Speech movement variability in people who stutter: a vocal-tract MRI study

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Abstract

Purpose: People who stutter (PWS) have more unstable speech motor systems than people who are typically fluent (PWTF). Here, we used real-time MRI of the vocal tract to assess variability and duration of movements of different articulators in PWS and PWTF during fluent speech production.

Method: The vocal tracts of 28 adults with moderate to severe stuttering and 20 PWTF were scanned using MRI while repeating simple and complex pseudowords. Mid-sagittal images of the vocal tract from lips to larynx were reconstructed at 33.3 frames per second. For each participant, we measured the variability and duration of movements across multiple repetitions of the pseudowords in three selected articulators: the lips, tongue body, and velum.

Results: PWS showed significantly greater speech movement variability than PWTF during fluent repetitions of pseudowords. The group difference was most evident for measurements of lip aperture, as reported previously, but here we report that movements of the tongue body and velum were also affected during the same utterances. Variability was highest in both PWS and PWTF for repetitions of the monosyllabic pseudowords and was not affected by phonological complexity. Speech movement variability was unrelated to stuttering severity with the PWS group. PWS also showed longer speech movement durations relative to PWTF for fluent repetitions of multisyllabic pseudowords and this group difference was even more evident when repeating the phonologically complex pseudowords.

Conclusions: Using real-time MRI of the vocal tract, we found that PWS produced more variable movements than PWTF even during fluent productions of simple pseudowords. This indicates general, trait-level differences in the control of the articulators between PWS and PWTF.

Introduction

Several studies indicate that movements of articulators differ in people who stutter (PWS) compared with people who are typically fluent (PWTF) (Frisch, Maxfield, & Belmont, 2016; Howell, Anderson, Bartrip, & Bailey, 2009; Jackson, Tiede, Beal, & Whalen, 2016; Loucks & De Nil, 2006; Loucks, De Nil, & Sasisekaran, 2007; Sasisekaran, 2013; Smith, Sadagopan, Walsh, & Weber-Fox, 2010). These kinematic differences were evident even when the speech produced was perceptually fluent, that is, it appeared to lack dysfluencies. The findings indicate that there are general (trait-level) differences in speech motor control in PWS that go beyond the expected movement differences accompanying stuttered moments (state-level).

Previous speech movement studies in PWS have mostly focussed on the measurement of: (i) speech movement variability; (ii) the amplitude and duration of speech movements; and (iii) the effort involved in speech production (reviewed in Wiltshire, 2019)The most consistent finding across these studies was that PWS have greater variability in speech movements across repeated utterances (Smith, Goffman, Zelaznik, Ying, & McGillem, 1995) when producing targeted jaw movements (Loucks & De Nil, 2006, 2012; Loucks et al., 2007), vowel sounds (Frisch et al., 2016), simple (Sasisekaran, 2013) and complex pseudowords (Smith et al., 2010), and simple sentences (Howell et al., 2009; Jackson et al., 2016; MacPherson & Smith, 2013). Speech movement variability increases in both PWS and PWTF as utterances become more complex (Smith et al., 2010) or speech more rapid (Namasivayam & van Lieshout, 2008) and this effect is more pronounced in PWS as syllable length or phonological complexity increases (Smith et al., 2010). In contrast, there is little consensus among studies investigating whether

PWS differ in the amplitude (Walsh, Mettel, & Smith, 2015; Van Lieshout, Ben-David, Lipski, & Namasivayam, 2014 cf Namasivayam & van Lieshout, 2008) and duration of movements (McClean & Tasko, 2004; Smith, Goffman, Sasisekaran, & Weber-Fox, 2012; Smith et al., 2010; Tasko, McClean, & Runyan, 2007; Usler, Smith, & Weber-Fox, 2017) or in the movement effort (Choo, Robb, Dalrymple-Alford, Huckabee, & O'Beirne, 2010; De Andrade, Sassi, Juste, & De Mendonça, 2008; de Felício, Freitas, Vitti, & Regalo, 2007; Walsh & Smith, 2013) made during speech production.

The aforementioned studies used a variety of methods to measure speech movements in PWS some of which were necessarily limited to measurement of one or two articulators at a time and required attaching recording equipment (such as electrodes) to articulators either within the vocal tract or externally, for example on the lips. The necessary attachment of recording devices to the articulators alters sensations and potentially interferes with feedback processes during speech production. In PWS, altering somatosensory feedback can enhance fluency (Snyder, Waddell, Blanchet, & Ivy, 2009), which could be problematic for interpretation of findings. To fully examine speech motor control in PWS without disturbing feedback or the actual movements themselves, it would be advantageous to use a non-invasive imaging technique such as MRI of the vocal tract.

Vocal tract MRI offers the opportunity to view the movements of the entire vocal tract, from larynx to lips at good temporal and spatial resolution (Carey & McGettigan, 2017; Kim, Kumar, Lee, & Narayanan, 2014; Niebergall et al., 2013; Ramanarayanan, Goldstein, Byrd, & Narayanan, 2013). A single image of the midline of the vocal tract (mid-sagittal slice) can be recorded in real time, producing 2D video data that captures the fast movement of the all the articulators simultaneously during speech. This allows us to measure the range of movements of different articulators simultaneously, variability of such movements over repeated utterances, and co-ordination between articulators during speech (Kim et al., 2014). Of particular interest, movement of articulators that are difficult to attach electrodes to can also be assessed, for example, the velum.

We used vocal tract MRI to scan the vocal tracts of a large sample of PWS and PWTF during speech production. In this report, we focussed on variability in speech movement production since this was the most reliable finding reported in previous studies. Participants produced several repetitions of pseudowords increasing in syllable length from one to three syllables and four-syllable pseudowords that differed in complexity (Smith et al., 2010). We measured lip-aperture variability during fluent repetitions of pseudowords aiming to replicate the previous findings for this articulator that were measured using infra-red light-emitting diodes attached to the lips (Smith et al., 2010). We also demonstrate one of the main benefits of vocal tract imaging, namely the ability to capture information from multiple articulators, by measuring movement variability in two additional articulators, the tongue body and the velum, during the same utterances. We examined whether variability in speech movements was related to stuttering severity. Finally, given the lack of consensus on whether speech movement durations differ in PWS, we explored whether increasing syllable number or phonological complexity differentially affected movement durations in PWS and PWTF.

Method

Participants

We scanned 31 adults who stutter and 20 typically fluent controls. Data from one PWS were excluded due to technical reasons. Data from a further two PWS were excluded because fewer than six out of ten utterances for each pseudoword were produced fluently during the scan (see analysis plan, below). This resulted in a sample of 28 adults who stutter (seven women, mean age = 30.57 years; range = 19-45 years) and 20 controls (four women, mean age = 29.4 years; range = 20-44 years). Groups were balanced for gender, age, ethnicity, and years of education (see Table 1). All PWS had at least mild stuttering severity, as assessed by the Stuttering Severity Instrument (SSI-4) (see Table 1). Participants reported normal or corrected-to-normal vision and normal hearing. Exclusion criteria included any neurological impairment or disorder of speech, language or communication other than developmental stuttering.

Participants' speech was assessed using the Stuttering Severity Instrument (SSI-4; Riley, 2009). This instrument measures the frequency and duration of stuttered moments as well as physical concomitants. Participants were recorded in person with video. One person's speech was recorded via teleconference due to technical reasons. Participants read a passage and had a conversation with the researcher for two minutes, each. Recordings were scored offline.

Table 1. Participant information.

	PWS			PWTF		
	Range	Median	IQR	Range	Median	IQR
Age (years)	19-45	29.5	25-34	20-44	28.5	25.25-32.75
Education (years)	10-22	17	14-18	13-24	18	17-19.75
SSI-4 score	16-40	28.5	22.25-31			
Age of stuttering onset (years)	3-10	4	3-6			

IQR = inter-quartile range

All PWS reported the onset of stuttering before 10 years old. Eighteen of the 28 PWS reported that they had received speech and language therapy over periods of time ranging from a few months to several years. No participants had received therapy within the last 6 months.

The University of Oxford Central University Research Ethics Committee approved the study. Participants gave informed written consent to participate in the study, in accordance with the Declaration of Helsinki, and with the procedure approved by the committee.

Experimental procedure

Prior to scanning, a researcher demonstrated how the pseudowords were pronounced and participants practised them aloud until they were accurate. This was achieved usually after three repetitions of the pseudoword set.

The pseudoword stimuli were those used by Smith et al (2010); three pseudowords of increasing length from 1-3 syllables (“mab” /mæb/; “mabshibe”, /mæbʃaIb/; “mabfieshabe” /mæbfaIʃeIb/) and two 4-syllable pseudowords with contrasting phonological complexity (“mabshaytiedoib”, /mæbʃeitaIdɔIb/; “mabteebeebee”, /mæbtibibi/). Pseudowords started with a bilabial sound. This was important for the analysis of lip aperture and identification of the start of the utterance.

During scanning, each pseudoword was read 10 times, in a random order. For each trial, the pseudoword was displayed on a screen and participants read it aloud at their natural speaking rate. Each trial lasted 3.5 seconds. In total, there were 50 trials resulting in a total scan run time of ~3 minutes.

MRI Acquisition

Data were collected on a 3T MRI system (Prisma, Siemens Healthineers) using a 64-channel head and neck receive array. Mid-sagittal images of the vocal tract from lips to larynx were acquired with in-plane spatial resolution of 2 mm x 2 mm using a radial FLASH sequence (TE/TR = 1.4/2.5ms) with golden angle sampling. Images were reconstructed at 33.3 frames per second using a second-order spatio-temporal total generalized variation constraint (Knoll, Bredies, Pock, & Stollberger, 2011).

Analysis procedure

The imaging data were reconstructed into a video format and analysed using a custom Matlab toolbox that uses grid-based, air-tissue boundary segmentation to track movements within the vocal tract (Kim et al., 2014). The schematic, below, shows the analysis pipeline (Figure 1).

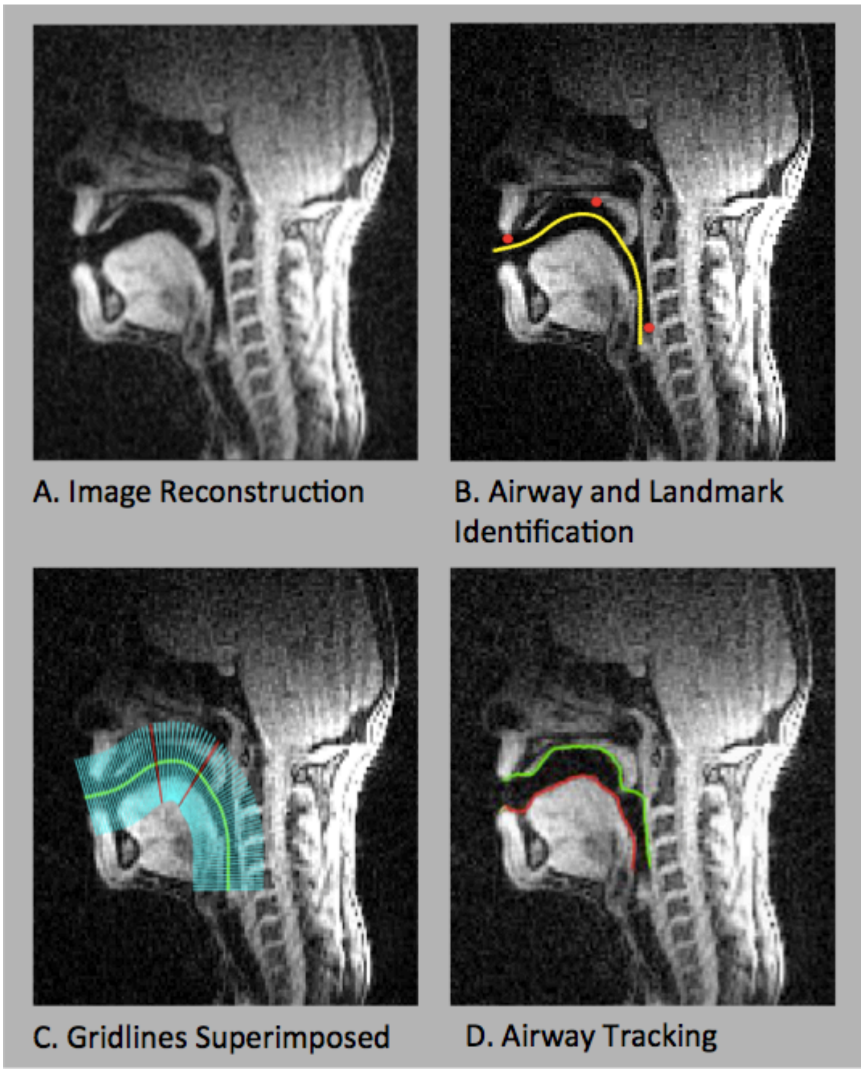

Figure 1. Image analysis pipeline. A: Example (single frame) of the reconstructed image. B: Using the air-tissue boundary toolbox (Kim et al., 2014), the airway was identified manually by drawing a line through the open vocal tract (yellow line). The lowest point of the upper lip, back of the hard palate and larynx were also identified manually (red dots). C: Equally spaced gridlines were placed orthogonal to the yellow line and centred on it. Gridlines highlighted in red were the ones used for tracking the tongue body and velum separately (see text). D: Tracking of air-tissue boundaries. Upper boundary shown in green; lower boundary shown in red.

Using the air-tissue boundary toolbox (Kim et al., 2014), the airway was identified manually by drawing a line through the open vocal tract (see yellow line, Fig. 1B). The lowest point of the upper lip, back of the hard palate and larynx were also identified manually (red dots in Fig. 1B). These points were used to guide the positioning of the grid. Gridlines were placed orthogonal to the midline of the vocal tract (green line, figure 1C) at 2mm intervals. The intersections of the upper and lower air-tissue boundaries with each gridline were identified based on an abrupt change in pixel intensity (where white pixels, tissue, met black pixels, air), interpolated, and smoothed to create two continuous boundary lines (red and green lines, Fig. 1D).

Lip aperture measurement

The distance between the first points along the upper and lower air-tissue boundaries gave the lip aperture in mm (see Fig. 1). The start of the utterance was identified as the latest time frame at which the lip aperture was zero for the /m/ sound. The end of the utterance was identified as the time frame that the lip aperture first returned to zero for the final bilabial closure of the word, e.g. /b/. An example of the lip aperture traces is shown in Figure 2.
Variability was calculated using the coefficient of variation (CoV); that is, the standard deviation of the size of the movements across 10 repetitions of each word, divided by the mean. The size was simply the sum of the aperture of the movements across frames capturing both the amplitude and duration of the movement. Movement duration was also averaged for each repetition by summing the total number of frames from the start to the end of the utterance as defined above.

Velum and Tongue Body measurements

Velum and tongue movements were measured in a similar way. For tongue body, the position of the lower air tissue boundary (shown in red, Fig. 1D) was tracked as it moved along a single gridline. We selected the gridline that was closest to the highest point of the dorsal boundary of the tongue body in the frame where the tongue reaches its most dorsal extent during the first /i/ sound of ‘mabteebeebee’. The lowest position of the tongue body along this gridline from the entire scan was selected as a reference point to which all frames were compared. For each frame, we measured the Euclidian distance from this reference point along the gridline to the position of the tongue body.

For the velum, the upper air-tissue boundary (ventral surface of the velum; shown in green, Fig. 1D) was tracked up and down a single gridline. This gridline was chosen as the closest to the middle of the velum, where the velum is seen to bend when raised, which corresponds to the position with the largest range of velum movement. The point at which this part of the velum was highest in the entire scan was selected as a reference point for the measurements made along this gridline in all other frames.

For the tongue body and the velum, the start and end frames of each utterance were the same as those used for the lip described above. Examples of the tongue body and velum movements are shown in Fig. 2.

The coefficient of variation for tongue and velum movements was determined as for the lip aperture.

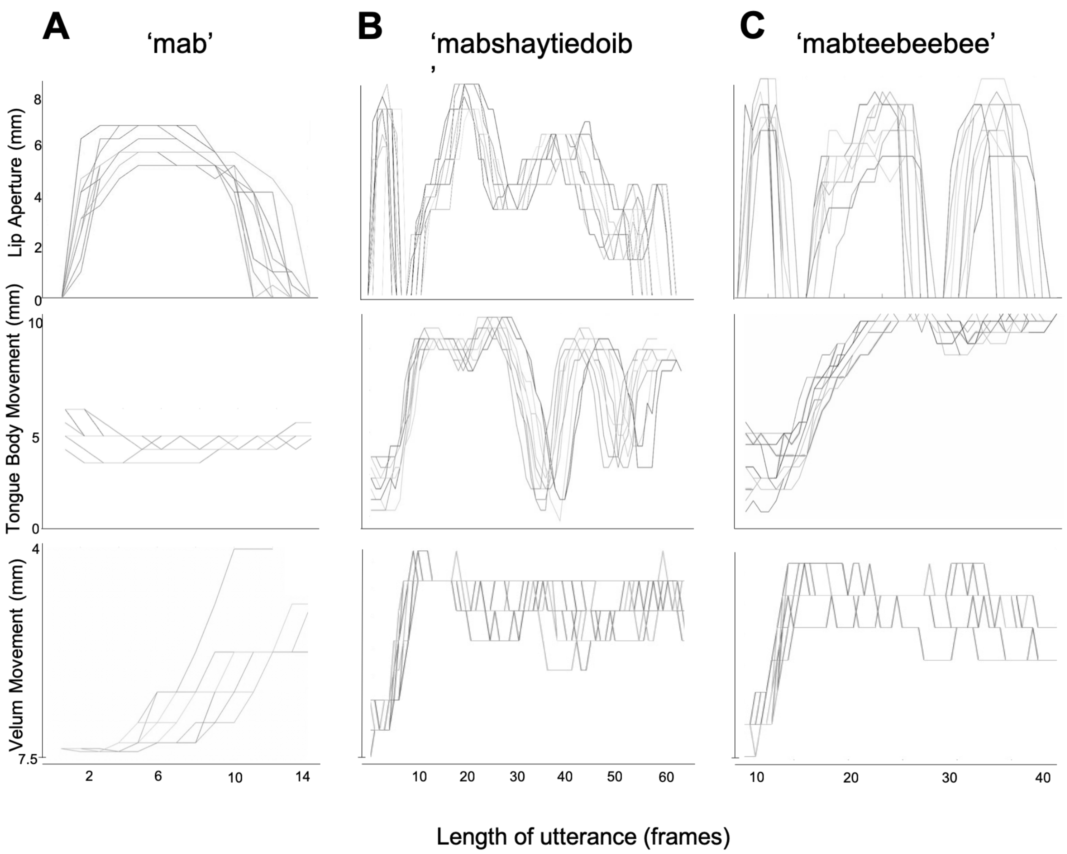

Figure 2. Examples of Movement Traces. Each plot shows 10 repetitions of the words (A) 'mab' and (B) 'mabshaytiedoib' and (C) 'mabteebeebee' for a single representative participant. Each line represents one repetition. The start and end points are defined as the frame where lip aperture departs from zero for the /m/ and returns to zero for the final /b/, respectively.

Analysis Plan

Errors made during the task, such as pronouncing the pseudoword incorrectly or stuttering during production of the pseudoword were rare. If a participant did not produce at least six (out of ten) fluent and accurate productions of a pseudoword, data for that pseudoword were excluded from analyses. Two full data sets (PWS) were excluded prior to analysis based on this criterion. Six PWS and two PWTF had partial data sets (missing data for one or more of the words). In total, 5.7% of words from the stuttering group and 4% of words from the control group were excluded. The exclusions were considered to be missing at random. Missing data is visualised in Fig. 4

We used linear mixed models (lme4 package in R; Bates, Mächler, Bolker, & Walker, 2015) to model interactions between group, word and articulator with subject included as a random factor. Importantly, linear mixed models are robust to a small amount of random missing data, allowing us to use data from nearly all our participants (Krueger & Tian, 2004).

Two linear mixed models were used to capture between-group differences in variability of speech movements in three separate articulators in relation to (i) word length (1 to 3 syllables) and (ii) phonological complexity (4-syllable complex and simple). Models included participant as random factor. For the group comparisons relating to duration, we used two additional models that did not include articulator as a fixed factor.

Main effects and interactions are reported using the 'anova' command from the base R stats package (R Core Team, 2019) with Type III Analysis of Variance using Satterthwaite's method (Luke, 2017). Full models (with comparisons between each factor for categorical variables) are shown in Supplementary Tables 1- 5. Marginal and conditional R^2 were calculated to represent the variability accounted for by the fixed effects alone and the fixed and random effects in the model, respectively. Normalized beta estimates were calculated using the *std beta* function of the *sjstats* package in R (Lüdecke, 2019) to facilitate comparison of effect sizes across the independent variables within each model.

Results

Movement variability

The amount of variability (CoV) for each pseudoword and participant in the two groups is plotted for each articulator in Fig. 3. The pattern of results across all articulators for each individual participant is shown in Fig. 4

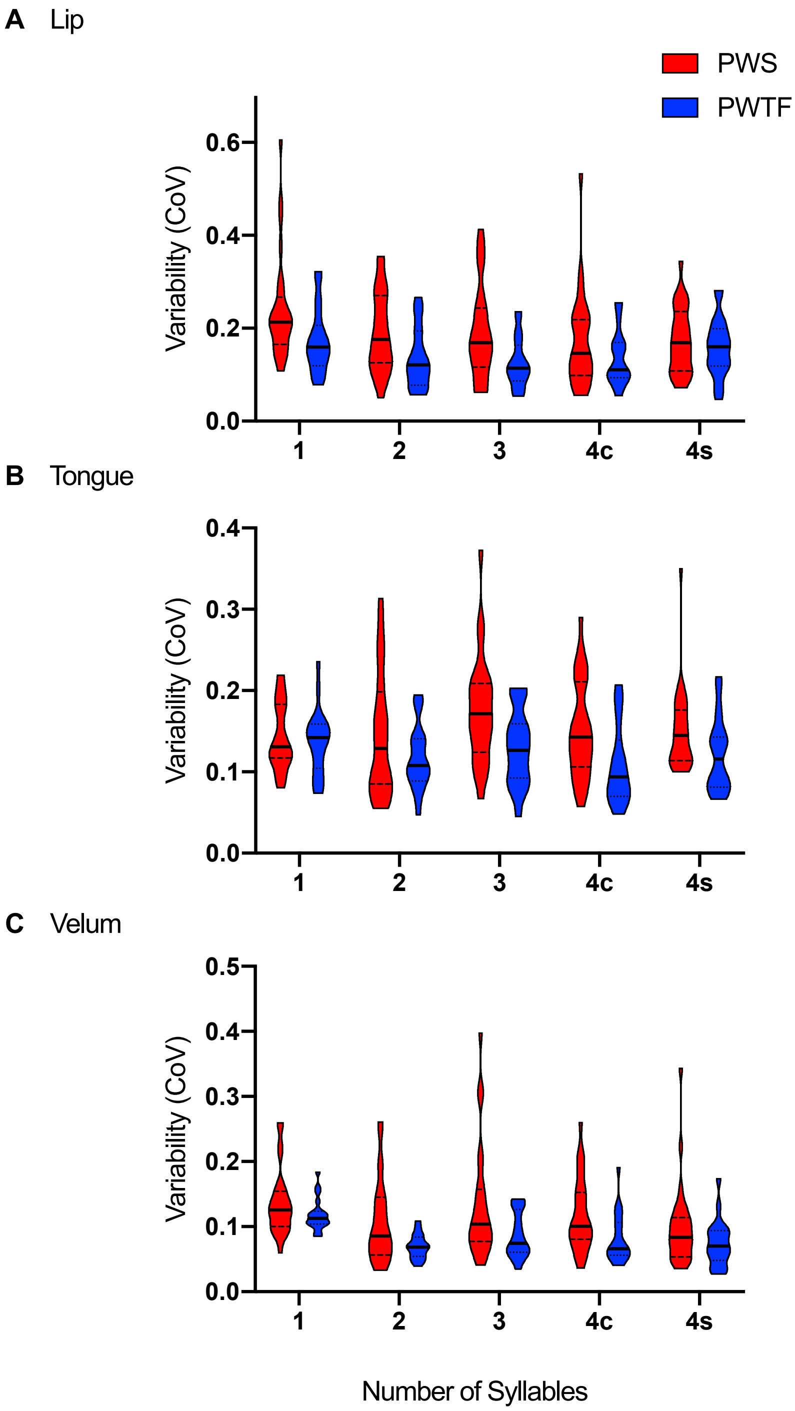

Figure 3. Variability of articulator movements over repeated utterances of the pseudoword set. CoV = coefficient of variation. PWS = People who stutter, PWTF = People who are typically fluent. 4c = 4-syllable, complex word ('mabshaytiedoib'), 4s = 4-syllable, simple word ('mabteebeebee'). Violin plots are shown to visualize the distribution of data and its probability density for each group separately for each syllable set. Solid horizontal lines represent the median and dashed lines show the inter-quartile range.

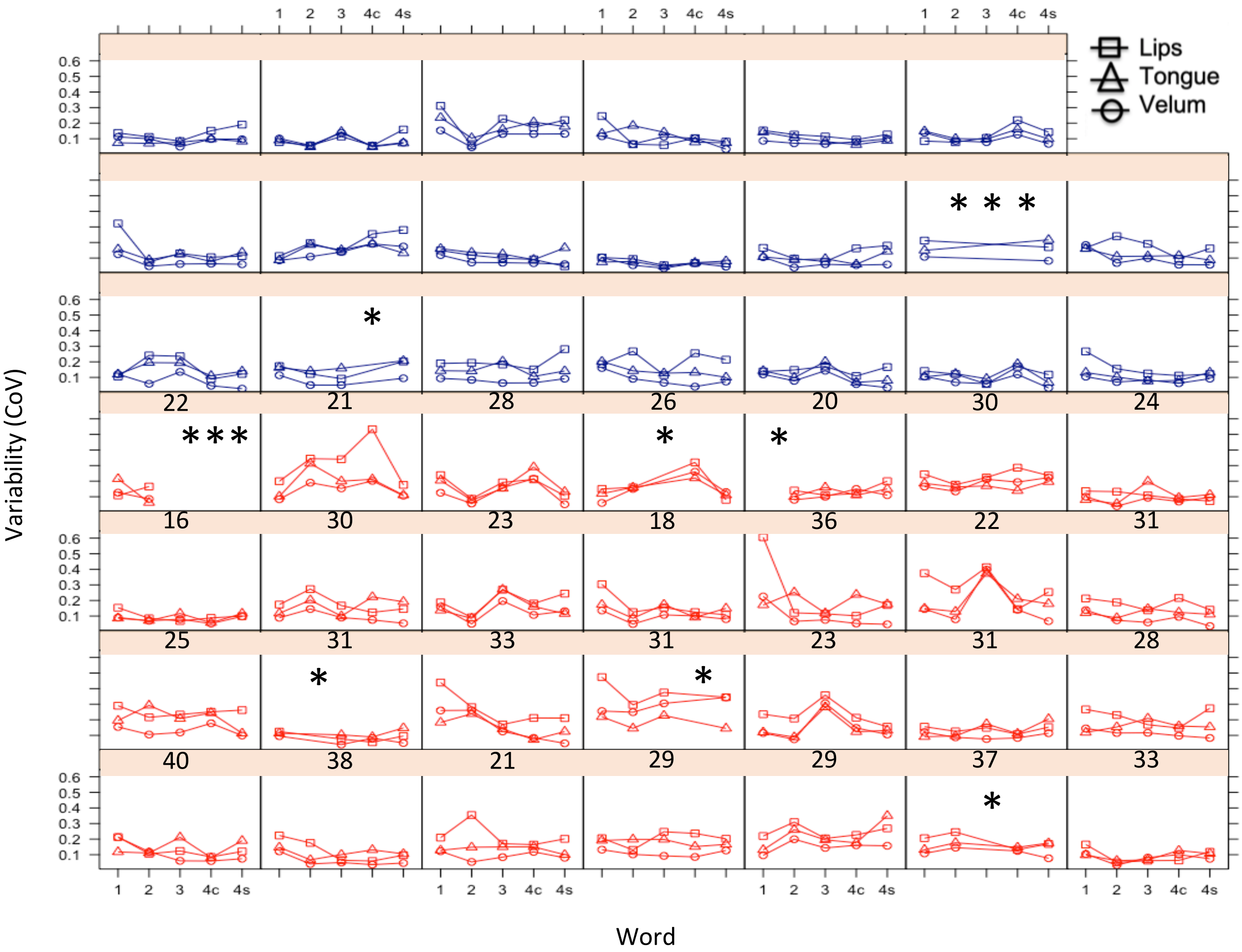

Figure 4. Individual variability scores for pseudowords with 1-3 syllables and the complex (4c) and simple (4s) 4-syllable pseudowords. Red participants = PWS, Blue participants = PWTF. Data from some participants are missing due to speech errors (see analysis plan, above). SSI scores are shown above individual data plots for PWS. * indicates data missing for one pseudoword.

We examined whether variability in speech movements during fluent repetitions of pseudowords differed between PWS and PWTF using two separate linear mixed-effects models. The dependent measure was the coefficient of variability for movement sizes in three different articulators for repetitions of (i) pseudowords of different syllable lengths (1, 2 and 3 syllables) or (ii) 4-syllable pseudowords of different phonological complexity (simple, complex). Fixed-effect terms in each model included group (PWS vs. PWTF), word (either 1, 2, and 3 syllables; or simple vs. complex), articulator (lips, tongue, and velum), and the group x pseudoword, group x articulator, pseudoword x articulator, and group x pseudoword x articulator interactions. The random-effects terms included participant, and the interaction of participant with the fixed-effects terms of group, word, and articulator.

Effect of pseudoword length on variability

The overall model predicting variability had a total explanatory power (conditional R^2) of 69.79%, in which the fixed effects explained 26.05% of the variance (marginal R^2). Within this model the main effects of group, word and articulator were significant. In addition, there was a significant interaction between group and articulator as well as between word and articulator. These interactions were explored using the full model results, which are presented in Supplementary Table 1.

PWS had significantly greater variability in their speech movements than PWTF (significant main effect of group ($F(1, 45.95) = 10.47$, $p = .002$). This group difference was greatest for lip compared with tongue (*$p < .001$)* and velum (*$p = .005$)* movements, which showed a similar size group difference (significant interaction between group and articulator; ($F(2, 262) = 6.05$, $p = .003$). For both groups, speech movement variability was greatest for repetitions of the one-syllable pseudoword relative to the two-syllable *($p < .001$)* and three-syllable pseudowords (*$p < .002$*), which did not differ (main effect of word ($F(2, 44.04) = 5.33$, $p = .008$). Movement variability was greatest for the lip relative to the tongue (*$p < .001$*) and velum (*$p < .001$*) movements, which did not differ (main effect of articulator ($F(2, 262) = 81.40$, $p < .001$). These last two factors interacted significantly (word x articulator interaction ($F(4, 262) = 6.60$, p <

.001) due to a more pronounced syllable length effect in the lip movements relative to movements of the tongue (*p < .001)* and velum (*p = .003).*

In sum, PWS had greater movement variability in general relative to PWTF and this effect was most pronounced in the lip movements. Pseudoword length did affect speech movement variability; it was maximal for repetitions of one-syllable pseudowords in both PWS and PWTF and the effect was most pronounced for lip aperture measurements.

The effect of phonological complexity on variability

The overall model predicting variability had a total explanatory power (conditional R^2) of 58.72%, in which the fixed effects explained 20.98% of the variance (marginal R^2). Within this model the main effect of group was significant. In addition, there was a main effect of articulator but there were no significant interactions. The full model output is presented in Supplementary Table 2.

PWS had significantly greater variability in their speech movements than PWTF (significant main effect of group (F(1, 39.5) = 6.08, *p* = .018) and this group difference was seen for the movements measured in lip, tongue, and velum (interaction with articulator was not significant). For both groups, speech movement variability was greatest for the lip relative to the tongue (*p = .008*) and velum (*p < .001*) movements, which did not differ (main effect of articulator (F(2, 174) = 88.71, p < 0.001). Phonological complexity did not affect speech movement variability in either PWS or PWTF or in any of the articulators measured (main effect of word was not significant and did not interact with any other factor).

In addition, the relationship between lip movement variability data and SSI was assessed for the pseudoword ('mabshaytiedoib'). We selected this pseudoword a priori for this analysis as it is the most complex. There was no correlation between variability score and SSI score (r = -1.39, p = .177).

In sum, as for the previous analysis of the shorter pseudowords described above, PWS had greater movement variability in general relative to PWTF. For both PWS and PWTF, movement variability across repeated utterances of 4-syllable pseudowords was most pronounced in the lip aperture measurements. Speech movement variability was not affected by phonological complexity. In addition, there was no relationship between variability and stuttering severity.

2. Movement Duration

The duration of responses for repetitions of each pseudoword and participant in the two groups is plotted in Fig. 5.

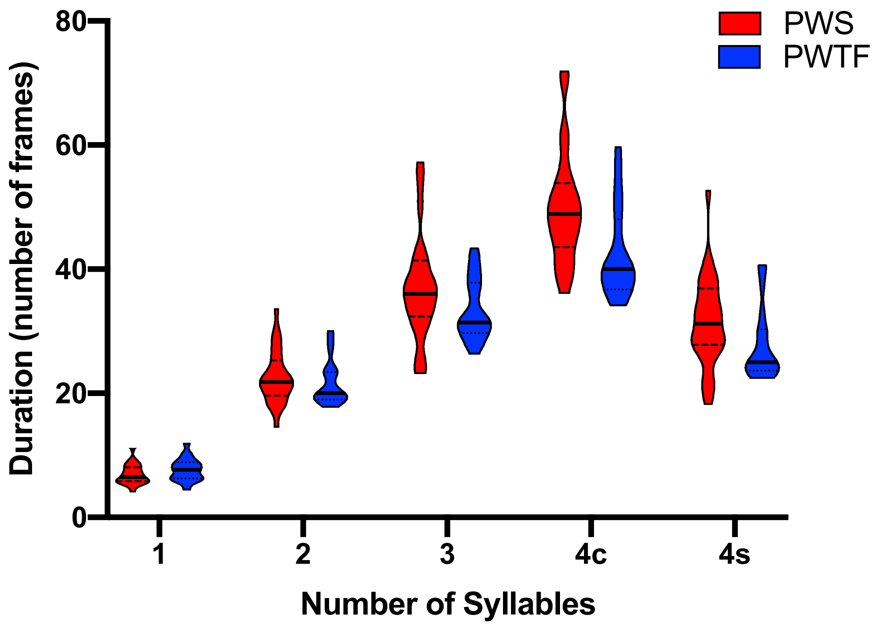

Figure 5. Duration of responses. See legend to Fig. 3 for details.

We examined whether movement durations during fluent repetitions of pseudowords differed between PWS and PWTF using a linear mixed-effects model to compare pseudowords of different syllable lengths. A similar model was run for the four syllable words to compare phonological complexity. Fixed-effect terms in each model included group (PWS vs. PWTF) and word (either 1, 2, and 3 syllables; or simple vs. complex), and the group x word interactions. The random-effects terms included participant, and the interaction of participant with the fixed-effects terms of group and word.

The overall model predicting duration had a total explanatory power (conditional R^2) of 93.79%, in which the fixed effects explain 85.67% of the variance (marginal R^2). Within this model, the main effect of word was significant (note: this was highly expected as words with more syllables were expected to have longer durations). In addition, there was a significant interaction between group and word (see Fig. 5). This interaction was explored using the full model results, which are displayed in Supplementary Table 3. The main effect of group was not significant.

PWS had significantly longer speech movement durations than PWTF when repeating the 2- ($p = .017$) and 3-syllable words ($p < .001$) compared with the 1-syllable word, and the 3-syllable pseudoword compared with the two-syllable pseudoword ($p < .001$) (significant interaction between group and word ($F(2,361.8) = 15.6$, $p < .001$); see Fig. 5). For both groups, movement durations were longest for repetitions of the 3- compared with the 2- ($p < .001$) and the 1-syllable pseudowords ($p < .001$) and were longer for the 2- compared with the 1-syllable pseudowords ($p < .001$) (significant main effect of word ($F(2,361.8) = 2618.1$, $p < .001$). The main effect of group was not significant.

The effect of phonological complexity on duration

The overall model predicting duration had a total explanatory power (conditional R^2) of 94.37%, in which the fixed effects explained 56.79% of the variance (marginal R^2). The full model results are displayed in Supplementary Table 4. PWS had significantly longer movement durations than PWTF for repetitions of 4-syllable pseudowords ($p = 0.004$). This group difference was significantly more pronounced for repetitions of the complex relative to the simple pseudowords ($p < .001$) (significant interaction between group and word). For both PWS and PWTF, speech movement durations were significantly longer for repetitions of the complex relative to the simple 4-syllable pseudowords ($p < .001$).

In sum, PWS show longer speech movement durations relative to PWTF. These group differences emerge only for repetitions of multi-syllabic pseudowords and were even more pronounced when the phonological complexity was increased. Expectedly, durations were longer for both groups when the number of syllables or the phonological complexity increased.

Discussion

We tested whether there were differences in articulator movements during perceptually fluent speech between people who stutter (PWS) and people who are typically fluent (PWTF). We used a novel method, MRI of the vocal tract, to capture movement of the lips, tongue body and velum of 26 PWS and 20 PWTF as they repeated pseudowords. The pseudowords were designed to determine the effects of word length (1-3 syllables) and phonological complexity (Smith et al., 2010). We found differences in the variability of articulator movement and duration of responses between PWS and PWTF. Overall, the stuttering group repeated the utterances with more variability than the control group but this effect did not interact with pseudoword length or phonological complexity. There was a main effect of pseudoword length that was driven by higher variability scores for the 1-syllable relative to the 2- and 3-syllable pseudowords. In addition, there was a main effect of articulator, accounted for by lower variability for velum movements compared with both the lip and tongue movements. There was no relationship between variability score and stuttering severity. We found an interesting interaction between pseudoword length and group for the duration measurement, such that PWS repeated utterances more slowly than PWTF as pseudoword length and phonological complexity increased. This work supports previous investigations of speech motor control in PWS showing a greater amount of variability in the fluent speech movements of PWS compared to PWTF (Frisch et al., 2016; Howell et al., 2009; Jackson et al., 2016; Loucks & De Nil, 2006, 2012; Loucks et al., 2007; Sasisekaran, 2013; Smith et al., 2010). We also extend previous findings by measuring articulators that, until now, have been difficult to capture due to their position within the vocal tract. Vocal tract MRI is shown to be a useful tool for measuring movements within the vocal tract with good temporal and spatial precision that is sensitive enough to measure subtle differences in speech motor control between typical and clinical groups.

The results of the current study reveal a strong effect of group on variability with PWS repeating pseudowords with greater variability than control participants. However, in contrast to previous findings, we did not find that complexity of the utterance (pseudoword length or phonological complexity) had an effect on the variability of utterances that was larger for PWS than PWTF (Kleinow & Smith, 2000; Smith et al., 2010; Soderberg, 1966). Instead we found a main effect of pseudoword length that was driven by higher variability for the shortest word compared with longer pseudowords. This was surprising; we expected that the shortest pseudoword should have the least amount of variability compared with longer pseudowords. Taken together, our results indicate that PWS have greater variability than PWTF even during short, simple utterances, possibly more so. It may be that the current study had greater sensitivity to detect differences during short, simple utterances compared with previous work due to the large number of participants (N=26). However, this does not explain why, in the current study, the shortest pseudoword was repeated with greater variability than the other longer pseudowords across both group and articulator. Replication of this latter effect is warranted.

A key difference in this study compared with the previous one (Smith et al., 2010), which used the same stimuli, was the measure used to capture variability of the movements. The previous study used the spatio-temporal index (STI; Riley, 2009) and here, we used the coefficient of variation (CoV). The key difference between these methods is that the STI uses normalisation to remove information regarding the amplitude and duration variability in order to determine variability of the relative timing of the articulator movement. In contrast, CoV captures variability in amplitude and duration, and normalises for the increased length of the word (as the standard deviation, is divided by the mean of the utterance). This enables direct comparison of variability across pseudowords of different lengths. In our opinion, these differences are unlikely to explain the subtle differences in results between the two studies.

In addition to measuring the lip aperture to replicate previous work, we aimed to measure the movement of articulators that were previously difficult to measure non-invasively due to their positioning within the vocal tract (tongue and velum). This exploits the benefits of vocal tract MRI. In addition to the lip aperture, we also measured variability for the tongue body and the velum. There was a strong correlation between the amount of variability for each of the articulators, but overall, there was less variability for velum movements compared with both lip and tongue movements. This effect of articulator may be due to the different involvement of the articulators in each of the utterances. The pseudowords were taken from a previous study and were designed to contain bi-labial sounds (lip closures) in order to capture the movements of the lips. The lack of nasals in this specific pseudoword set reduced the amount of velum movement required to produce the utterances. Overall our results suggest that variability generalises across articulators (e.g. if participants had high variability for the lips, they were likely to have high variability for the velum and tongue as well).

Importantly, many PWS have levels of variability that are within the range of PWTF. This means that increased variability cannot be considered a diagnostic characteristic of developmental stuttering. Instead, there could be subtypes within PWS whereby reduced control over the articulators is characteristic of a subset of PWS, only. Interestingly, these potential subgroups are not explained by severity of stuttering, as there was no relationship between severity (SSI score) and variability.

Variability is thought to represent a general measure of speech motor control, in which random noise is inserted into the motor plan at some stage prior to execution. It is thought that this noise comes from altered communication within the nervous system; from planning to execution of speech. For example, reduced connectivity between sensory and motor regions of the brain in PWS compared with PWTF may introduce noise at the neural level (Connally, Ward, Howell, & Watkins, 2014; Neef, Anwander, & Friederici, 2015; Neef et al., 2011; Watkins, Smith, Davis, & Howell, 2008). However, it is clear that this noise cannot be pinned to one specific process within the nervous system using measures of kinematic variability. In addition, this noise may also be caused by cognitive or social factors. Variability, as measured here, can tell us about general differences in the control of speech movements between PWS and PWTF but cannot reveal the source of such variability.

As well as there being ambiguity about the source of variability, it is unclear whether greater variability has further implications for stuttering. Hypotheses that predict differences in the feedforward and feedback control of speech (Bohland, Bullock, & Guenther, 2010; Guenther, 2016; Max, Guenther, Gracco, Ghosh, & Wallace, 2004) propose that stuttering is caused by a discrepancy between the expected utterance (sensory and auditory predictions) and the actual utterance produced. An error signal may be produced in two ways; either the predictive space is typical, but the movements fall outside of this range or the movements are the same, but the prediction space is smaller, resulting in less tolerance of varied movements. Our data support the first prediction: more variability may lead to greater chance that the sensory-motor feedback will not match with a predicted response resulting in an error signal. The error signal generated may cause an inhibitory response, leading to a block, repetition or prolongation of the sound. Thus, even though our analysis was restricted fluent utterances, it is hypothesised that more variable movements increase the likelihood that the system will act to inhibit speech.

Our data failed to reveal a simple linear relationship between the amount of variability and stuttering severity. This may be explained by the fact that SSI measures a range of characteristics of stuttering, including duration of stuttered moments and physical concomitants. In addition, stuttering severity is known to be affected by factors beyond speech motor control, such as learned anxiety in response to stuttering (Alm, 2014).

The relationship between variability and severity may be further complicated by compensation strategies. For example, PWS may reduce their speech rate in order to maintain fluency (Andrews, Howie, Dozsa, & Guitar, 1982). As greater demands are placed on the speech motor system, it could be that PWS compensate by slowing down their speech (Max, Caruso, & Gracco, 2003; Peters, Hulstijn, & Starkweather, 1989; Van Lieshout, Hulstijn, & Peters, 1996). Our data support this hypothesis: some PWS produced utterances with longer durations than PWTF but only when the pseudowords became more complex (either due to more syllables or phonological complexity). Slowing speech rate would allow accumulation of evidence from feedback (sensory reafference) (Watkins, Chesters, & Connally, 2016). This may be an automatic response at the neural level or could represent a conscious effort to maintain fluency. Fluency-enhancing techniques such as altering auditory feedback, choral speaking, and singing all typically involve slower production and speech and language therapies often focus on slowing speech rate in order to improve fluency. The participants in our study received therapy, some of which targeted speech rate. It is therefore plausible that some PWS consciously slow down their speech when the utterance becomes more difficult. Future studies should examine the effect of slowing down speech rate on variability.

In summary, we part-replicated previous findings that show PWS have greater variability in the movements of the articulators during fluent utterances compared with PWTF (Kleinow & Smith, 2000; Smith et al., 2010). In addition, we extended our previous knowledge by exploiting the benefits of vocal tract MRI to measure multiple articulators within the vocal tract. Our results show that vocal tract MRI is sensitive to subtle differences in articulator movement between PWS and PWTF, even during perceptually fluent speech.

Declarations of interest: none

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Supplementary Materials

Full model outputs

Table 1 Effect of word length on variability

Predictors	std. Beta	Estimates	Variability (CoV) CI	p
(Intercept)		0.24	0.22 – 0.26	**<0.001**
Group PWS:PWTF	-0.14	-0.07	-0.11 – -0.03	**<0.001**
Word 1:2	-0.10	-0.05	-0.08 – -0.02	**0.001**
Word 1:3	0.22	-0.05	-0.09 – -0.02	**0.002**
Word 2:3	0.05	0.03	-0.01 – 0.06	0.102
Articulator Lip:Velum	0.09	-0.10	-0.13 – -0.08	**<0.001**
Articulator Lip:Tongue	-0.33	-0.10	-0.12 – -0.08	**<0.001**
Articulator Velum:Tongue	-0.09	0.01	-0.02 – 0.03	0.611
Group PWS:PWTF * word 1:2	0.08	0.02	-0.03 – 0.06	0.490
Group PWS:PWTF * word 1:3	-0.64	0.01	-0.04 – 0.06	0.778
Group PWS:PWTF * word 2:3	0.23	-0.01	-0.06 – 0.04	0.688
Word1:2 * Lip:Velum	0.03	0.02	-0.01 – 0.05	0.181
Word1:3 * Lip:Velum	0.36	0.05	0.02 – 0.08	**0.003**
Word2:3 * Lip:Velum	-0.08	0.03	-0.01 – 0.06	0.098
Word1:2 * Lip:Tongue	-0.09	0.05	0.02 – 0.09	**0.001**
Word1:3 * Lip:Tongue	0.29	0.09	0.06 – 0.12	**<0.001**
Word2:3 * Lip:Tongue	0.11	0.03	0.00 – 0.07	**0.040**
Word1:2 * Velum:Tongue	0.06	0.03	-0.00 – 0.06	0.051
Word1:3 * Velum:Tongue	0.13	0.04	0.01 – 0.07	**0.021**
Word2:3 * Velum:Tongue	0.08	0.01	-0.03 – 0.04	0.691
Group PWS:PWTF * Lip:Velum	-0.33	0.05	0.02 – 0.09	**0.005**
Group PWS:PWTF * Lip:Tongue	-0.44	0.06	0.03 – 0.10	**<0.001**
Group PWS:PWTF * Velum:Tongue	-0.12	0.01	-0.02 – 0.05	0.489
Group PWS:PWTF * Word 1:2 * Lip:Velum	-0.61	-0.03	-0.08 – 0.02	0.189
Group PWS:PWTF * Word 1:3 * Lip:Velum	0.36	-0.03	-0.08 – 0.02	0.179

Group PWS:PWTF * Word 2:3 * Lip:Velum	0.00	0.00	-0.05 – 0.05	0.968
Group PWS:PWTF * Word 1:2 * Lip:Tongue	-0.09	-0.04	-0.09 – 0.01	0.168
Group PWS:PWTF * word 1:3 * Lip:Tongue	0.29	-0.05	-0.10 – -0.00	**0.045**
Group PWS:PWTF * Word 2:3 * Lip:Tongue	0.10	-0.02	-0.07 – 0.03	0.527
Group PWS:PWTF * Word 1:2 * Velum:Tongue	0.64	-0.00	-0.05 – 0.05	0.949
Group PWS:PWTF * Word 1:3 * Velum:Tongue	0.09	-0.02	-0.07 – 0.03	0.509
Group PWS:PWTF * Word 2:3 * Velum:Tongue	-0.04	-0.02	-0.07 – 0.04	0.553
Random Effects				
Marginal R^2			0.261	
Conditional R^2			0.698	
$N_{participant}$			48	
Observations			411	

R formula = variability ~ group * word * articulator + (1 + word | p_code), REML = TRUE, contrasts = contra.sum)

Table 2. Effect of phonological complexity on variability.

		Variability (CoV)		
Predictors	*Std. Beta*	*Estimates*	*CI*	*p*
(Intercept)		0.18	0.15 – 0.20	**<0.001**
Group PWS:PWTF	-0.26	-0.04	-0.08 – 0.00	0.077
Word 4c:4s	-0.04	-0.00	-0.03 – 0.03	0.932
Articulator Lip:Velum.	-0.11	-0.05	-0.08 – -0.03	**<0.001**
Articulator Lip:Tongue	-0.15	-0.02	-0.05 – 0.00	0.086
Articulator Velum:Tongue	0.11	0.03	0.01 – 0.06	**0.008**
Group PWS:PWTF * Word 4c:4s	-0.38	0.02	-0.02 – 0.07	0.382
Word 4c:4s * Lip:Velum	-0.01	-0.02	-0.05 – 0.02	0.275
Word 4c:4s * Lip:Tongue	0.00	-0.00	-0.04 – 0.03	0.894
Word 4c:4s * Velum:Tongue	0.00	0.02	-0.02 – 0.05	0.337
Group PWS:PWTF * Lip:Velum	-0.02	0.00	-0.04 – 0.04	0.981
Group PWS:PWTF * Lip:Tongue	-0.01	-0.01	-0.05 – 0.03	0.714
Group PWS:PWTF * word 4c:4s * Lip:Velum	-0.02	-0.01	-0.06 – 0.04	0.706
Group PWS:PWTF * word 4c:4s * Lip:Tongue	0.12	-0.01	-0.06 – 0.05	0.822
Group PWS:PWTF * Word 4c:4s * Velum:Tongue	0.04	0.00	-0.05 – 0.06	0.878
Random Effects				
Marginal R^2		0.210		
Conditional R^2		0.587		
$N_{participant}$		47		
Observations		273		
R formula = variability ~ group * word * articulator + (1 + word | p_code), REML= TRUE, contrasts = contra.sum				

Table 3. Effect of word length on duration

		Mean Duration (frames)		
Predictors	*Std. Beta*	*Estimates*	*CI*	*p*
(Intercept)		6.87	5.46 – 8.29	**<0.001**
Group PWS:PWTF	0.03	0.82	-1.37 – 3.00	0.465
Word 1:2	0.63	15.75	14.83 – 16.67	**<0.001**
Word 1:3	1.12	28.57	27.62 – 29.52	**<0.001**
Word 2:3	0.5	12.82	11.87 – 13.76	**<0.001**
Group PWS:PWTF * Word 1:2	-0.05	-1.74	-3.16 – -0.31	**0.017**
Group PWS:PWTF * Word 1:3	-0.12	-4.10	-5.54 – -2.66	**<0.001**
Group PWS:PWTF * Word 2:3	-0.07	-2.36	-3.81 – -0.92	**0.001**
Random Effects				
Marginal R^2		0.857		
Conditional R^2		0.938		
N $_{participant}$		48		
Observations		411		
R formula = mean_duration ~ group * word + (1 | p_code), REML = TRUE, contrasts = contr.sum				

Table 4. Effect of phonological complexity on duration

		Mean Duration (frames)		
Predictors	*Std. Beta*	*Estimates*	*CI*	*p*
(Intercept)		49.33	46.55 – 52.10	**<0.001**
group PWS:PWTF	-0.26	-6.21	-10.47 – -1.96	**0.004**
Word 4c:4s	-0.77	-17.82	-18.69 – -16.95	**<0.001**
Group PWS:PWTF * word 4c:4s	0.09	2.51	1.15 – 3.87	**<0.001**
Random Effects				
Marginal R^2		0.568 /		
Conditional R^2		0.944		
N $_{p\_code}$		47		
Observations		273		
R formula = mean_duration ~ group * word + (1 | p_code), REML = TRUE, contrasts = contr.sum				