

## Research Article

# Quantitative Assessment of Interutterance Stability: Application to Dysarthria

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**Purpose:** Following recent attempts to quantify articulatory impairment in speech, the present study evaluates the usefulness of a novel measure of motor stability to characterize dysarthria.

**Method:** The study included 8 speakers with ataxic dysarthria (AD), 16 speakers with hypokinetic dysarthria (HD) as a result of Parkinson's disease, and 24 unimpaired control participants. Each participant performed a series of sentence repetitions under habitual, fast, and slow speaking rate conditions. An algorithm to measure utterance-to-utterance spectro-temporal variation (UUV; Cummins, 2009) was used. Speech rate and intelligibility were also measured.

**Results:** UUV scores were significantly correlated with perceptually based intelligibility scores. There were significant differences in UUV between control speakers and the AD

but not the HD groups, presumably because of differences in intelligibility in the samples used and not because of differences in pathology. Habitual speaking rate did not correlate with UUV scores. All speaker groups had greater UUV levels in the slow conditions compared with habitual and fast speaking rates.

**Conclusions:** UUV results were consistent with those of other variability indices and thus appear to capture motor control issues in a similar way. The results suggest that the UUV could be developed into an easy-to-use clinical tool that could function as a valid and reliable assessment and outcome measure.

**Key Words:** acoustics, assessment, dysarthria

The last few decades have seen a surge in the development of more and more refined techniques and measurements to investigate movement disorders. Such methods are useful not only to shed more light on the symptoms of these disorders and their causes but also because they can be of significant clinical value in that they can support differential diagnosis of different types of motor speech problems, function as outcomes measures for treatment approaches, and allow clinicians to detect subclinical problems, thus enabling them to time treatment more effectively.

These methods are based on a wide variety of methodological paradigms. Noteworthy developments are articles by Liss and colleagues, who have published a number of methodologies over recent years that have been successful in discriminating different types of dysarthric speech from each other and healthy control speakers (Liss, LeGendre, & Lotto, 2010; Liss et al., 2009; Utianski, Liss, Lotto, & Lansford, 2012). A further technique worth scrutinizing is the

variability measurement pioneered by Smith and colleagues (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995) and subsequently expanded on by a number of other research groups. These have been used less to discriminate between different types of dysarthria but more to highlight differences in motor control across healthy and disordered speakers as well as different elicitation paradigms.

Liss et al.'s (2009, 2010) and Utianski et al.'s (2012) research focused on a group of 70 speakers with four different types of dysarthria (ataxic, mixed spastic-flaccid, hypokinetic, and hyperkinetic) and healthy control speakers. They investigated the discriminating possibilities of a range of acoustic measures that focus on both the segmental and suprasegmental aspects of speech, namely, rhythm (Liss et al., 2009), amplitude envelope modulations (Liss et al., 2010), and long-term average spectra (Utianski et al., 2012). In each case, they were able to demonstrate their measures' ability to distinguish between healthy and impaired speakers as well as between different types of dysarthric speakers with relatively good success. Their measures were thus able to reflect particular qualitative aspects of the speech signal that might be present in one but not another type of dysarthria. It became evident that some measures were more suitable to detect impairments in particular disorders—for example, some were distinguished better by rhythm measures if this was a particular feature

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of the disorder, whereas other dysarthria types were better discriminated with the amplitude measure. The authors thus advocate that the complete protocol of measures should be used rather than just one measure in isolation. Such an application would be facilitated by the fact that they are all based on the same speech data, which makes the analysis more clinically viable by reducing assessment time. One of the drawbacks of Liss et al.'s (2009, 2010) and Utianski et al.'s (2012) methodology, however, is that their measures are time-consuming to evaluate and require a good knowledge of acoustics (e.g., in order to identify consonant and vowel boundaries in the spectrographic signal for the rhythm measure) as well as data processing skills by the examiner, probably to a level that cannot be expected of the average clinician.

Another technique that has been used increasingly to research motor control aspects of speech and that has the potential for being applicable in the clinical context is the spatiotemporal variability index (STI; Smith et al., 1995). The STI is a composite measure of articulatory variability that examines the stability and patterning of speech movement sequences. Its value reflects the degree to which movement patterns are consistent over a number of repetitions. Variability is thought to reflect movement control as the production of fluent and intelligible speech requires the coordinated action of the relatively autonomous acting pulmonary, laryngeal, and vocal tract articulation components. The ability of speakers to consistently and accurately execute a specific pattern of speech motor movements during a sequence of identical speech productions is reflected in the degree of token-to-token variability in the resulting speech output. Any abnormalities in strength, speed, steadiness, or accuracy of speech movements will likely be reflected in the amount of variability present in speech production tasks with reiterated utterances.

The STI was initially used in studies of healthy speakers to gain insight into the nature of speech motor control processes. These studies highlighted that the stability of speech movements could be reduced under certain experimental conditions, such as increased or slowed speech rate (Smith et al., 1995), the performance of concurrent tasks (Dromey & Bates, 2005; Dromey & Benson, 2003; Dromey & Shim, 2008), or the complexity of the carrier phrase (Kleinow & Smith, 2000). Wohlert and Smith (1998) furthermore noted that older speakers tended to be more variable than younger participants. The STI has also been able to highlight differences between disordered and unimpaired speakers as demonstrated by Kleinow and Smith (2000) as well as Smith and Kleinow (2000) in studies of people who stutter and by Kleinow, Smith, and Ramig (2001) in studies of people with hypokinetic dysarthria (HD). In addition, the STI has been used to demonstrate which therapy techniques were likely to be most beneficial for speakers. Kleinow et al. (2001) found that loud voice resulted in more stable articulation, suggesting that the Lee Silverman Voice Treatment (Ramig, Countryman, Thompson, & Horii, 1995) is an effective treatment to improve loudness as well as articulation. In another study, by McHenry (2003), the STI highlighted differences across speakers in disease severity and, in addition, indicated which treatment strategy for slowed speech (stretched speech versus

inserting pauses) was most appropriate for the speakers. McHenry (2003) thus argued that the STI has an important role to play diagnostically as well as in establishing optimum treatment strategies.

The above studies have established differences between disordered and unimpaired speakers and provided a range of experimental setups that serve to bring to light such differences. They furthermore highlighted the value of the STI for increasing our understanding of motor control processes. However, similar to Liss et al.'s (2009, 2010) and Utianski et al.'s (2012) methods, the STI is insufficiently developed to function as an effective research or clinical tool. One of the biggest drawbacks is the invasive and complex nature of the associated technology, which generally involves lip tracking. This requires specialist equipment, and the procedures might not be easy to tolerate for participants with motor and sensory impairments. Participant numbers in previous studies have therefore been low, impacting on the statistical power and predictions made by these experiments. To address these problems, methods involving acoustic data collection and analysis have been successfully validated in replicating findings of the kinematic STI (Howell, Anderson, Bartrip, & Bailey, 2009). Acoustic recordings are a well-established method of data collection in speech disorders and allow capturing of performance from a large number and wider variety of speakers. In addition, they allow greater freedom in experimental setup, such as in the choice of speech task and recording environments. A further methodological development has been to use a nonlinear data processing approach (functional data analysis [FDA]; Lucero, 2005; Lucero & Koenig, 2000; Ramsay, Munhall, Gracco, & Ostry, 1996). This approach differs from the STI in that it produces separate information on spatial and temporal variability. Studies by Anderson, Lowit, and Howell (2008) and by van Brenk and Lowit (2012) applied FDA to acoustic data in the form of formant, intensity, and pitch tracks and demonstrated that the technique has good potential for distinguishing between different types of dysarthria.

FDA involves the labeling of only the beginning and end of an utterance and thus requires less time to segment than, for example, the rhythm measures evaluated by Liss et al. (2009). However, a good knowledge of acoustics and a significant amount of time are still necessary to check the signal for any aberrant data points, particularly in the case of formant and pitch analyses, thus precluding it from being a readily usable clinical tool in its current form. For any acoustic or other instrumental measure to have any clinical value, it is thus necessary to develop an evaluation procedure that is quick and easy to use, yet that at the same time provides valid data that reflect the severity and type of speech impairment experienced by an individual.

In what follows, we pursue another variant on measuring variability that might achieve this goal. A common insight underlying several of the above studies is the observation that utterance-to-utterance invariance is a characteristic of highly skilled coordinated action and that impaired speech is commonly associated with an increase in variability or, equivalently, a decrease in stability (Anderson et al., 2008; Kleinow et al., 2001; McHenry, 2003; van Brenk & Lowit,

2012). Given that it is relatively easy to obtain audio recordings of repeated productions of a standard phrase, we present a computational method that quantifies the utterance-to-utterance variability. Measuring variability is not entirely straightforward for a rich multidimensional signal such as speech. We made use of a parametric representation of speech, the mel-frequency scaled cepstral coefficient (MFCC), which is known to capture numerically many of the spectral and temporal properties of speech that are important for speech perception. These representations are used as a standard in both speech recognition and speech synthesis applications. We combined this representation of speech with the dynamic time warping algorithm, which allows one sequence to be mapped onto another, and we used a quantitative measure of the amount of warping to arrive at an index of utterance-to-utterance variability (UUV). We wished to see whether the quantification of UUV could provide a sensitive index of dysarthria suited to evaluating severity either as an outcome measure or as a diagnostic tool. The tool would thus provide a significant contribution to evidence-based practice, allowing clinicians to demonstrate effectiveness of their interventions and researchers to evaluate different treatment methods against each other.

## Method

### *Participants*

The speakers and tasks reported in this study form a subset of a larger study (see van Brenk & Lowit, 2012). All data collection and analysis procedures adhered to current ethical guidelines and had been approved by Strathclyde University as well as relevant health boards. We examined data from eight speakers with ataxic dysarthria (AD) and from 16 speakers with hypokinetic dysarthria (HD) as a consequence of Parkinson's disease, along with age- ( $\pm 5$  years) and gender-matched healthy control speakers. For one HD participant, matching was possible only by age but not gender (Table 1). All speakers were native speakers of British English. Suitability for participation in the experiment was assessed through informal evaluation of the speakers' hearing and visual skills, a cognitive screen (Addenbrooke's Cognitive Examination—Revised; Mioshi, Dawson, Mitchell, Arnold, & Hodges, 2006), and a short medical history to exclude any previous speech and language problems or other health issues that could have affected task performance. The severity and type of the dysarthria were judged by the referring speech-language therapist (SLP) and confirmed by two of the current authors. To quantify the level of severity for experimental purposes, intelligibility scores were derived from three tasks, a monologue about a holiday, passage reading ("The Grandfather Passage"; Darley, Aronson, & Brown, 1975), and the Unpredictable Sentence Intelligibility Test (McHenry & Parle, 2006). The monologue and passage reading were scored on a 9-point scale (Dobinson, 2007), and the sentences were scored on a percentage scale (percentage of words correctly transcribed). Fifteen trained listeners (SLP students) evaluated the data. To assess the overall consistency among

the 15 listeners, we calculated the intraclass correlation coefficient (ICC; Sheard, Adams, & Davis, 1991). The ICC was .868 (95% CI [.778, .933]) and thus showed good agreement between listeners. Results of all three assessments correlated strongly with each other. For ease of reference, only the data of the Sentence Intelligibility Test, expressed as percentage of correctly transcribed words, are reported here (Table 1). The data show that there was a difference in intelligibility between the HD and AD speakers, with the AD speakers generally showing a lower intelligibility level (mean intelligibility: HD = 84%, AD = 68%), although there was some overlap between the two groups.

### *Recording and Analysis Procedure*

Participants were recorded in a quiet environment in their homes, at the university, or at the local clinic they were attending. Audio recordings were taken using a wave recorder (Edirol R-09HR) connected to a head-mounted condenser microphone (AKG C-420). The data recorder supplied Phantom Power to the microphone. Data were sampled at 44.1 kHz at 16 bits. The head-mounted device allowed for a constant distance of approximately 4 cm between the speaker's mouth and microphone during recording.

### *Experimental Tasks*

The experimental task consisted of a simple utterance repetition paradigm. Participants were instructed to repeat the phrase "Tony knew you were lying in bed" with as little variability as possible from one utterance to the next. In the larger study, which focused on spatiotemporal variability, they repeated this task under six different conditions. For the purposes of the current analysis, three tasks commonly used in previous research on variability were chosen, that is, habitual, fast, and slow speaking rates. Coordinative stability is frequently rate dependent, which motivates the examination of multiple speaking rates. It also allowed the comparison of the current results with those from other previously published measures, such as STI and FDA, that detected higher levels of variability in altered rate conditions (e.g., Smith et al., 1995), which allowed us to evaluate the validity of our results. Participants were allowed to self-select rate in the habitual condition and were instructed to speak half as fast or twice as fast as their usual rate for the slow and fast conditions, respectively. The aim was to achieve 20 to 25 repetitions of the phrase; however, not all speakers could achieve this target.

### *Measurement Parameters*

The method under investigation in this study was UUV, measured across the repetitions of the test utterance. The variability measured was not simply durational, as would be the case in, for example, the various forms of the Pairwise Variability Index (Low, Grabe, & Nolan, 2000). Rather, we used a full spectral representation, the MFCC, estimated in overlapping sliding windows of approximately 23 ms, and we used the similarity of the entire spectral representation in evaluating similarity among successive utterances. The method

**Table 1.** Participant information, stating gender, age, medical diagnosis, intelligibility level, and medication (HD participants only).

Participant	Gender	Age	Diagnosis	Intelligibility level	Medication
AD1	M	40	CA	79	
AD2	F	38	FA	58	
AD3	F	63	MS	85	
AD4	M	58	SCA8	47	
AD5	F	44	MS	72	
AD6	M	70	MS	55	
AD7	M	37	MS	69	
AD8	M	46	MS	79	
<i>M (SD)</i>		49.5 (12.5)		68 (13.4)	
AD controls	3 F, 5 M				
<i>M (SD)</i>		49.8 (14.3)			
HD01	M	40	IPD	98	A 1 × 16 mg K 1 × 10 mg
HD02	F	55	IPD	93	A 4 × 6 mg E 6 × 25 mg
HD03	M	48	IPD	89	A 1 × 4 mg
HD04	M	56	IPD	90	A 6 × 2 mg B 4 × 25/100 mg D 4 × 12.5/50 mg F 4 × 200 mg
HD05	F	76	IPD	89	D 4 × 25/100 mg
HD07	M	76	IPD	63	B 1 × 150 mg E 2 × 25 mg G 3 × 25/100/200 mg H 1 × 40 mg L 1 × 25 mg
HD09	M	54	IPD	94	C 8 × 50/12.5 mg G 8–10 × 50/200/200 mg
HD10	M	64	IPD	88	A 3 × 7 mg
HD11	M	75	IPD	72	C 3 × 50/12.5 mg D 6 × 25/100 mg
HD12	M	73	IPD	76	B 1 × 50/200 mg D 6 × 25/100 mg
HD13	M	78	IPD	70	B 3 × 25/100 mg C 2 × 100/25 mg
HD14	F	75	IPD	88	A 3 × 8 mg B 1 × 50/200 mg E 3 × 62.5 mg
HD15	M	78	IPD	88	C 2 × 100/25 mg D 3 × 25/100 mg I 3 × 0.7 mg and 3 × 0.18 mg
HD16	M	67	IPD	77	A 3 × 4 mg B 1 × 50/200 mg D 3 × 25/100 mg
HD17	M	60	IPD	98	A 3 × 8 mg B 3 × 25/100 mg C 1 × 100/25 mg D 4 × 50/200 mg J 1 × 100 mg K 1 × 1 mg D 4 × 25/100 mg
HD20	F	65	IPD	75	
<i>M (SD)</i>		65 (11.8)		84 (10.5)	
HD controls	5 F, 11 M				
<i>M (SD)</i>		63.6 (11.3)			

*Note.* AD = ataxic dysarthria; HD = hypokinetic dysarthria; M = male; F = female; CA = cerebellar ataxia; FA = Friedreich's ataxia; MS = multiple sclerosis; SCA = spinocerebellar ataxia; IPD = idiopathic Parkinson's disease; A = Ropinirole; B = Sinemet Controlled Release (carbidopa/levodopa); C = Madopar Controlled Release (levodopa/benserazide); D = Sinemet-Plus (carbidopa/levodopa); E = Sinemet (levodopa); F = Entacapone; G = Stalevo (carbidopa/levodopa/entacapone); H = Stimvastatin; I = Pramipexole; J = Amantadine; K = Rasagiline; L = Atenolol.

was introduced in Cummins (2009) for the assessment of the degree of synchrony in parallel utterances of the same text, but we repurposed it here to identify UUV in successive phrases. Full details of the computational procedure are provided in Cummins (2009). An estimate of this variability was obtained for each speaker and condition, as described below.

First, an automated Praat script was used to divide up the recording into individual utterances. This script used a sliding window to look for pauses based on waveform intensity. To facilitate the analysis of a lot of data, the resulting segmentation into individual utterances was visually checked rapidly by the experimenter, omitting data where the algorithm either failed to place a boundary correctly or placed inappropriate boundaries. For each sequence of utterances, then, utterance  $i$  was compared with utterance  $i + 1$ , by aligning the two utterances and estimating the amount of warping that would be required to map one onto the other. For highly similar utterances, this is a low number, and for disparate utterances, it increases. For  $n$  utterances, this provides  $n - 1$  comparisons, and these estimates can then be used for intra- and intergroup comparisons.

Two utterances to be compared were first represented as sequences of MFCCs, yielding a sequence of vectors for each utterance. Dynamic time warping (DTW) was used to map one utterance on to the other. The estimate of variability is derived from the mapping process and is proportional to the amount of compression and stretching required for the optimal mapping of one utterance onto the other. Technical details of the algorithm are as follows: We used the first 12 MFCC parameters, as is standard in speech technological applications, omitting the zeroth, or energy, component. We estimated MFCCs using Hamming windows of 1,024 samples, or approximately 23 ms, with an overlap of half a window between successive frames. DTW was then used to map one sequence (the comparator) onto the other (the referent), yielding a warp path, which can be represented as a function stretching above and below a horizontal line, as explained in Cummins (2009). The unsigned area under this curve, estimated during voiced portions of the referent only, provides the quantitative assessment of dissimilarity for the two utterances. Restriction to the voiced-only portions has been found to improve the stability of the method when used on many speakers and texts. The entire comparison procedure is automated within MATLAB.

Within-trial variability in the interutterance variability score was rather high for both disordered speakers and control participants. This presumably arose because of the difficulty in maintaining an invariant repetition style for a prolonged speaking time. We therefore removed from a trial all interutterance variability scores that were more than two times the interquartile range from the median. All subsequent analyses were performed on the trimmed data. Trimming removed between 2.0% and 7.0% of data points. Comparable amounts were removed for both control participants and those with dysarthria.

A further measure taken from the data for control purposes was rate. Because participants can respond to the experimental imperative to speak more or less rapidly in

various ways, we initially evaluated both articulation and speech rate behavior. Subsequent statistical comparisons with other speech parameters revealed the same results for both measures, and we therefore restrict the discussion to articulation rate. As some of the disordered speakers had a tendency to omit individual phonemes from their production, we decided to use the reciprocal of articulation rate by measuring the average interval duration within a trial from the onset of voicing in “Tony” to the end of voicing in the word “in.” To validate the measure, we calculated the actual articulation rate for the control speakers on the basis of their interval durations, which provided a mean of four syllables per second, which is within the normal range for a reading task. For simplicity of language, we will use the term *articulation rate* in the following discussion.

### Statistical Analysis

We used a range of parametric tests to investigate the relationship between the various measurement parameters. For within-group comparisons, all control participants were pooled into one group. For across-group comparisons, the division between AD and HD controls was maintained to ascertain a close match with the disordered groups in terms of age and gender. Bonferroni corrections were applied to all statistical analyses.

## Results

### Articulation Rate and UUV

We first examined articulation rate to see whether participants did in fact modulate rate as a function of experimental condition. Within each condition, we conducted paired  $t$  tests for rate, with the conservative Bonferroni correction of  $p$  values for repeated tests. The results are provided in Table 2, from which it can be seen that the control group and the HD group successfully modulated rate, whereas the ataxic group (AD) did not display substantial modulations.

We then compared the UUV exhibited by each participant group to their respective controls in each of the rate conditions, habitual, fast, and slow. Figure 1 shows the distribution of the median UUV scores for both patient groups and their respective control participants. Bonferroni-protected paired  $t$  tests are reported in Table 3. It is evident

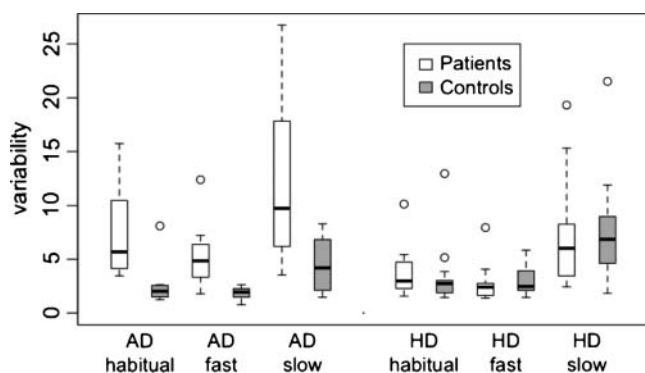
**Table 2.** Bonferroni-protected  $t$  tests of the differences observed in a measure of articulation rate.

Rate	Ataxic dysarthria	Hypokinetic dysarthria	Control group
Habitual vs. fast	$t(7) = 2.3, ns$	$t(15) = 5.2^{**}$	$t(23) = 8.6^{**}$
Habitual vs. slow	$t(7) = -1.7, ns$	$t(15) = -3.3^*$	$t(23) = -4.4^{**}$
Fast vs. slow	$t(7) = -2.1, ns$	$t(15) = -4.8^{**}$	$t(23) = -5.5^{**}$

*Note.* Because of the Bonferroni correction, only significance levels rather than exact  $p$  values are reported.

\* $p < .05$ . \*\* $p < .001$ .

**Figure 1.** Box plot of utterance-to-utterance variability scores for disordered speakers and their relevant controls in the three rate conditions.



that UUV differentiates between the AD group and their controls but not between the HD group and their respective controls, despite the fact that participant numbers are considerably smaller in the AD comparison.

To further examine the relationship between the UUV scores and rate, we performed a repeated measures analysis for each group separately across the three speaking conditions, habitual, fast, and slow rate (the AD and HD control participants were considered as one group for this analysis). We applied the Greenhouse-Geisser correction for departure from sphericity. The medians are shown in box plots in Figure 2. There was a significant effect of condition for control participants,  $F(1.4, 32.6) = 12.4, p < .001$ ; for the HD group,  $F(1.0, 15.7) = 8.1, p < .05$ ; as well as for the AD group,  $F(1.3, 9.3) = 5.2, p < .05$ . Tukey honestly significant difference post hoc tests revealed significant differences in UUV between slow and habitual rates for controls and HD participants and between slow and fast conditions for all three groups, with slow rates having the highest UUV in each case. These results suggest that although speakers' performances were affected by the speaking task, the direction of between-task differences was similar across all participant groups.

### Correlations Between UUV, Rate, and Intelligibility

In summary, the results showed that UUV changed across rate conditions in all three participant groups but that

**Table 3.** Bonferroni-protected *t* tests of UUV differences between participant groups at each rate.

Group	Habitual	Fast	Slow
AD vs. AD control	$t(7) = 2.5, ns$	$t(7) = 3.5^*$	$t(7) = 2.8^*$
HD vs. HD control	$t(15) = 0.52, ns$	$t(15) = -0.66, ns$	$t(15) = -0.28, ns$

*Note.* Because of the Bonferroni correction, only significance levels rather than exact *p* values are reported.

\* $p < .05$ .

the AD group were more affected in the UUV than the HD group compared with their respective control participants. There are a number of potential reasons for this difference in results between the HD and AD groups. One factor could have been rate, which was modulated differently in the two groups. The other could have been dysarthria severity, as the HD group had higher intelligibility levels than the AD group. Finally, the results could reflect inherent differences in the underlying pathology and how this affects the speaker's ability to repeat the same utterance in a consistent manner.

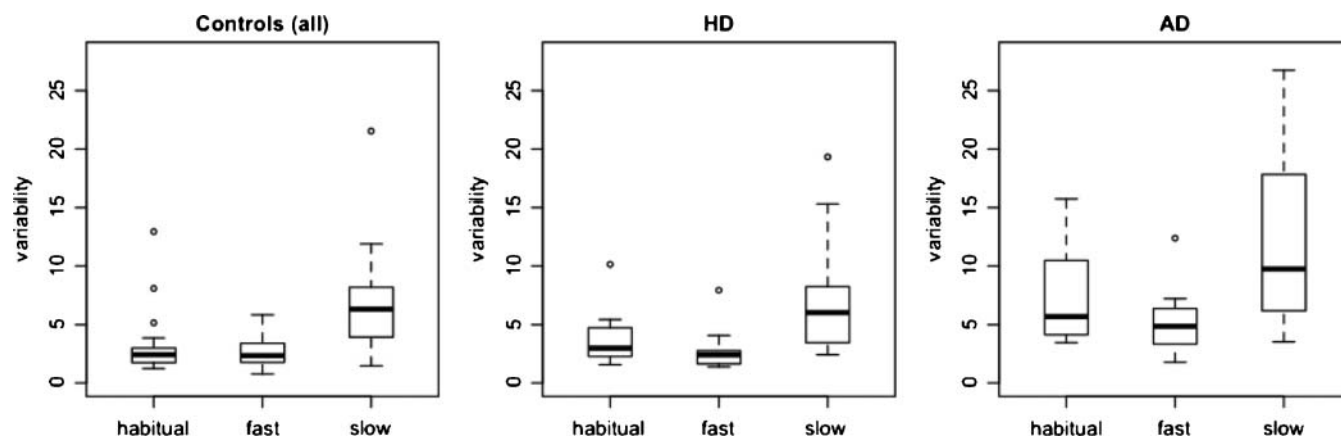
To investigate the above possibilities, we performed a number of correlational analyses. We first examined the relationship between articulation rate and UUV for AD and HD participants separately. For both groups, correlations in the habitual and fast rate conditions were nonsignificant, but in the slow condition all participants displayed strong correlations between UUV and rate: AD,  $r(6) = .78, p < .05$ ; HD,  $r(14) = .74, p < .01$ . The fact that both HD and AD speakers were affected in similar ways suggests that rate differences between the two groups were not the cause of the varying results observed for the UUV. However, these results lead to some further interesting questions. First, the fact that UUV performance at habitual and fast rates was independent of actual articulation rate but that there was some relationship at slow rates requires further investigation. Second, the similarity in results between HD and AD participants is interesting given the absence of any significant rate changes across the conditions displayed by the AD group. This suggests that although rate itself was not a factor, task demands might have been; that is, AD speakers appeared to have greater difficulties slowing down, affecting their stability in motor control while executing this task.

Sentence intelligibility (Table 1) was negatively correlated with UUV for the HD group only in both habitual and fast rates but not the slow rate: habitual,  $r(14) = -.65, p < .01$ ; fast,  $r(14) = -.62, p < .05$ . Figure 3 plots UUV against intelligibility for both disordered groups in the habitual rate condition. A single regression line based on the combined data has been fitted:  $r(22) = -.68, p < .001$ . These data suggest at least a tendency for the relationship between intelligibility and UUV. It was particularly interesting to see changes in UUV even at the mild end of the severity range where speakers did not necessarily fall outside the normal range for intelligibility yet. This might suggest that the UUV is able to detect early, subclinical signs of speech disorders; however, this would require further investigation with larger participant numbers.

## Discussion

### Validity

This article investigated whether the UUV has the potential to act as a valid and clinically viable tool to quantify the severity of dysarthric speech and perhaps to differentiate among speech pathologies. In terms of its validity, the across-task comparisons for healthy as well as disordered

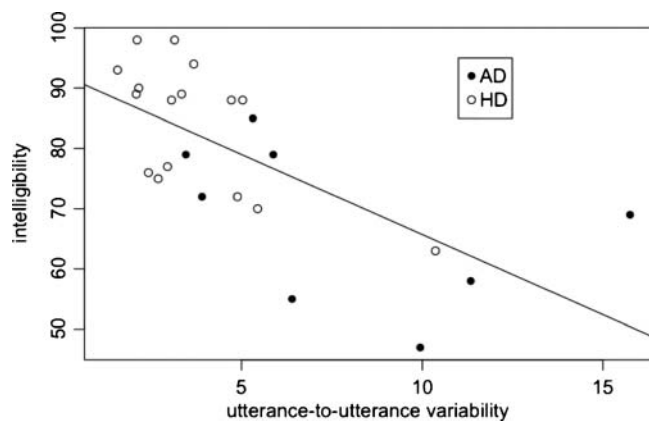
**Figure 2.** Box plot of utterance-to-utterance variability scores for each group across speaking rate conditions.

speakers showed the same differences as have previously been reported for STI, that is, higher variability for slow speech rates compared with habitual and fast rates (McHenry, 2003; Smith et al., 1995). In addition, we also found that the disordered groups followed the same pattern of across-task differences (cf. Kleinow & Smith, 2000; Smith & Kleinow, 2000). The UUV thus appears to capture similar aspects of motor control as these other measures.

In addition, there was a strong correlation with the perceptual intelligibility scores for HD patients. A larger participant number might have resulted in a similar result for the AD speakers, as the current data showed at least a trend toward such a relationship in this group. The results thus suggest that the UUV metric may exhibit good validity for representing the severity of a speech disorder. It therefore is comparable to previously published variability measures, such as the STI or the FDA, in this respect. McHenry (2003) reported correlations between severity and the STI in an

HD population. Similarly, van Brenk and Lowit (2012) identified a relationship between a number of FDA variables and intelligibility, albeit for the AD rather than the HD group. However, their results were based on a larger participant sample, and when the analyses were rerun on the current speaker selection, both their HD and AD groups showed significant relationships between intelligibility scores and variability in the fast speaking condition. The suggested sensitivity of the UUV across the range of severities present in the current sample would have significant clinical advantages in that the measure should be applicable as an outcome measure. More research will have to be performed to establish the minimum detectable change in a speaker's intelligibility as represented by the UUV; however, these preliminary results are highly encouraging in this respect.

The current results thus suggest that the UUV has the same potential as other measures of variability to reflect the severity of a person's speech disorder and capture task-dependent variations in motor control demands. What sets it apart is that it has a practical advantage in terms of processing time and skills required by the examiner, which makes it a more viable option for clinical application.

**Figure 3.** Scatter plot of utterance-to-utterance variability scores for the habitual condition and intelligibility results for HD and AD speakers.

### Technical Implementation

Measurements are based on the same easy-to-capture data as the acoustic STI and FDA paradigms, that is, audio data of simple sentence repetitions. The measurement process includes two steps, each of which is straightforward and requires no technical knowledge of signal processing. The first step is segmentation of a string of utterances into individual utterances. This requires application of a relatively simple Praat script that identifies phrase boundaries and visual inspection of their correct placement, a task that even those not particularly skilled at acoustic analysis can perform and that can be done relatively quickly compared with some other methods. The second step, quantifying UUV, is implemented in a series of MATLAB functions. This step would require some further development to make it applicable in a stand-alone

version without the MATLAB platform. A reference implementation and some supporting Praat scripts that can help in the segmentation of long strings of utterances are provided as supplementary materials. These are intended as a starting point for researchers interested in developing their own full implementation. Discussion of the many possible variants of the basic time warping algorithm are provided in Senin (2008).

As a note of caution, our experience with the application of this method suggests that it will be of most utility in cases in which UUV is mild to moderate, offering the possibility of sensitively indexing changes in articulatory stability over time. In repeated productions of the sort used here, a single highly aberrant token will generate values that appear as outliers in the series. We found such outliers in both the control data and the patients and to comparable extent in each group, suggesting that it is a reliable characteristic of such sequential productions. This suggests that a certain degree of utterance-to-utterance stability should be considered a prerequisite for the application of the method, and alternatives might have to be sought for more severe cases. However, the current participant sample did not include patients at the more severe end of the spectrum, and further studies need to be conducted to assess the method's suitability across the full range of client presentations.

### Future Directions

There are evidently a number of limitations in the current research, most prominently the small participant numbers, particularly in the AD group. Having said that, our study does not compare unfavorably with many other studies trying to develop new technologies; for example, although the Liss et al. (2009, 2010) and Utianski et al. (2012) studies had 70 speakers in total, these were distributed across five speaker groups, resulting in an average of 14 speakers per group. In addition, the fact that our correlation results are strong even with our small group sizes lends further support to the viability of the UUV as a valid measure of intelligibility and motor control. Another factor that significantly limited our ability to comment on the diagnostic value of the UUV is the fact that the HD and AD groups were not comparable in terms of their severity. No judgments can thus be made in terms of how our measure compares with those proposed by Liss et al. (2009, 2010) in its discriminating capacity, and thus, this needs to be the focus of further research.

In conclusion, we have introduced a new quantitative measure of UUV that can be used in the quantitative assessment of dysarthria. Preliminary results show good comparability to existing validated measures, highlighting the potential to develop this measure into a clinically viable assessment tool and outcome measure in addition to its application to fundamental research on motor control in both healthy and disordered speakers. These findings now need to be confirmed by conducting further research with larger and more varied participant groups, further investigating the diagnostic value of the UUV and its sensitivity to change, and establishing a firm normative range for this measure.

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