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RESEARCH ARTICLE

The integrity of anticipatory coarticulation in fluent and non-fluent tokens of adults who stutter

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Abstract
This article analysed the acoustic structure of voiced stop + vowel sequences in a group of persons who stutter (PWS). This phonetic unit was chosen because successful production is highly dependent on the differential tweaking of right-to-left anticipatory coarticulation as a function of stop place. Thus, essential elements of both speech motor planning and execution can be parsimoniously assessed. Five adult PWS read three passages 3 times in a randomised order. These passages contained an overabundance of words beginning with initial [bV], [dV] and [gV] sequences. Digital audio and visual recordings were analysed to first identify fluent and stuttered target words, which were then spectrally analysed to yield locus equation (LE) regression plots. The slope of the LE regression function directly indexes the coarticulatory extent of the vowel's influence on the preceding stop consonant. The PWS revealed LE parameters falling within the normal ranges based on previously documented data obtained from fluent speakers. Theoretical considerations of possible underlying factors responsible for stuttering disfluencies are discussed relevant to these findings.

Keywords: *stuttering, acoustic analysis, coarticulation, speech production*

Introduction

The disfluencies characterising stuttering strongly suggest breakdowns in the motor programming that underlies speech production. Precisely why and where in this complex neural network (e.g. generating the plan-to-selecting/sequencing the commands-to-coordinating the execution) the fluency disruptions occur is largely unknown.

A wide spectrum of experimental findings and theoretical positions characterises this field of study, from higher order linguistic-based deficits (e.g. Watkins, Yairi & Ambrose, 1999; Anderson & Conture, 2000; Anderson, Pellowski, & Conture, 2005; Hakim & Ratner, 2004; Hall, 2004), to timing constraints between planning and execution phases of production units at the phonetic stage of language output (e.g. Forster & Webster, 2001; Ludlow & Loucks,

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2003; Howell, 2004; Namasivayam & Van Lieshout, 2008). Fitting into this broad experimental continuum, the present study examines the fluent and disfluent productions of stop + vowel sequences in persons who stutter (PWS). The production of stop + vowel sequences is highly dependent on the integrity of a centrally based pre-production algorithm – right-to-left anticipatory coarticulation. Moreover, and most importantly, this algorithm can be empirically documented. Thus, investigating anticipatory coarticulation in a PWS provides a 'poor man's X-ray' or 'window' into the brain during both an articulatory planning and motor output stage of stop + vowel production.

Henke's (1966) classic model of R-to-L anticipatory coarticulation was an early attempt to theoretically conceptualise two underlying principles operating during anticipatory coarticulation. A 'look-ahead scanner' anticipated articulatory features of upcoming segments readied for production, and a 'compatibility notion' determined whether the advanced production of the targeted segment(s) would violate articulatory/acoustic constraints inherent to any of the intervening segments or not. Although it is beyond the scope of this study to investigate the R-to-L anticipatory coarticulation in all its manifestations in speech, we have chosen one classic example, stop + vowel coarticulation, as it represents the 'litmus' case for producing CV sequences possessing perceptual invariance despite extreme acoustic variability because of its contextual environment. If stuttering is in fact the result of a breakdown in the temporal–spatial programming for speech production (Van Riper, 1971), it is reasonable to expect some degradation in the nuanced control of degree of anticipatory coarticulation in the production of stop place categories in PWS.

Stromsta (1986), from examination of sound spectrograms of stuttered relative to fluent productions, concluded that 'the lack of anticipatory coarticulation is probably the primary element in the core behavior of stuttering' (p. 111). His assessment of anticipatory coarticulation, however, was simply based on observing truncated segments rather than well-formed F2 transitions. To Stromsta, anticipatory coarticulation was a binary event – it was either present or absent. Other studies performing acoustic analyses of CV productions in PWS have also reported atypical F2 formant structures (e.g. Yaruss & Conture, 1993; Chang, Ohde, & Conture, 2002).

Our methodological approach was slightly different. We asked the following question: When F2 transitions allowed measurement of a sufficiently formed CV unit, did it or did it not effectively encode the proper degree of anticipatory coarticulation to ensure acoustic contrastiveness across stop place equivalence classes? Evidence showing altered patterns of vowel-induced coarticulation for stop place productions would implicate breakdowns in a specific motor speech algorithm highly dependent on the proper integration of planning and execution stages of speech production (Howell & Dworzynski, 2005). Evidence showing normal ranges of anticipatory coarticulation values, both within and across stop place categories, would suggest that 'the core element of stuttering' (if there is such a thing) arises from a different component of the speech/language production system, operationally distinct from anticipatory coarticulation.

The acoustic analysis of stop place + vowel categories can be assessed by a simple metric – locus equations (LEs). LEs are linear regressions of the frequency of the F2 transition sampled at its onset on the frequency of F2 when measured in the vowel nucleus (Lindblom, 1963). These frequency values are plotted for a single consonant produced with a wide range of following vowels. F2onsets are plotted along the *y*-axis and F2midpoints along the *x*-axis. For a given stop place category, for example, [dV] as in '*deet, dit, debt, date, dat, dot, dut, doot, daught, dote*', data coordinates have been consistently shown to tightly cluster in a positively correlated distribution. This scatter plot is fit with a linear regression line, the 'LE', of the form $F2onset = k^{*}F2vowel + c$,

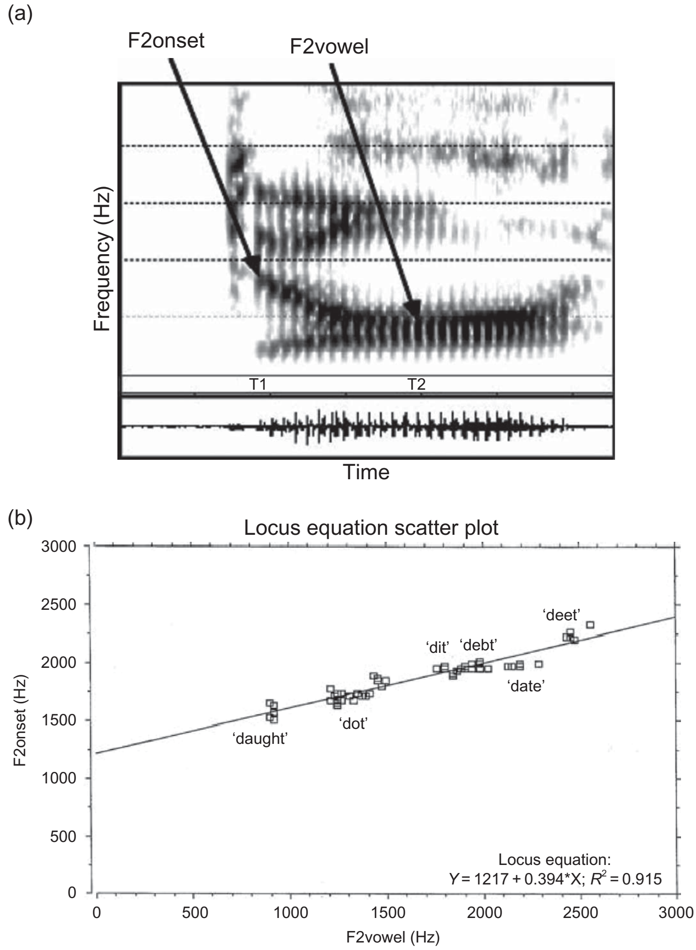

Figure 1. (a) The measurement points on the speech spectrogram where F2onset (Hz) and F2vowel (Hz) points were measured – the first glottal pulse for F2onsets and the vowel midpoint for F2vowel; (b) A representative locus equation scatter plot for 50 [dVt] tokens produced across 10 vowel contexts.

where *k* and *c* are constants, slope and *y*-intercept. Figure 1(a) illustrates the two LE measurement points on the speech spectrogram – F2onset (Hz) and F2vowel (Hz) whereas Figure 1(b) illustrates a representative LE scatter plot and regression equation derived from such coordinates for alveolar stop [dVt] productions with 10 vowel contexts (repeated 5 times each). Notice the lawful and linear appearance of this stop place category when plotted in this simplified fashion.

Stop place categories are composed of allophonic variants that form a perceptual equivalence class. Despite considerable variation of *within-category* F2 transitions – direction, extent and rate of change, all lawful variants of a given stop can be characterised as possessing a specified range of anticipatory coarticulation across speakers and stop place categories (expressed as a value from 0.0 to 1.0), with 0.0 being absolutely no anticipatory coarticulation and 1.0 showing maximum anticipatory coarticulation. Numerous LE studies, across several languages, have documented the linear orderliness and contrastive LE slope values indexing stop place categories (e.g. Nearey & Shammass, 1987; Krull, 1988; Duez, 1989; Sussman, McCaffrey, & Matthews, 1991; Sussman, Hoemeke, & Ahmed, 1993; Celdran & Vallalba, 1995; Sussman, Fruchter, & Cable, 1995; Sussman & Shore, 1996; Sussman, Duder, Dalston, & Cacciatore, 1999). Significant departures from normal LE slopes/*y*-intercepts, however, have been documented in children diagnosed with Developmental Apraxia of Speech (DAS) (Sussman, Marquardt, Doyle, & Knapp, 2002). The restricted ranges and near-identical LE slope values for [bV, dV, gV] tokens produced by children diagnosed with DAS were direct reflections of their poor speech intelligibility.

The main goal of our study was to capture the extent of anticipatory coarticulation in disfluent relative to fluent productions *of the same tokens in the same speaker*. Previous studies examining coarticulation in children who stutter (CWS) avoided measuring disfluent productions (Chang et al., 2002). They reported '*no appreciable differences*' (Chang et al., 2002, p. 685) in LE slopes between groups, but a larger difference in formant transition rates (FTRs) between labial and alveolar tokens in CWNS relative to CWS. Thus, their claim is a kinematic-based difference (speed of movement) between stuttering and control groups, rather than a direct coarticulation-based difference. Several aspects of their study, however, are problematic and may have compromised their results and related conclusions.

First, fricatives /s/ and /z/ were included in their speech samples. Fricatives are not appropriate for LE analyses because (1) they are continuants and, more importantly, (2) do not possess the encoding ambiguity inherent in the F2 transition of stop + vowel sequences that originally motivated the introduction of LEs (Lindblom, 1963). If languages did not contain stop plosives followed by vowels, the LE metric would not have been derived. In addition, there are no articulatory place distinctions to be captured by the F2 transitions of /s/ versus /z/, merely voicing differences, and the long duration noise of fricatives hinders accurate assessment of F2onset frequencies.

Although disfluent CV productions can present more difficult speech waveforms to analyse, we feel it is critical to assess the speech motor programme when it breaks down, as well as when it succeeds. Analysis of the stuttered repetitions of CVs, interspersed among fluent productions of those same CVs, can hopefully provide a direct assessment of the integrity of the speech motor control mechanisms underlying stop + vowel productions in PWS.

Methods

Participants

Criteria for diagnosis of stuttering. Certain criteria had to be met for participants to be considered eligible to participate in the present study. Specifically, they (1) had to present with greater than three instances of stuttering (i.e. sound/syllable repetitions, and/or audible and inaudible sound prolongations) per 100 words on each of three consecutive 100 word conversational samples and (2) had to self-identify as a stutterer and (3) also had to confirm the presence of stuttering as a young child [i.e. no person with late onset ($\geq$7 years) was included]. In addition to the three aforementioned criteria, the second and third authors completed interviews (and analysed the related samples for the above-described disfluencies) with each of the participants and had to provide additional qualitative and quantitative diagnostic confirmation/corroboration of the participant's self-report of stuttering before allowing participation in the study. In addition, through review of participants' medical history and also self-report we insured that no participant had any history of stroke, traumatic brain injury or any other trauma and/or medication that could potentially impair cognitive and/or speech motor functioning.

Based on these criteria, the initial participant pool consisted of eight adult participants: two females and six males (age range = 21 years, 2 months to 41 years, 9 months). Three of the adults who met the criteria for participation in the study were currently enrolled in therapy with the main goal being stuttering modification. Two of the participants were enrolled to begin therapy the following month. The remaining three participants reported that they had not received any form of formal speech-language therapy for stuttering in over 3 years. None of the participants had reported any previous history of speech and/or language therapy other than for stuttering. Although eight adults met the criteria for participation, the resulting data from these participants did not allow for the stuttering of all participants to be included in the final data corpus (see the section on *Data analysis*).

Control comparisons. LE coordinates from two recent studies were used as control comparisons for the participants in the present study (Lindblom, Agwuele, Sussman, & Cortes, 2007; Agwuele, Sussman, & Lindblom, 2008). These two studies were selected as suitable controls for the following reasons: (1) participants in the two control studies were in the same age range and gender as the PWS in this study; (2) the control participants also read aloud CVC stimuli from printed text; (3) the researchers in these two studies used Praat software with the same settings and F2 measurement protocols used in the present study; (4) the same investigator (first author of present study) performed the bulk of the measurements in both control studies and the present study; (5) the data in all LE studies to date, spanning over two decades, show the same general range of LE slopes and scatter (SSE) as the selected Praat-based recent studies used for comparison to PWS and (6) if there is one experimental procedure in phonetic analysis that does not require a brand new control group to compare with our PWS participant group, it is LE analyses as they are consistent and reliable across all normal speakers, even when used with different spectral analysis techniques (e.g. CSL, MacSpeech Lab, Praat, etc.).

Speech, language and hearing measures. All participants passed a bilateral pure tone hearing screening at 20 dBHL for 500, 1000 and 2000 Hz (ASHA, 1995). In addition, based on informal analysis of their conversational speech and also self-report, all participants had to speak English with native competence and also had to present with articulation, voice, resonance and language within normal limits. Health/medical history was also reviewed and no persons had any report of stroke, traumatic brain injury or any other trauma and/or medication that could potentially impair cognitive and/or speech motor functioning.

Severity of stuttering. After confirmation that the participant met the criteria for diagnosis as a stutterer, each participant completed a conversational sample ($N = 300$ words) with a certified speech-language pathologist that was audio-taped and analysed using a 9-point scale (O'Brian, Packman, Onslow, & O'Brian, 2004) for auditory analysis of stuttering severity. Results revealed that 3 participants were rated as mild, 2 as moderate and 3 as severe. In addition to this rating scale, the participants conversational sample ($N = 300$ words) was analysed by the second and the third authors using the more commonly used measure of stuttering severity, Stuttering Severity Instrument-3 (Riley, 1994). The severity rating results using this tool yielded the exact same findings as was reported with the 9-point scale above with the exception of two of the three participants who were rated as 'mild' receiving a score of 'very mild' on the SSI-3.

Procedures. Each participant read three short passages 3 times each in random orderings in the sound-treated Developmental Stuttering Laboratory (DSL). The passages were fictional and composed with an overabundance of words beginning with the stop consonants /bdg/

followed by varied vowel contexts. The three passages contained 18, 19 and 20 lines of text. One passage contained 52, 34 and 37 words beginning with [bV], [dV] and [gV] sequences, respectively; the second passage had 45, 27 and 25 such sequences and the third passage contained 40, 26 and 31 such CV sequences. A wide variety of consonantal endings followed the initial CV sequences that were analysed, including CV, CVC, CVCC, CVCV, CVCVC and CVCVCVC. The three passages are included in the Appendix.

Given the current and past treatment history of the participants and the need to be able to analyse stuttered productions, each participant was instructed to read the passages without any deliberate use of previously learned strategies. The testing workstation in the DSL is configured to allow for direct to disk recording of participants for later video and audio analysis. To guarantee the highest fidelity recordings, the DSL is outfitted with high-quality condensor microphones, studio-grade microphone pre-amps and studio-grade wiring and accessory electronics. For this study, each recording of the participant reading the passages featured a closeup video image of the participant's face and a small video inset window showing the testing workstation's display of the reading that the participant was completing at the time of the recording.

Data analysis. From both video and audio playback of the readings, target words were annotated by a certified speech-language pathologist (the second author) to indicate fluent/stuttered productions of words beginning with labial, alveolar and velar stops. Video recordings were made to insure visible plus auditory identification of stuttered words. If we had only used audio-recordings, it was possible that stuttering-like disfluencies, particularly inaudible sound prolongations could have been missed in the data analysis. To be included in the final data corpus, the participant had to produce at least nine stuttered tokens of each of the three CV forms. Given that stuttering tends to be reduced in reading, there were three participants who were excluded from the study because they did not produce enough stuttered CV productions to allow for suitable LE scatter plots and thus reliable comparisons. For the remaining five participants who met the criterion for the amount of stuttered tokens, digital wave files of the readings were produced and spectrally analysed via Praat (5.0.47) software (http://www.praat.org). In total, there were 2970 tokens acoustically analysed for this study. Fluent tokens totalled 1817 and stuttered tokens totalled 1153, of which 569 were [bV], 313 were [dV] and 271 were [gV]. There was no way to ensure an exact match between the number of fluent repetitions of a given token with stuttered productions of that same token. Because LE analyses focus on category-level outcomes, not individual CV sequences, this unavoidable 'mismatch' between the exact number of instances of fluent/disfluent productions of the same token was not considered important.

Finally, all stuttered and fluent tokens for each of the five participants were reviewed by the second author twice (with the initial identification and second analysis separated by a period of 1 week). These tokens were then confirmed by the first author and also by at least one additional member of the transcription team, yielding 100% intra- and inter-rater agreement on the stuttered relative to fluent tokens. Table I summarises the breakdowns across the five participants showing the totals of fluent versus stuttered tokens across the stop place categories.

Acoustic analysis. Spectrograms were generated using a view range of 0–5000 Hz, at a window length of 0.0005 seconds and with a 50.0 dB dynamic range. The time and frequency resolutions were 1000 and 250 steps, respectively. The method of analysis was Fourier transform and the window shape was Gaussian. The spectrogram was drawn with auto-scaling and 6.0 dB/octave pre-emphasis. These pre-sets were identical to those used in all previous LE studies using Praat software.

Table I. Participant age (years; months), stuttering severity and summary of the number of tokens analysed across the three stop places that were produced fluently and stuttered.

PWS	Age	Severity	[bV] fluent	[bV] stuttered	[dV] fluent	[dV] stuttered	[gV] fluent	[gV] stuttered
1	24;4	S	202	239	100	171	136	148
2	21;10	M	147	26	65	12	86	21
3	41;9	S	29	70	32	47	16	42
4	22;4	M	156	47	97	39	109	18
5	24;9	S	304	187	219	74	229	42
Total			838	569	513	343	576	271

Note. S, severe; M, moderate.

Second formant values were measured at two points within the CV sequence: F2onset and F2vowel midpoint. Following established practice, F2vowel mean values were obtained from two sources: (1) wide-band spectrograms and (2) narrow-band Fast Fourier Transforms (FFTs) taken from spectral windows corresponding to the same F2vowel midpoints determined by positioning the marker on the spectrographic display. The mean F2vowel midpoint was the average of the two measures. F2onsets (Hz) were taken from an expanded wide-band spectrogram view of the stop release burst and the first few glottal cycles of the speech waveform. Corresponding to the first clearly recognisable glottal pulse of the vowel, following the release burst of the stop, the cursor was placed at the dead centre of the F2 resonance pulse corresponding to this initial pitch period.

As far as possible, all measurement loci followed procedures previously described in Sussman et al. (1991; 1993; 1995; Sussman & Shore, 1996). Criteria for F2 midvowel placement were (1) if F2 was steady-state or diagonally oriented, the estimated vowel midpoint was taken for measurement; (2) if F2 was U-shaped or the inverse, the lowest or highest point of F2 trajectory was taken for measurement. Although the criteria for F2 midpoints were subjectively determined by visual inspection, no sample points from what might be considered the vowel off-glide were taken.

All measurement values for F2onset and F2midvowel frequencies were entered onto Excel spreadsheets for subsequent generation of LE scatter plots and regression analyses. For each speaker, the data coordinates were combined across the three repetitions of each passage to yield one grand LE scatter plot per stop for fluent and stuttered productions. Because of the extremely large size of our data corpus, six undergraduate student volunteers were recruited to assist in the spectrographic measurements. They were individually trained on Praat for several practice sessions under the supervision of the first author. When measurement reliability tests consistently showed correspondence between the student and instructor (i.e. first author) analyses (<125 Hz), the student teams were allowed to measure fluent/stuttered target tokens in a given passage/ repetition by themselves. The first author, in addition to measuring many of the passages, also double-checked every student data summary for errors before final plots were made.

Results

*LE slopes/*y*-intercepts*

The initial dependent variable of interest was the slopes of the LE regressions, as they quantitatively index the degree of anticipatory coarticulation for each stop category (Krull, 1988; Sussman et al., 1991). Shallow slope values (e.g. 0.15–0.45) indicate lower degrees of anticipatory coarticulation, as the stop consonant is more resistant to being affected by the following vowel context. By ‘affected’ we mean the location and shape of tongue blade/body at stop place occlusion is directly influenced by the front-back/high/low features of the vowel. Alveolar stops /d,t/ are characterised by the lowest slopes as vowel contexts only weakly affect the occlusion point of the tongue blade during stop closure. Steeper regression functions, characterised by slope values within the range 0.70–1.00, index greater degrees of anticipatory coarticulation, as the following vowel contexts strongly influence the place and shape of the tongue at occlusion. Saying ‘*geese*’ versus ‘*goose*’, characterised by the more forward tongue placement prior to the vowel /i/ relative to tongue backing for /g/ prior to /u/, illustrates the high degree of coarticulation in [gV] contexts. Labials are also characterised by high slope values as the speaker’s tongue can already be in the vowel position well in advance of the labial occlusion formed independently by the lips.

Table II shows LE slope coefficients and corresponding *y*-intercepts for each participant across the three stop categories for both fluent and stuttered productions. To allow comparison to a normative group of speakers (as was discussed in the section *Participants*), LE coordinates from two recent studies is shown at the bottom of Table II (Lindblom et al., 2007; Agwuele et al., 2008). Figure 2 was derived from the data shown in Table II to provide a more meaningful visualisation of [bV], [dV] and [gV] LE parameters as plotted within a higher-order, F2 transition-based, acoustic space. LE slopes are plotted along the *x*-axis, and *y*-intercepts along the *y*-axis. Several things are of interest in this scatter plot. First, each of the three enclosures includes LE coordinates for each of the five speakers producing the hundreds of tokens comprising each stop place category. Within each enclosure there are 10 data points – five coordinates for fluent and five for stuttered CV productions. Fluent productions are shown by triangles and disfluent by squares. Also included within each enclosure are LE slope/*y*-intercept means for [bV], [dV] and [gV] productions obtained from the normal control speakers. These mean values were derived by averaging across the LE data published in Lindblom et al. (2007) and Agwuele et al. (2008) ($N = 9$). The [bV], [dV] and [gV] slope/*y*-intercept means for the nine normal speakers analysed in those two studies are shown by the filled grey circles within each stop place enclosure. It can be seen that these normative slope/*y*-intercept coordinates fit within the boundary enclosure of each stop place category produced by the five PWS.

Within each cluster fluent/disfluent productions are indistinguishable as no discernible subgroupings emerged correlated with the two fluency conditions. All stop + vowel productions of PWS, as acoustically characterised by LE slope/*y*-intercepts, for both fluent and

Table II. Locus equation slope/*y*-intercept (Hz) coefficients for PWS in fluent and stuttered tokens. Locus equation slopes/*y*-intercepts from control speakers ($N = 9$) are shown below as a normative comparison.

	Fluent			Stuttered		
PWS	[bV]	[dV]	[gV]	[bV]	[dV]	[gV]
1	0.79/215	0.35/1156	0.81/528	0.86/102	0.36/1161	0.81/450
2	0.83/139	0.55/766	0.84/375	0.77/234	0.48/883	1.17/132
3	0.93/198	0.29/1329	1.05/211	0.83/193	0.24/1436	0.81/516
4	0.89/51	0.57/960	0.93/333	0.87/98	0.58/925	0.87/375
5	0.73/340	0.39/1162	0.89/494	0.62/536	0.17/1564	1.11/100
Mean	0.83/187	0.44/1075	0.90/388	0.79/233	0.37/1194	0.95/315
Controls	0.75/ 283	0.55/873	0.91/328			

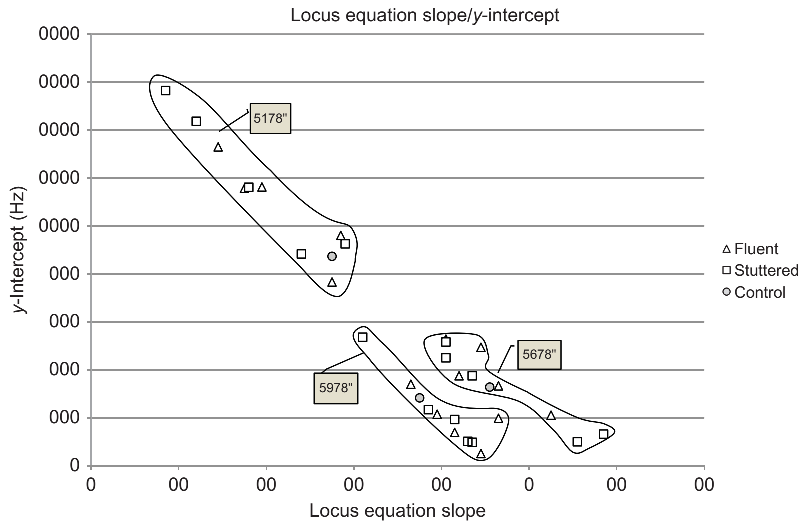

Figure 2. Locus equation (LE) slope *x*–*y*-intercept for [bV], [dV], [gV] tokens, produced both fluently (triangles) and stuttered (squares) for each subject ($N = 5$). LE coordinates for each stop place category are enclosed by an outline to allow visualisation of distinct, non-overlapping stop place categories. Normal control values for [b, d, g] tokens are indicated within each enclosure by filled grey circles.

stuttered productions, fall within the three non-overlapping distribution ranges of LE stop place coordinates.

However, an interesting observation can be seen relating to the location of the control group coordinates (black circles) relative to the stuttering data coordinates within each stop enclosure. Labial and velar distributions show the normal control coordinates in the mid-range of the distribution of our PWS data values, but the [dV] norm is located at the very lower edge of the alveolar [dV] enclosure. Three PWS displayed LE coordinates for [dV] productions considerably distant from the control norm – the three participants rated as severe. The two most distant points (blue squares) were from participant #5 (stuttered tokens: slope = 0.17; *y*-intercept = 1564 Hz) and participant #3 (stuttered tokens: slope = 0.24; *y*-intercept = 1436 Hz). Moving closer towards the control norm for [dV] are the fluent tokens of participant #3 (green triangle) with slope = 0.29; *y*-intercept = 1329 Hz. The third participant rated as severe was participant #1. His coordinates, along with the fluent tokens of participant #5, are the next cluster of points, moving closer to the control norm [dV]. The upper left area of the [dV] enclosure reflects the lowest extents of anticipatory coarticulation (<0.40), concomitant with a more forward occlusion location for alveolar stops on the roof of the mouth (indexed by high *y*-intercept values). Despite the 'quasi-outlier' nature of the three severe PWS, their LE [dV] data coordinates are still well within normal tolerance limits seen in non-stuttering fluent speakers (Sussman et al., 1991). The two speakers (participants #2 and #4) whose coordinates are closest to the [dV] control norm are the two PWS rated as moderate on our severity measure.

For velar productions, the three closest coordinates to the [gV] norm were also from the two moderate stutterers (#2 and #4) for both stuttered and fluent tokens, with the more distant coordinates once again being participants #1, #3 and #5, the most severe stutterers. Labial outputs did not show this pattern, as coordinates from moderate and severe stutterers

Table III. Standard error of estimate (Hz) for PWS broken down into fluent relative to disfluent CV productions. Normative control values of SEE are shown at bottom.

	Fluent			Stuttered			
PWS	[bV]	[dV]	[gV]	[bV]	[dV]	[gV]	Mean
1 (S)	123	100	178	93	107	152	125.5
2 (M)	92	77	109	108	147	116	108.2
3 (S)	87	75	169	91	65	145	105.3
4 (M)	125	112	186	174	128	159	147.3
5 (S)	146	120	199	129	121	283	166.3
Mean	114.6	96.8	168.5	119	113.6	171	130.5
	[bV]	[dV]	[gV]				
Controls ($N = 80$)	100	83	125				

closely surrounded the [bV] norm. The one data point furthest away from the [bV] control norm was the stuttered tokens ($N = 187$) of participant #5.

Standard error of estimate. A well-documented attribute of LEs is the tight clustering of data points (F2onset and F2midvowel) around the linear regression line. The tightness of fit is numerically captured by the standard error of estimate (SEE), or the average distance (in Hz) of each point in the scatter plot from the regression line. Table III presents the SEEs of our five PWS across the stop place categories, showing fluent relative to disfluent productions. Interestingly, there were no differences seen in SEEs across fluent and stuttered productions. However, the SEEs for PWS were considerably higher for both stuttered and fluent tokens relative to SEEs from normal control speakers (shown at bottom of Table III). The control values represent mean SEEs for [bV], [dV] and [gV] LEs summarised across six studies comprising 80 adult speakers closely matching the age range of our participants (Sussman et al., 1991; 1993; 1995; Sussman & Shore, 1996; Sussman, Dalston, & Gumbert, 1998). At first glance, comparison of SEEs across stuttering severity levels did not reveal much of a difference. The mean SEE for the three severe PWS (#s 1, 3, 5) was 132.4 Hz relative to 127.8 Hz for the two moderate PWS (#s 2, 4). A subsequent SEE analysis examining fluent versus disfluent output was completed to further explore this issue and will be discussed in an upcoming subsection (see 'Stuttering severity').

The higher SEEs in LE plots of CV productions of PWS (relative to normal controls) indicate more variation in repeated productions of our [bV], [dV], [gV] target words, both stuttered and fluent. Although the overall degree of coarticulation was well within normal ranges and, most importantly, showed non-overlapping clusters of stop place categories, the benchmark LE 'linear tightness' was not as evident across the fluent/disfluent productions in our five participants.

Euclidean distances. Mean LE coordinates (slope and *y*-intercept) for the three stop place categories provide a simple graphic representation of the relative separation of stop place categories in a higher-order and derived acoustic space. A quantification of the 'acoustic distance' between stop place categories can be derived by (1) connecting the three $<x, y>$ data coordinates producing a 'triangle,' and (2) calculating Euclidean distances between stop place coordinates. *y*-Intercept values were first normalised by dividing by 2000 to provide a uniform scaling (0–1.0) to match slope scale values. Euclidean distances were calculated

Table IV. Euclidean distances, expressed as the perimeter of a triangle, separating locus equation slope/*y*-intercepts coordinates for the three stop place categories. Normative control values are shown below the table for comparison purposes.

PWS	Fluent	Stuttered	Mean
1 (S)	1.35589	1.48521	1.42055
2 (M)	0.88850	1.65659	1.27255
3 (S)	1.89964	1.75903	1.82934
4 (M)	1.17979	1.04321	1.11150
5 (S)	1.31226	2.41085	1.86156
Mean	1.32722	1.67098	1.49910
Controls	1.35891 (citation) 1.16325 (spontaneous)		

Note. S, severe; M, moderate.

using the standard formula $([x_1 - x_2]^2 + [y_1 - y_2]^2)^{1/2}$. This was done for each speaker across the two conditions (fluent vs. stuttered). Table IV presents the total Euclidean distances, or perimeter of the bounded 'b-d-g' triangle. For comparison purposes, similar Euclidean distance measurements obtained from LE analyses of both citation and spontaneous speech are shown at the bottom of the table (data taken from Sussman et al., 1998). The control means at the bottom of Table IV were based on LE data from 22 normal speakers (11 male and 11 female, age range = 21–55 years; male mean = 33 years, 6 months, female mean = 35 years, 2 months). The fluent productions of the stuttering group closely matched the Euclidean distances obtained from citation form tokens in the normative population (1.3272164 vs. 1.358912). Spontaneous (relative to citation-form) speech shrinks the distances between stops in normal speakers. At issue is whether speech output from reading is closer to citation form (which is sometimes referred to as 'lab speech'), or more like spontaneous natural speech. In any case, stuttered productions had *larger* Euclidean distances than either citation or spontaneous speech norms. Larger distances imply a greater acoustic separation of stop place categories.

Stuttering severity. Table V illustrates the effect of stuttering severity on two of the dependent measures: standard error of estimate and Euclidean distances. The five participants were separated into a moderate stuttering group (#s2, 4) and a severe stuttering group (#s1, 3, 5). Standard error of estimate values are shown in the top portion of the table. SEEs were averaged across [bV, dV, gV] tokens for the two stuttering subgroups, and shown for fluent relative to disfluent productions. It can be seen that the moderate PWS had the lowest mean

Table V. Standard error of estimate and Euclidean distances as a function of stuttering severity and output disfluency.

	Fluent	Stuttered
Standard error of estimate (Hz):		
Moderate	117	139
Severe	133	132
Euclidean distances:		
Moderate	1.03415	1.3499
Severe	1.52259	1.88503

SEE score (117 Hz) for their fluent productions, with an increased degree of scatter around the regression line for stuttered productions (SEE = 139 Hz). The severe PWS had higher SEEs across the board, regardless of fluency condition.

The bottom half of Table V shows data for Euclidean distances. Moderate stutterers had the smallest separation distances for fluent productions, with an increase in stop category separation during stuttered output. The severe stutterers had greater Euclidean distances relative to moderate stutterers, and also an increase in separation distances when output was stuttered relative to fluent. Thus, even within a relatively small group of PWS, stuttering severity differentially affected articulatory performance as captured by these two measures.

Discussion

The LE analysis of stop + vowel productions in five PWS indirectly assessed the integrity of two inter-related speech processes: (1) the planning algorithm responsible for programming the graded extents of anticipatory coarticulation across stop place categories; and (2) the articulatory motor control producing the CV sequences. The main conclusion that can be drawn from our data is that the inherent relationships between vowel contexts and stop place categories were not altered in either fluent or disfluent CV productions in PWS. The non-overlapping distribution patterns of stop place categories in a derived and higher order LE space (see Figure 2), across both fluent and disfluent productions, argues against any serious deficits in the motor planning/execution of stop + vowel anticipatory coarticulation in PWS. Disfluencies certainly occurred, primarily at the initiation of speech, but when finally 'off the ground', the speech output signal, in regard to categorical values of LE slopes, was very similar to what has been documented across two decades of LE studies in fluent speakers across several languages, and what was documented in children who stutter by Chang et al. (2002).

Despite the ubiquitous evidence of kinematic shortcomings of PWS in the stuttering literature [e.g. longer VOTs, longer stop closure and vowel durations, longer intervals for movement displacements to reach peak velocity, altered temporal sequencing patterns among upper lip, lower lip and jaw, slower F2 transition rates of change (FTR) relative to fluent speakers (e.g. Zimmerman, 1980; Harrington, 1987; Robb & Blomgren, 1997; Max, Caruso, & Gracco, 2003)], the PWS in our study adequately programmed and successfully produced a more complicated articulatory process – controlling the appropriate degree of vowel context-dependence inherent to the three stops /bdg/.

A brief account of what is entailed in this production scenario is as follows: in bilabial stops the lips form the closure and the tongue body is free to anticipate the shape of the following vowel. For [d] the tongue blade/tip is the primary articulator. The tongue body can be shaped by the following vowel, although its mobility is somewhat limited by the anterior closure. Coarticulation in [g] differs from both [b] and [d] in that the same articulator is used for both C and V – the tongue body. Three different scenarios of coarticulatory coordination must first be planned and then controlled. Failure to coordinate these complex lingual events precludes producing the contrastive acoustic output that helps cue stop place (Sussman, 2010). PWS seem to follow the famous quote: '*. . . we speak to be heard in order to be understood*' (Jakobson, Fant, & Halle, 1963, p. 13). Despite the blocks, hesitations, repetitions, slower-than-normal FTRs and so on, PWS succeed in being understood. The subtle deviancies observed in the F2 transition (Yaruss & Conture, 1993; Chang et al., 2002) and the array of documented kinematic shortcomings (e.g. see Max, Guenther, Gracco, Ghosh, & Wallace, 2004 for review) seen in PWS can be viewed as physical surface markers of stuttering behaviours, but not directly related to the underlying causal factors of the disorder (see 'Theoretical Considerations' for additional etiological discussion).

The effect of stuttering severity

An interesting aspect of the severity variable emerged in all dependent measures examined. Although at a global level we have argued against any significant break downs in speech output that would compromise the correct degree of anticipatory coarticulation in stop + vowel productions, there were subtle indications of less-than-stellar output performances as a function of stuttering severity. Figure 2 showed that the three severe stutterers (#s 1, 3, 5) were typically the most distant data coordinates from control norms within the alveolar and velar stop enclosures (most notably seen in the [dV] LE enclosure). The two moderate/mild PWS were generally closer to the control group LE means. Table V also showed a clear contrast in SEE and Euclidean distance measures as a function of stuttering severity. Moderate/mild PWS displayed somewhat tighter distributions in their fluent output relative to the severe PWS. A possible contributing factor to this outcome might simply be due to the inclusion of the truncated and aborted repetitions of many of the target words in the data pool of stuttered tokens. Obviously, the severe stutterers would have more of these truncated CVs than the moderate stutterers. Rather than discarding these disfluent and repetitive CV syllables preceding successful output of the full target word, we made full use of all the CVs as long as an unambiguous stop and vowel sound were spectrally and acoustically discernable. Often the vowel produced was not the intended target vowel (e.g. repeated [də] . . ., or [dæ] . . . CVs for /a/ in attempting to produce *Don*). These truncated productions, though legitimate stop + vowel sequences, and thus fair game for a LE analysis, might have contributed to a less than benchmark linear scatter plot for the severe PWS.

Another possibility is that PWS rated as severe may engage in a more 'clear speech' hyperarticulated effort after the frustrations of prolonged, disrupted, attempts at producing fluent output. This more emphatic output signal could be one reason for the greater separation of the stop category representations in stuttered speech as measured by the Euclidean distance metric. As shown in Table V, our severe stuttering subgroup had greater Euclidean distances connecting the three stop place categories, for both fluent and stuttered tokens, but especially so for stuttered output. However, these differences may also be more likely related to a *response* to stuttering than a causal contributor. The limited size of our participant group precluded statistical analyses of these data trends, but the large data base underlying these observations contribute to a sense of confidence in the overall validity of these conclusions.

Theoretical considerations

Characteristic disfluencies of stuttering occur when words, or parts of words, are started prematurely, before the plan for that segment is finalised. Since we (by necessity) used a paradigm of reading text out loud, rather than spontaneous speech, all higher levels of linguistic planning (semantic, syntactic, morphological, etc.) are provided for in the text. However, despite the elimination, and hence simplification, of the higher order language planning epochs, stuttering disfluencies occurred (1183 measured) in our participants during read speech that were, on the surface at least, identical to those encountered in spontaneous speech. Assuming for the moment that read speech and spontaneous speech can be conceptualised as being the same *at the final phonetic planning/execution stage*, we will now use Levelt's model (1989) for the planning, selection, and linguistic programming of language output to attempt to explain the present findings.

In this section we attempt to extrapolate from our data to help narrow down the possibilities where PWS's speech begins to disintegrate into blocks, prolongations, repetitions. Levelt's 'phonological spell out' stage would be a prime candidate to focus on as the stuttering breakdown seems to occur prior to any overt motor programming. Levelt (1989) argues that there is an allotted timeframe within which the lexeme is mapped onto the lemma. Research has suggested that this mapping process is much more efficient with increasing language development. Specifically, the phonological representations in the lexicon become more robust with development in order to deal with an ever increasing vocabulary and the need to access words that may only differ by one sound segment in an automatic, 'on the fly' fashion (e.g. Treiman & Breaux, 1982; Elliot, Hammer, & Evan, 1987; Charles-Luce & Luce, 1990; 1995; Treiman & Zukowski, 1991; Metsala, 1997; Brooks & MacWhinney, 2000). There are data to suggest that persons who stutter have less specified or rather less robust phonological representations (e.g. Byrd, Conture, & Ohde, 2007; Anderson, 2008; Anderson & Byrd, 2008). Thus, one could argue that it might take more time for PWS to complete the phonological spell-out. Further, it is important to note that the spell-out is completed incrementally in a left to right fashion. If indeed they are not able to access and/or maintain the complete spell out within a timeframe that is commensurate with activation then what is programmed and ultimately executed is an incomplete or wrong plan (e.g. Howell & Au-Yeung, 2002, Bosshardt, 2006; Byrd et al., 2007; cf. Packman, Onslow, Coombes, and Goodwin, 2001). This plan is either continuously executed until the spell out is complete or it is abandoned entirely, a phenomena that reflects the disfluencies characteristic of stuttering (e.g. sound repetitions, syllable repetitions, inaudible and audible sound prolongations). If the plan is sufficient to generate, at minimum, the initial CV portion of a larger word, then results from the present study seem logical as the proper degree of vowel overlap with the stop would be satisfactorily programmed. Support for this notion that the integrity of the CV plan is intact is found in both Howell and Vause (1986) and Howell and Williams (1992) as findings revealed that the formant structure of the vowel was accurately produced.

Future research should consider the syntactic complexity of the tokens in which the CV . . . . productions were placed and also the location of the CV . . . . productions as these two variables could influence both the linguistic and the motoric complexity of the production. For example, Kleinow and Smith (2000) examined the speech output of adolescents who stutter by comparing tokens that varied in length to those that varied in linguistic complexity while at the same time measuring motoric stability during production. Results revealed that the tokens that were more syntactically complex resulted in increased motoric instability in persons who stutter. In contrast, the tokens that were longer, but were not more syntactically complex did not influence motoric stability. This relationship between length, syntactic complexity and motoric stability was not present in the non-stutterers, suggesting an interaction between linguistic processing and motor programming that may be unique to stutterers. Studies such as the one completed by Kleinow and Smith (2000) wherein the relative impact of the motor planning can be explored while controlling for linguistic planning would help to confirm that the lack of disruption to coarticulation noted in the present study was not solely or perhaps even partially related to the tokens in which the CV . . . . productions were made. That being said, the fact that we have compared stuttered versus fluent productions of the same words allow us to feel more confident that our findings are not the result of some methodological artefact.

To review, the data from this study suggest that stuttering does not appear to be the result of any inefficiency in the person's abilities to plan the proper degree of anticipatory coarticulation in producing stop + vowel segmental sequences. Rather, once the plan is accessed, their coarticulation is largely similar to that of normals. This does not discount the potential motoric contribution of stuttered speech, but it does lend support to the notion that stuttering is not solely related to issues with speech motor control and that the combined influence of motor and linguistic properties appears to be more plausible, at least, with what we know thus far regarding the complex nature of this disorder.

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Appendix

Passage A: Down at the farm

It was both a bad and good day at the big game farm. Bob the goat, bit Gabby the big gold goose and Gabriel the dumb but gorgeous duck. Bill, the bold but destitute farmer, got the door of the beige barn open and banged the beautiful dinner bell to call all the animals together, including Don the donkey, Gitmo the dog, Dan the gander, Gib the gecko and even Dave the dandy buffalo. Dina, the farmer's gorgeous daughter, also decided to come to the barn yard gathering. Bella, the farmer's other daughter, also came down to the big farm from Boston. Bill, Dina and Bella were born on the big farm and they did not want to destroy the good benefits they deserved from the bounty the farm gave them. Boom, thunder struck! Boom! boom! and down came gobs of gushing rain in big buckets. Bill, Gabby the goose, Bob the goat and Don the donkey were standing down by the big dead bush; Bella was getting bored and sat by herself. Because of a good coincidence, a bumble bee landed on Bob the goat and bit him by his big fuzzy beard. He now knew what a bite could do, and he did not like it one bit. Everyone laughed and Bob, Gabby, Gabriel, Gib, Don, Gitmo, Dan and Dave, as well as Dina and Bella walked back to the beige barn and got some goodies to eat for all the barn yard family. 'Golly', said Dina, 'the bumble bee bite was a good lesson for all of us'. We sure did act like goofy goons, but we all had a good day down on the big beautiful farm.

Passage B: Boston versus New York

Boston is called Bean Town. New York is known as the Big Apple. Big deal! Give me a bold bean over a delicious fruit. I was born in Boston, but I am a big fan of both of these ethnically diverse cities. Both towns are beautiful, and down right gorgeous to behold. Down at the harbour, boats come and go all day long. Garbage trucks dump their loads into downtown dumps, and tug boats bustle to dump their load out at sea. By the shoreline, dead beat homeless men give their best effort to clean the dandy cars of the beautiful folks, as the ferries get into line to deliver dozens of passengers and then depart for distant parts of the big bold city.

Boston is famous for the BIG DIG and NY for big hot dogs; Boston is by the sea, and NY is an island, with beaches, dunes and beige sea gulls. Sports games are played everywhere: even golf, badminton, dominoes, bowling, dagger throwing and gold mining can be found in both cities. The subways are dirty, but good people ride them all day long. Get yourself a ticket for a dollar! What a bargain! You get a bonus when you decide to get on a bus because you gather a birds-eye view of the comings and goings of the citizens of both towns.

Both towns have big and beautiful zoos with gayly lit lights giving off a golden hue to the night-time sky. Barnyard animals can also be seen there: ducks, goats, donkeys, ganders, geese, geckos, gazelles and wild game.

Passage C: Travel

I won a bold bet the other day – a free big trip to three countries. They had to be on different continents. Deciding was not going to be easy. I decided on:

Bolivia, Denmark and Gambia. Bolivia was a good choice because my Dad was born there. Dad believed it was God's Garden of Eden so to say. '*It's so beautiful*' he said, '*did I ever show you my birth place?*' He did, about a gazillion times. One day he bought a guide book for me. The big banana plantations were gorgeous. Down by the ocean the big boats unloaded dozens of golden boxes of goods from all over the world. Bolivia was going to be a bold adventure for a boy like me. Gas was cheap there too!

Denmark was my second country because my dear darling mother was born there. She has beautiful blond hair and delicate features. 'Good choice' said my mom! '*Denmark is not a big country, but the people are beautiful, and you will gain a lot.*' Danish customs were the best – dozens of local bazaars, cheap gas, dainty flowers, gobs of hotels, cheap dinners, gambling and good beer. What could be a better destination?

Gambia was a daring choice. The price of gas is beyond reasonable. Big game farms have gorillas, goats and dazzling gazelles. There are no gangs, however. I also gained extra miles flying there. The God-like gates of Gambia are beautiful. Gaping daffodils dot the sun-baked golden hillsides. I will be able to buy gifts very cheaply.