stressed syllable of a test sentence. Particularly low values were obtained for the vowel duration measure based on conventional segmentation techniques, that is, d_v. This parameter obviously reflects, besides speaking rate, phonatory influences that are irrelevant to the perception of the speech tempo of dysarthric speakers.

The fact that d_v and d_{cv} were poor predictors of perceived tempo is compatible with the findings of Edwards & Beckman (1988), who more generally stated that conventional segmentation yields only gross indicators of the perceived timing structure of speech (see also Fowler & Tassinary, 1981). The intensity-based measures chosen here seem to model more closely the cyclic alterations of "sonority" in a syllabic chain and may thus have been the cause of their particularly high correspondence with perceived tempo.

Figure 2 demonstrates that the relation between $\log(d_3)$ and perceived speech rate was fairly linear. Remarkable deviations from the regression line occurred predominantly within or near the range of normal syllable durations. In particular, 3 patients with syllable durations below the normal minimum received disproportionately high tempo ratings (2.2 to 3.2), whereas one severely impaired patient with a normal mean syllable duration (see arrow in Figure 2) obtained a slowness score of −2.8. In the former three cases the listeners were apparently guided by complex acoustic cues including, besides syllabic length, the articulatory quality of speech (Ziegler et al., 1988). On the other hand, frequent intersyllabic pauses may have caused the listeners to rate the latter as markedly slowed. In the patient marked by an arrow in Figure 2, d_{eff} (which respects speech pauses) was markedly increased and provided a more appropriate index of perceived rate than d_3 did.

Variation of Syllabic Timing

Whereas the preceding paragraph was focused on average measures of syllabic timing and their relations to perceived rate, the following sections describe how syllable durations varied over different tasks or within a syllabic chain.

Plosive-related variation. One source of variability in the duration measures considered here is related to the experimental variation of the consonantal constituents of the target syllable S_3. The consonant effect was studied by computing median values of d_3 for each of the target plosives /p/, /t/, and /k/ separately, with a sample size of 8 in each case (4 [vowels] × 2 [repetitions]). Pairwise comparisons between plosive groups were made on the basis of between-plosive differences relative to a speaker's overall median value of d_3.

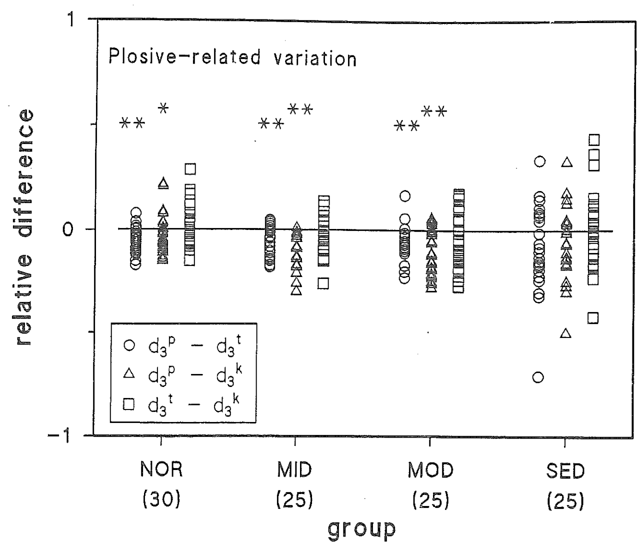

FIGURE 3. Pairwise relative d_3-differences between test sentences with varying target plosives (averages). *: $p < 0.05$; **: $p < 0.01$.

Figure 3 presents these data for the normal group and for the three groups of mild, moderate, and severe dysarthrics. In the normal group there was a small plosive effect, showing up in a slight decrease of syllable durations in labial as compared to lingual consonants (/p/ vs. /t/: $p < 0.05$; /p/ vs. /k/: $p < 0.01$; Wilcoxon, matched pairs).

Among the patients, only the severe group demonstrated a substantial increase in consonant-based variations, with large differences occurring in all plosive pairings. The bias between labials and linguals found in the normal group was no longer present (/p/ vs. /t/: $p = 0.30$; /p/ vs. /k/: $p = 0.14$; Wilcoxon, matched pairs). In the mild and moderate cases, on the contrary, the difference between /p/ and /k/ syllables was slightly more pronounced (to the disadvantage of /k/) as compared to the normal group ($p < 0.01$ in both subgroups).

Despite these group tendencies, each of the three severity groups contained individuals whose relative between-plosive differences were within the normal range. Moreover, the results show that an overproportionate lengthening of the /kV/ target syllables, as we suggested earlier for spastic dysarthria (Ziegler & von Cramon, 1986), was by no means universal in the heterogeneous dysarthric group considered here. Thus, an analysis of consonant-related duration differences appears to have some potential for detecting differential impairments of single articulators in individual patients, which may be relevant for the development of tailored therapeutic approaches and for the assessment of specific treatment effects.

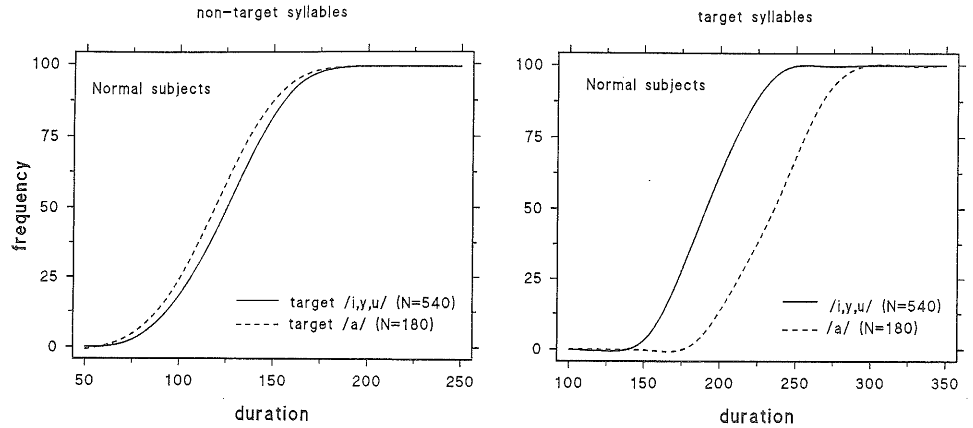

FIGURE 4. Cumulative distributions of extended nucleus durations (in msec) of nontarget syllables S_1, S_2, S_4 (left) and of the target syllable S_3 (right) in the normal subjects. Solid lines: high target vowels; dashed lines: low target vowel.

Vowel-related variation. The duration of a syllable is known to vary systematically with the height of the vowel that constitutes its nucleus. Whereas the high vowels /i, y, u/ of the target syllables used here may be considered to have similar intrinsic durations, the low vowel /a/ can be expected to have increased length (Antoniadis & Strube, 1984). Intrinsic vowel length effects are commonly ascribed to differences in the articulatory maneuvers associated with the production of high and low vowels, particularly the constraining effect of mandibular lowering for /a/ (see e.g., Fischer-Jørgensen, 1964). An alternative hypothesis was proposed by Newekłowsky (1975), who suggested that high vowels are shortened in compensation for their increased subglottal pressure.

Figure 4 demonstrates the effect of intrinsic vowel duration in the normal population of this study by presenting cumulative distributions of extended nucleus durations for a sample size of 180 in the case of /a/ (30 [subjects] × 3 [plosives] × 2 [repetitions]) and 540 in the case of /i, y, u/ (30 [subjects] ×3 [plosives] × 3 [vowels] × 2 [repetitions]).

The right panel refers to the duration of the target CV-syllable, that is, d_3, the distribution of which differs in the expected direction between /a/ and the high vowels (Kolmogorov, $p < 0.001$). The left panel presents distributions of d_w, that is, the mean value of the extended nucleus durations of the non-target syllables of a sentence. It demonstrates that a small target-vowel-related difference was present in these data, too, despite the fact that the corresponding syllables did not contain any difference in their vocalic components (Kolmogorov, $p < 0.05$). The observation that the non-target syllables of a sentence with target vowel /a/ were consistently shorter than the corresponding syllables in sentences with target vowels /i/, /y/, or /u/ indicates a small albeit consistent "compensatory shortening" effect in normal subjects.

Figure 5 presents data on these effects for the normal-speaking individuals and for the three severity groups. Differences between individual median values of "target /a/" and "target /i,y,u/" utterances are presented for each subject of the four groups and for d_3 and d_w, separately. Again, these data were normalized relative to individual sample median values, in order to eliminate the influence of absolute tempo.

All normal-speaking subjects showed a marked intrinsic vowel effect ($p < 0.001$; Wilcoxon) and, apart from one exception, a small amount of "compensatory shortening" of non-target syllables in /a/ sentences ($p < 0.01$; Wilcoxon). The proportion by which /a/ was lengthened relative to the high vowels varied between 18% and 42%, with a median value of 27%. The weak syllables of sentences with target /a/ were on the average 4% shorter than their counterparts in sentences with high target vowels, and with one exception all normal-speaking subjects showed a small effect in this direction.

In the dysarthric patients as a group there was a progressive tendency towards a reduction of intrinsic vowel effects. From the mild to the severe group an increasing number of patients had small or even negative d_3 differences between

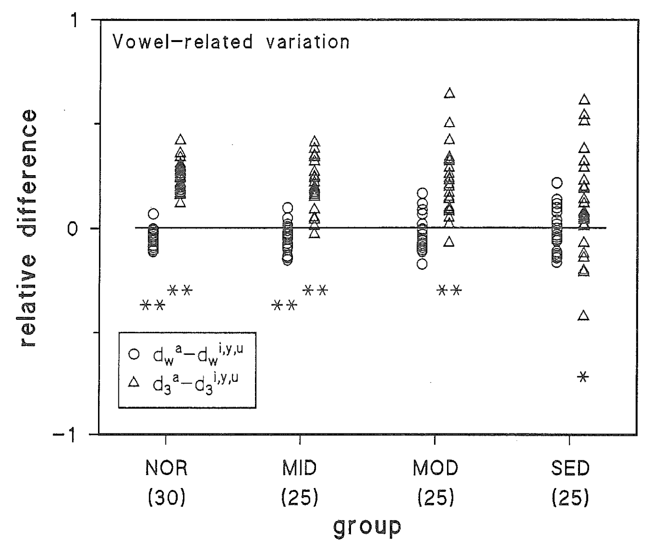

FIGURE 5. Relative extended nucleus duration differences between test sentences with varying target vowel height. Circles: nontarget syllables S_1, S_2, S_4; triangles: target syllable S_3 (triangles).

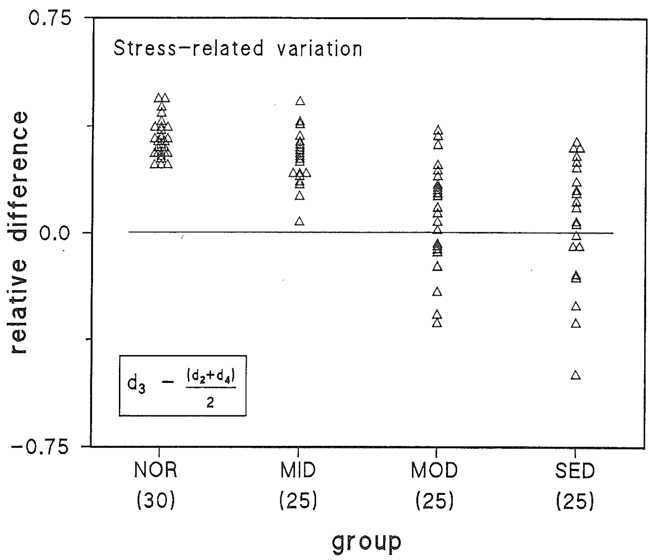

FIGURE 6. Relative extended nucleus duration differences between stressed and unstressed syllables.

low and high vowels, and an increasing number of patients obtained positive signs in their corresponding weak syllable differences. Yet, in all groups, cases of normal or even increased vowel height effects on d_3 were also observed.

To the extent that intrinsic vowel duration reflects specific differences in the amplitudes of vowel-related articulations, an undershooting of speech movements in dysarthria would, as a consequence of the established correlation between duration and amplitude (Ostry & Munhall, 1985), result in a reduction of intrinsic vowel effects. Similarly, if an increased duration of low vowels reflected the influence of mandibular movement components, the levelling of duration differences between high and low vowels in dysarthric speech would be explained most readily by a reduction of jaw movement amplitudes. As an alternative explanation, a failure to compensate for subglottal pressure differences between high and low vowels or a reduction of such differences in dysarthric patients may also have contributed to the observed decrease in intrinsic vowel effects (Neweklowsky, 1975).

Stress-related variation. The variations reported so far were based on between-sentence comparisons of test sentences differing in their target vowels and consonants. However, systematic syllable duration effects may also be expected *within* the syllabic chain of a sentence. A major source of such "syntagmatic" variation is sentence stress. Stress-related effects can be expressed by the difference between stressed and unstressed syllables. Due to intrinsic vowel effects the low vowel /a/ was skipped in these computations, resulting in a data base of 18 sentences (3 [plosives] × 3 [high vowels] ×2 [repetitions]). In order to compensate for rate-dependent variations, the stressed-unstressed differences were normalized by individual median values of d_3.

In the controls, the resulting quotient ranged between .24 and .47, with a median value of .33 (Figure 5), meaning that the stressed syllable was between 24% and 47% longer than the unstressed syllables studied here.

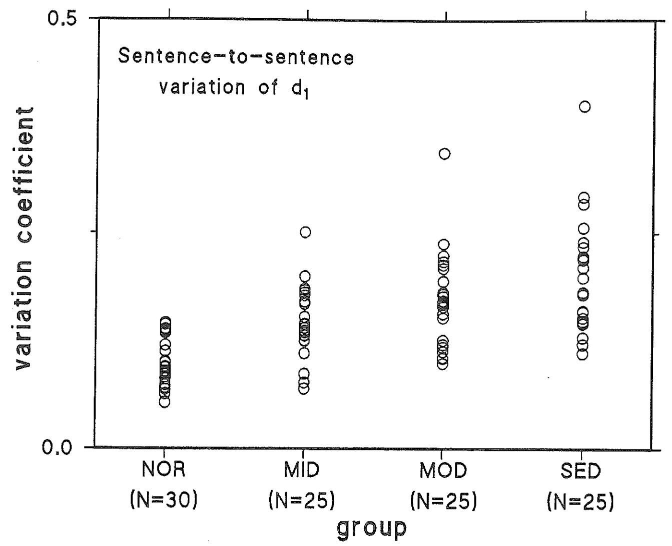

FIGURE 7. Variation coefficient of the extended nucleus duration of syllable S_1.

In the patients as a group there was a severity-dependent reduction of this difference and, in a few single cases, a paradoxical relative lengthening of unstressed syllables. Group median values were .26 (mildly dysarthric subjects), .11 (moderately dysarthric subjects), and .03 (severely dysarthric subjects). However, even among the severely impaired cases there were still patients who maintained a normal stressed-unstressed difference. Upon closer examination such normal patterns turned out to be independent of absolute syllable duration, that is, both extremely slowed and mild-to-moderately slowed patients were found among the severely dysarthric patients with normal stress patterns. Thus, the feature of syllable isochrony or overproportionate lengthening of unstressed syllables actually appears to constitute a dysarthric symptom in its own right, independent of absolute slowness. An informal check of the distribution of this symptom revealed that its occurrence was not confined to patients who sounded "ataxic," as one would expect on the grounds of the results of Darley, Aronson, and Brown (1975) and Kent et al. (1979).

Residual sentence-to-sentence variation. Having described the systematic sources of variance in syllabic timing it remains to be determined how the duration of syllables varied between repetitions of the same task. Because the sentence repetitions used in the present design included 12 different target words in a total of 24 repetitions, an analysis of the residual unsystematic variability had to be confined to those parts of the carrier phrase that are maximally independent of plosive- and vowel-related variations in the speech materials. Although distance effects from the target syllable S_3 cannot a priorily be excluded, the syllable S_1 may be considered to contain only negligible vowel- or consonant-related variance in its duration.

Figure 7 presents a nonparametric measure of variation of d_1, that is, the 90th percentile of the absolute deviations of all sample values from the individual median value, normalized to individual median values. In the normal subjects this "variation quotient" ranged between 0.05 and 0.15, with a median value of 0.09, meaning that 90% of the S_1 repetitions varied by less than 15% in the worst case.

The dysarthric group was characterized by a severity-dependent increase in the sentence-to-sentence variability of d_1. Group median values were .14 (MID), .17 (MOD), and .20 (SED), respectively. In the most severe subgroup, variations of up to 40% occurred. Again, the general tendency toward an increased variability met with a great number of exceptions because even among the most severe patients there were a few cases with a high consistency in the timing of syllable S_1.

General Discussion

The present article was aimed at an analysis of syllabic timing in a heterogeneous group of patients with dysarthria of predominantly traumatic and cerebro-vascular origin. The syllable was chosen as the unit of analysis because it may be considered as the carryer of the rhythmic organization of spoken language. Moreover, a syllable-based approach does not presume the existence of a fully elaborated segmental make-up, which is highly important in the analysis of severely dysarthric speech. This methodological point has been substantiated by the results of the present study. In the examined population 20 out of 75 patients were not reliably treatable with conventional segmentation techniques, and for the remaining patients it may be questioned whether the data obtained from conventional segmentation provided valid correlates of articulatory timing: Neither the vowel duration parameter (d_v) nor the plosive-to-plosive cycle (d_{cv}) represented particularly good predictors of perceived speech rate, nor did these parameters demonstrate any particular invariance relative to the time course of sonority rises and falls as reflected by extended nucleus durations. Thus, the technique of syllable duration measurements based on speech wave envelopes turned out to be a necessary prerequisite for investigating a broad spectrum of dysarthric patients with a common design.

The patients of this study were found to cover a large range of syllable durations, from values slightly below normal up to more than 500 msec. The acoustic measures of syllabic rate were closely related to perceived severity of overall dysarthric impairment. Listeners' perceptions of speech rate turned out to be particularly sensitive to logarithmic measures of syllable duration, the duration of the stressed syllable being more significant than across-sentence averages of syllable durations. The role played by the logarithmic transform in the perception of speech rate fits well with the psychoacoustics of pitch and loudness perception, where logarithms are known to play a fundamental role as well (e.g., Handel, 1989).

Dysarthric speakers with close-to-normal syllabic rates were perceived as either accelerated or normal or slowed, depending on factors that were not within the scope of this study. It seems plausible that factors like pausing and articulatory precision may both have contributed to the listeners' judgments in these cases.

Three sources of systematic variability were considered in the present article: the influence of consonant place of

articulation on target syllable length, intrinsic vowel effects, and stress-related differences between target and non-target syllables. Besides these, the token-to-token variation of syllabic timing independent of experimental variations of the speech task was measured.

Regarding the variability of timing, the data obtained from the dysarthric subjects expressed two opposing tendencies: on the one hand a reduction of normal duration contrasts (like in the cases of stress-related variations or of intrinsic vowel effects) and on the other a strengthening of normal effects (like in the case of consonant-related variations and between-repetition variability). On the whole, these effects were severity-dependent, although in all instances a number of exceptions occurred.

Regarding consonant-related variations, the results are suggestive of a tendency towards an overproportionate affliction of lingual versus labial movements: a temporal lengthening of lingual consonant articulations relative to labials, to a small extent also present in normal speakers, seems to have occurred more often than the reverse. However, in the subgroup of severe dysarthria, gross differential effects could be observed in either direction, meaning that this measure has some relevance in the assessment of differential articulatory impairments in single case analyses or as the basis for therapeutic decisions in tailored treatments.

From the logic of this strengthening of normal effects, one might have expected the intrinsic vowel duration differences to be increased rather than reduced in the dysarthric population. On the group average, however, the reverse was true. To the extent that intrinsic vowel effects are ascribable to the mandibular movement component of low vowel articulation, the reduction or even absence of such effects may have resulted from a compensatory reduction of jaw movement amplitudes, a "strategy" that has been described in subjects with Parkinson's dysarthria (Forrest, Weismer, & Turner, 1989). In a few cases of moderate or severe dysarthria an exaggeration of intrinsic vowel effects was observed, which may have been the result of bradykinetic jaw movements of normal or even exaggerated amplitude.

There was also a small "secondary" influence of vowel height in the normal and the mildly dysarthric subjects of this study which has, to our knowledge, not been described before: With few exceptions the subjects of these groups exhibited a slight compensatory shortening of the non-target syllables in sentences with target vowel /a/. This effect is "syntagmatic" in nature because it concerns the relative timing of subsequent syllables in a syllabic chain. Similar effects are well known from other skilled motor activities, like tapping. The assumption of an internal clock controlling the temporal organization of rhythmic tapping, for instance, predicts that the lengthening of one intertap-interval would be compensated for by a shortening of the following interval, in order to keep in time with the clock (e.g., Wing & Kristofferson, 1973; see also Nagasaki, 1990). Temporal compensation has also been observed in speaking, when an increase in utterance length is usually associated with a decrease in the duration of its constituent segments (e.g., Kohler, 1986; Lehiste, 1972). These effects are commonly interpreted in the sense of an underlying rhythmic hierarchy that strives for an approximately equal spacing of rhythmic chunks (Kohler, 1986; Nagasaki, 1990). The fact that in the dysarthric group this effect was no longer present may speak for a reduced ability to make the subtle articulatory adaptations that would be required to realize such compensations (Kent et al., 1979).

The same interpretation applies, in a much stronger sense, to the stress-related variation of syllable durations examined in this article. A "proportionate scaling" model of slowed speech would predict that stressed and unstressed syllables are lengthened by the same relative amount, while preserving their ratio (cf. Viviani & Laissard, 1991). Contrary to this expectation a severity-dependent levelling of stressed/unstressed differences was observed here. The tendency towards syllabic isochrony was rather universal in the heterogeneous sample of the present study, meaning that it cannot be considered particularly specific of ataxic dysarthria (Kent et al., 1979). A possible model of explanation would ascribe the overproportionate lengthening of unstressed syllables more generally to a slowed processing of afferent information: If such information is required in the sequencing of opening and closing movements, it is plausible that a slowing of afferent processes would afflict the shorter "strokes" of a sequence more than the longer ones and thereby result in a tendency towards isochrony.

The finding of an increased between-trial variability of the duration of syllable S_1 in most of the moderately and severely impaired patients is consistent with the view that reduced temporal stability represents an unspecific sign of an untrained, immature, or impaired motor system. The temporal variability of a movement is known to decrease during maturation (e.g., Cazalets, Menard, Crémieux, & Clarac, 1990; Fowler & Turvey, 1978) and during skill acquisition in adults (Adams, 1987), and it is increased in most kinds of motor disorders, such as parkinsonism (Teasdale, Phillips, & Stelmach, 1990). In speech, increased variabilities of acoustic segments were found in ALS patients (Caruso & Burton, 1987) and in patients with Friedreich's disease (Gentil, 1990). Inconsistent findings were reported for Parkinson's dysarthria by Weismer (1984) and for cerebellar dysarthria by Kent et al. (1979) and Ziegler & Wessel (1992). Our results, too, suggested that increased variability of syllabic timing is not obligatory, although it appears to be a rather common feature of dysarthric speech.

In conclusion, the heterogeneity found at all levels of the present analysis suggests that measures of syllabic timing yield highly individual patterns of speech disturbance in dysarthria and may thus contribute to an understanding of a patient's specific impairment. The severity-dependent tendencies found in these data generate hypotheses that can be tested in specific neurologic syndromes like parkinsonism or cerebellar disease.

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