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Research Article

Conflicting Evidence for a Motor Timing Theory of Stuttering: Choral Speech Changes the Rhythm of Both Neurotypical and Stuttering Talkers, but in Opposite Directions

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ABSTRACT

Purpose: Talking in unison with a partner, otherwise known as choral speech, reliably induces fluency in people who stutter (PWS). This effect may arise because choral speech addresses a hypothesized motor timing deficit by giving PWS an external rhythm to align with and scaffold their utterances onto. This study tested this theory by comparing the choral speech rhythm of people who do and do not stutter to assess whether both groups change their rhythm in similar ways when talking chorally.

Method: Twenty adults who stutter and 20 neurotypical controls read a passage on their own and then a second passage chorally with a neurotypical partner. Their speech rhythm was evaluated using Envelope Modulation Spectrum (EMS) analysis to derive peak frequency, a measure of the dominant rate of modulation in the sound envelope, as well as peak amplitude (the amplitude of the peak frequency), across several octave bands associated with different features of speech.

Results: The two groups displayed opposing patterns of rhythmic change during choral reading. People with a stutter increased their EMS peak frequency when they read chorally, while neurotypical talkers' choral speech was characterized by reduced peak frequency compared to solo reading.

Conclusions: Our findings show that the choral speech rhythm of PWS differs from that of neurotypical talkers. This indicates limited support for the hypothesis that choral speech addresses a motor timing deficit by giving PWS a rhythmic cue with which to align.

Persistent developmental stuttering is a lifelong neurological condition affecting around 1% of adults worldwide (Yairi & Ambrose, 2013). This condition, which is characterized by syllable repetitions, prolongations, and silent "blocks" during speech, can cause communication difficulties with potentially far-reaching effects on well-being and quality of life (Craig et al., 2009). Although there is no "cure" for stuttering, people who stutter (PWS) do experience periods of relative fluency (Bloodstein, 1949; Bloodstein et al., 2021). Although these periods are often spontaneous and unpredictable, many PWS report that they are also reliably more fluent in specific situations (Bloodstein, 1950; Budde et al., 2014). Understanding which situations induce fluency, and the mechanism by which they do so, may provide insights into the etiology of stuttering and inform therapies.

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Fluency-enhancing situations vary considerably from person to person, with participants reporting reduced stuttering in conditions ranging from "speaking to an animal" to “when under fire during the war” (Bloodstein, 1950). However, researchers have noted that many tactics that are commonly observed to reduce stuttering induce a different speech rhythm. For example, a large body of evidence demonstrates reliable increases in fluency when PWS speak in time with a metronome (Hutchinson & Norris, 1977; Toyomura et al., 2011), another speaker (Rami & Diederich, 2005; Saltuklaroglu et al., 2009), or other rhythmic activities such as walking, arm swinging or foot tapping (Andrews et al., 1982; Barber, 1939; Bloodstein, 1950).

This evidence has led some researchers to suggest that stuttering is a manifestation of an underlying difficulty with the initiation and timing of complex rhythmic motor gestures (Etchell et al., 2014; Max et al., 2003). Rhythmic stimuli thus act as a “pace-setting” mechanism that induces fluency by introducing an external signal to align with, so that the talker need not struggle to generate their own rhythmic patterns (Dechamma & Maruthy, 2018; Pattie & Knight, 1944). This theory appears to be supported by research demonstrating that PWS show increased variability in rhythmic movement such as finger tapping (Sares et al., 2019; Slis et al., 2023) and differences in lip, jaw, and vocal tract movement (McClean et al., 2004; Wiltshire et al., 2021) compared to typical speakers, although other work has found no difference between PWS and controls for simple isochronous rhythm production tasks (Max & Yudman, 2003).

Choral speech, in which talkers read or recite words in unison, is known to be among the most effective ways to induce this “rhythm effect” on fluency (e.g., Andrews et al., 1982; Barber, 1939; Kalinowski & Saltuklaroglu, 2003). Reading chorally immediately and dramatically reduces stuttering frequency and duration by between 90% and 100% compared to solo speech (Dechamma & Maruthy, 2018; Kiefte & Armson, 2008; Meekings et al., 2023) and is more effective than other commonly used fluency enhancing manipulations such as altered auditory feedback (Kiefte & Armson, 2008) or speaking in time with other rhythmic stimuli (Barber, 1939; Bloodstein, 1950). This, therefore, offers an ideal paradigm with which to investigate the “pace-setting” theory.

If PWS experience difficulties generating and sequencing motor speech gestures, and speaking chorally induces fluency because it provides an external signal for PWS to synchronize with, then

1. The speech rhythm of PWS should change when they read chorally.
2. This change in rhythm should be correlated with increased fluency.
3. The change in rhythm should also match that of typical controls.

Previous work supports the first two elements of this hypothesis: choral reading changes the speech rhythm of PWS, and this change in rhythm is associated with improvements in fluency (Dechamma & Maruthy, 2018; Meekings et al., 2023). When neurotypical talkers speak chorally, their speech also changes in relatively consistent ways that make their rhythm more predictable, for example, by regularizing vocalic interval durations (Cerda-Oñate et al., 2021; Cummins, 2009). If PWS use their partner’s speech as a rhythmic guide during choral reading, then it is to be expected that their speech rhythm will also become more predictable, similar to that of typical talkers during choral speech.

However, studies into the choral speech rhythm of PWS have not evaluated the choral speech rhythm of a neurotypical control group, while studies into neurotypical choral speech have typically used duration-based measures that may be skewed by disfluencies, meaning that it is difficult to compare these results to the population of PWS. Additionally, Meekings et al. (2023) found that while one measure of rhythm (Envelope Modulation Spectrum [EMS] peak frequency) correlated with induced fluency, the “rhythmic signature of choral speech”—a combination of acoustic metrics that most reliably characterized the choral speech of PWS—did not significantly predict fluency in choral speech. It thus remains unclear whether these changes in speech rhythm are the result of copying neurotypical talkers, or whether choral speech induces fluency by some other means, which then causes differences in speech rhythm (since fluent speech is by definition rhythmically different from stuttered speech). To establish a causal link, it is necessary to compare the choral speech behavior of PWS with that of neurotypical controls.

In this article, we use EMS analysis to characterize speech rhythm during choral reading in PWS and neurotypical controls. The envelope of speech contains multiple regular amplitude fluctuations corresponding to, for example, patterns of word stress, or syllable durations. EMS analysis quantifies the periodicity of these slow modulations in the amplitude envelope of speech by Fourier transforming the envelope to derive a “rhythm spectrum” that has peaks in frequencies that correspond to repeating patterns (Tilsen & Johnson, 2008). These spectra are computed for the full signal and for octave bands centered around frequencies from 125 to 8000 Hz; each band contains independent information about rhythmic patterns at different levels of the speech signal, such as syllables, vowels or bursts, and fricatives (Crouzet & Ainsworth, 2001; Liss et al., 2010), although the exact correspondence between envelope measures and phonetic features is still under investigation (MacIntyre et al., 2022).

In contrast to duration-based measures of rhythm, such as speech rate, EMS metrics are not skewed by characteristic features of atypical speech such as long silent pauses (White & Mattys, 2007), meaning that the analysis can be applied to the whole speech signal with no need to remove potentially significant disfluencies (Liss et al., 2010). Previous research has used this approach to investigate atypical speech patterns in people with dysarthria (Liss et al., 2010), apraxia of speech (Basilakos et al., 2017), and PWS (Dechamma & Maruthy, 2018; Meekings et al., 2023).

There are several different metrics that can be derived from the EMS, but here, we focus on peak frequency and peak amplitude. The "rhythm spectrum" generated by EMS analysis contains multiple peaks, each representing the frequency at which a particular amplitude modulation repeats itself. The peak with the highest amplitude is the most periodic pattern. Measuring the frequency at which that peak occurs tells us the overall dominant rate of modulation in the signal, while its amplitude tells us how dominant that pattern is. These metrics have been used in previous research on this subject (Dechamma & Maruthy, 2018; Meekings et al., 2023). Specifically, these studies found that choral speech in PWS was associated with an increase in both fluency and mean peak frequency across several octave bands compared to solo speech. Dechamma and Maruthy (2018) additionally found that PWS's mean peak amplitude was lower during choral speech than solo reading. Meekings et al. (2023) also identified six EMS metrics that, in combination, significantly predicted whether a participant was speaking chorally or not. These metrics were peak frequency in the 125 Hz, 1 kHz, and 2 kHz octave bands, energy between 4 and 10 Hz in the 4 kHz band, energy between 3 and 6 Hz in the full band, and ratio of the energy above and below 4 Hz in the 8 kHz band. Although the weighted linear combination of these variables that predicted choral speech rhythm did not significantly predict fluency, these results do suggest that EMS peak frequency across multiple bands is an important component of choral speech rhythm.

To sum up, this study aims to evaluate the theory that PWS become more fluent when they speak chorally because they adopt the same choral speech patterns as neurotypical talkers. If this is true, we expect to see both groups' speech rhythm (measured using EMS mean peak frequency) become more similar during choral reading compared to solo speech. If, however, rhythmic changes are caused by fluency rather than vice versa, we might expect the choral speech rhythm of PWS to look more similar to the fluent speech of neurotypical talkers when they speak nonchorally.

Even if PWS and neurotypical controls use different speech rhythms when talking chorally, it may be the case that the choral speech task induces more consistent speech rhythm in both partners, which in itself is an aid to fluency. To assess this, we look at changes in peak amplitude: we expect speech that is more consistent in its rhythm to have higher peak amplitude.

Method

Ethical approval for this study was granted by the University College London (UCL) Psychology Ethics Committee for the group of PWS (Approval ID: ICN-PWB-13-12-13) and the University of York Psychology Ethics Committee for the neurotypical controls (Approval ID: 2212).

Participants

PWS and neurotypical participants were recruited and tested separately at UCL and the University of York, respectively. All participants were adult British English speakers with normal hearing.

Twenty-five PWS (17 men, eight women; M_{age} = 37.5 years) were recruited through STAMMA, the British Stammering Association, as part of a larger neuroimaging study (Meekings et al., 2020). They were paired with one of four experimenters to complete the choral speech task; the experimenters' voice was not recorded. All participants were adults who self-identified as PWS. Their speech was assessed using Riley's Stuttering Severity Instrument–Fourth Edition (SSI-IV; Riley, 1972), and participants were included in the final analysis if they had a stutter of any severity as defined by the SSI-IV. Their SSI-IV scores ranged from 6 to 44 out of a possible 46 (M = 23.4). Thirty-six neurotypical controls (27 women; seven men; two nonbinary persons; M_{age} = 20.3 years) were recruited through the University of York and completed the task in pairs; both partners' voices were recorded.

Participants and choral speech pairs were not controlled for gender as this has not been found to influence choral speech behavior (Poore & Ferguson, 2008). Hearing threshold was assessed using an Amplivox 116 Screening Audiometer with Audiocup headphones. Participants were included if their binaural four-frequency pure-tone average hearing threshold was 20 dB HL or less. One participant with a stutter did not meet this threshold and was excluded from the analysis. All other participants had normal hearing. Additional four PWS and eight neurotypical pairs' data were excluded due to recording quality issues. More details on the reasons for exclusion are given in the Analysis section below. Thus, 20 neurotypical participants (15 women, three men, two nonbinary persons) aged between 18 and 26 years (M = 20.1, SD = 1.8) and 20 adults who stutter (eight women, 12 men) aged between 18 and 61 years (M = 38.4, SD = 12) were included in the final analysis.

Procedure

Participants provided informed consent and completed a hearing screening as described above. They were then seated in a sound-attenuated booth to complete the reading-aloud tasks. At the end of the experiment, they were debriefed and asked to complete a short demographics questionnaire to collect information about age and gender. The experiment took around 40 min in total.

Stimuli for the experiment were taken from Riley's SSI-IV and consisted of two passages from the adult reading materials, adapted from a travel journalism article (Riley, 1972). Passage A was 374 syllables, and Passage B was 369 syllables. Participants were asked to read one of the passages on their own and the second in unison with their partner. The order of the conditions was always the same (solo followed by choral reading) to avoid any spillover effects on speech rhythm from the choral condition. However, the passage presented in each condition was pseudorandomized such that half the participants read Passage A in the solo condition and Passage B in the choral condition and half vice versa.

Before beginning each task, participants were instructed to read the given passage through, ask the experimenter if they had any questions about word pronunciation, and then signal when they were ready to begin. The experimenter then began the recording and gave a visual or verbal signal for the participant to begin reading aloud. Participants were told to "keep together as much as possible" during the choral condition but were otherwise not given specific instructions on how to complete the tasks.

Technical Specifications

During the choral condition, all participants were visually separated from their partner and heard each other through headphones. PWS and neurotypical participants were tested separately at different institutions with conditions kept as similar as possible across the groups within the constraints of the available space and equipment.

PWS sat inside a sound-attenuated booth and spoke into a RODE NT1-A one-inch cardioid condenser microphone connected to a Windows computer via a Fireface UC audio interface (RME Audio, Haimhausen). They heard their partner through Beyerdynamic DT 770 Pro closed-back circumaural headphones. Their voices were recorded in stereo at 44.1 kHz with 16 bit quantization using Adobe Audacity 3.0. Their choral speech partner was positioned outside the testing booth, spoke into an AKG 190E cardioid dynamic microphone connected directly to the booth sound system (i.e., not routed through a computer and thus not recorded) and heard their partner through AKG K240 Studio on-ear headphones.

Neurotypical pairs were seated in a sound-attenuated booth with a dividing screen between them, wearing Beyerdynamic DT 770 Pro headphones. They spoke into Sennheiser HSP-4 cardioid condenser microphones connected to a Windows computer via an RME Fireface UFX II audio interface. Audio was recorded in stereo (with one participant in each channel) at 44.1 kHz with 16 bit quantization using Audacity (Version 3.4.2).

Analysis

Preprocessing

Audio files were reviewed in Audacity and were excluded from analysis if either member of a participant pair had recording or sound quality issues that might affect acoustic analyses (e.g., audio clipping or frequent nonverbal sounds such as coughing or laughing). Four PWS and eight neurotypical pairs were excluded from analysis for this reason, as detailed in the Method section.

The remaining audio files were converted from stereo to one mono file per participant with a sampling rate of 32 kHz using the tuneR package in R, to meet the file specifications necessary for the EMS analysis. This analysis was conducted on the mono files using a custom script in MATLAB R2023b following the procedure outlined in Liss et al. (2010). The amplitude envelope was extracted from the full-band signal and 6 octave bands centered around 125, 250, 500, 2000, 4000, and 8000 Hz. These envelopes were half-rectified, low-pass filtered at 30 Hz using a fourth-order Butterworth filter, and downsampled to 80 Hz. The power spectra of the resulting envelopes were calculated using the Goertzel algorithm and converted to decibels for frequencies up to 10 Hz. The peak frequency of each power spectrum was measured using the same MATLAB script and entered into the analysis. Analysis was conducted on mean peak frequency values and peak amplitude values collapsed over all octave bands, in keeping with previous research indicating that they are significant predictors of changes between solo and choral reading conditions in the choral speech of PWS (Dechamma & Maruthy, 2018; Meekings et al., 2023). Stuttering utterances in both conditions were additionally evaluated for stuttering frequency, measured as the percentage of syllables stuttered.

Statistical Analysis

A linear mixed-effects regression model (1) was constructed to assess differences in EMS peak frequency as a function of condition (choral vs. solo speech) and group (neurotypical vs. PWS), with a condition by group interaction term. The model included random intercepts for subject and passage to control for rhythmic differences between the passages and individual variation in features such as age and vocal characteristics. Peak amplitude was assessed using a linear model with no random effects (2), as an LMER demonstrated that variance attributable to the two random factors included in model (1) was at or close to zero.

For PWS, fluency (percentage of syllables stuttered while reading each passage) was modeled as a function of EMS peak frequency to evaluate the relationship between rhythmic changes and fluency and condition to confirm the fluency-inducing effects of choral speech. This model included random intercepts for subject only, as- similarly to the model for peak amplitude- adding random intercepts for passage led to singular model fit owing to a lack of variance.

(1) Peak frequency ~ Condition * Group + (1 | Subject) + (1 | Passage)

(2) Peak amplitude ~ Condition * Group

(3) Fluency ~ Peak frequency + Condition + (1 | Subject)

Analysis was performed using R version 4.3.1 (R Core Team, 2021), with lme4 1.1.34 (Bates et al., 2015) to run the linear mixed-effects models and lmerTest 3.1.3 (Kuznetsova et al., 2017) to provide *p* values using Satterthwaite's approximation for degrees of freedom. Data processing and visualization were performed using tidyverse (Version 2.0.0; Wickham et al., 2019).

Results

EMS Peak Frequency

When neurotypical dyads spoke chorally, their peak frequencies became more similar. Figure 1 illustrates this pattern, demonstrating that choral speech leads to rhythmic convergence in neurotypical dyads.

Since we were unable to assess convergence for the PWS dyads, we instead compared their speech rhythm behavior with that of the neurotypical dyads in each condition. There was a significant effect of condition ($\beta = -0.17$, $SE = 0.06$, $t = -2.74$, $p = .006$) and group ($\beta = -0.27$, $SE = 0.08$, $t = -3.38$, $p < .001$), and a significant condition by group interaction ($\beta = 0.39$, $SE = 0.09$, $t = 4.003$, $p < .001$). Results are illustrated in Figure 2, shown for each passage separately to allow for the probability that reading different materials evokes different speech rhythms.

Consistent with previous research, PWS's EMS peak frequency was higher during choral reading compared to reading alone. Neurotypical participants exhibited the opposite pattern: their peak frequency was higher when they spoke on their own compared to reading chorally.

Additionally, during solo reading, PWS's peak frequency was significantly lower than controls: neurotypical controls read the passages with a mean peak frequency of 0.63 overall, compared with 0.36 for participants with a stutter. This pattern reversed when participants spoke

Figure 1. Boxplot and connected dot plot showing the rhythm (Envelope Modulation Spectrum mean peak frequency) with which neurotypical Participants A and B read each passage in the solo and choral conditions. Dots and lines are color coded by participant pair. Each box represents the interquartile range, with a horizontal line showing the median value. Whiskers extend to 1.5 times the interquartile range. EMS = Envelope Modulation Spectrum.

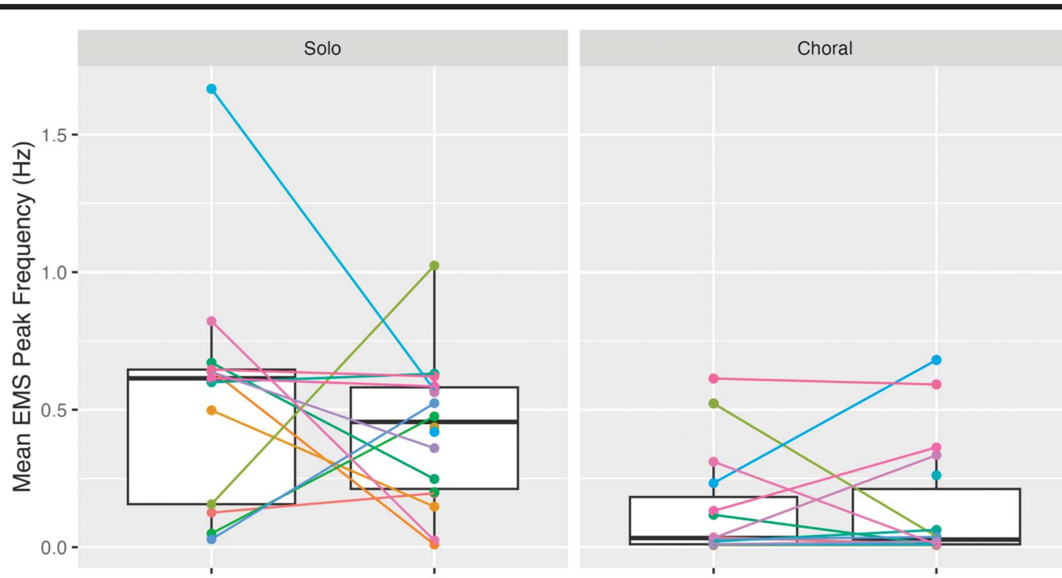
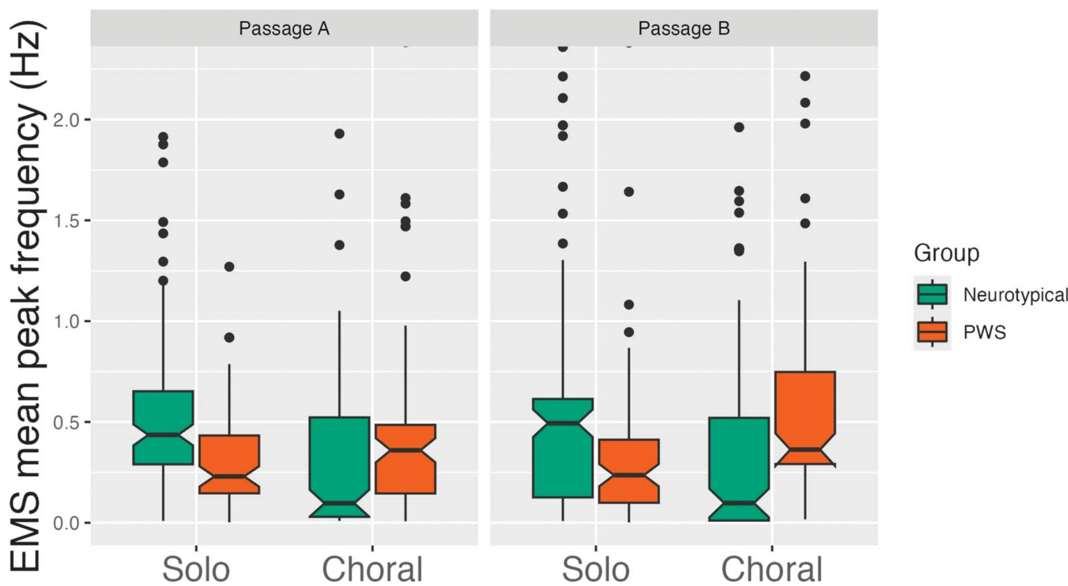


Figure 2. Boxplot showing the dominant rhythm (EMS mean peak frequency) with which each group read each passage in the solo and choral conditions. Each box represents the interquartile range, with a horizontal line showing the median value. Whiskers extend to 1.5 times the interquartile range. Boxes are color coded by participant group (green = neurotypical, orange = people who stutter). EMS = Envelope Modulation Spectrum.

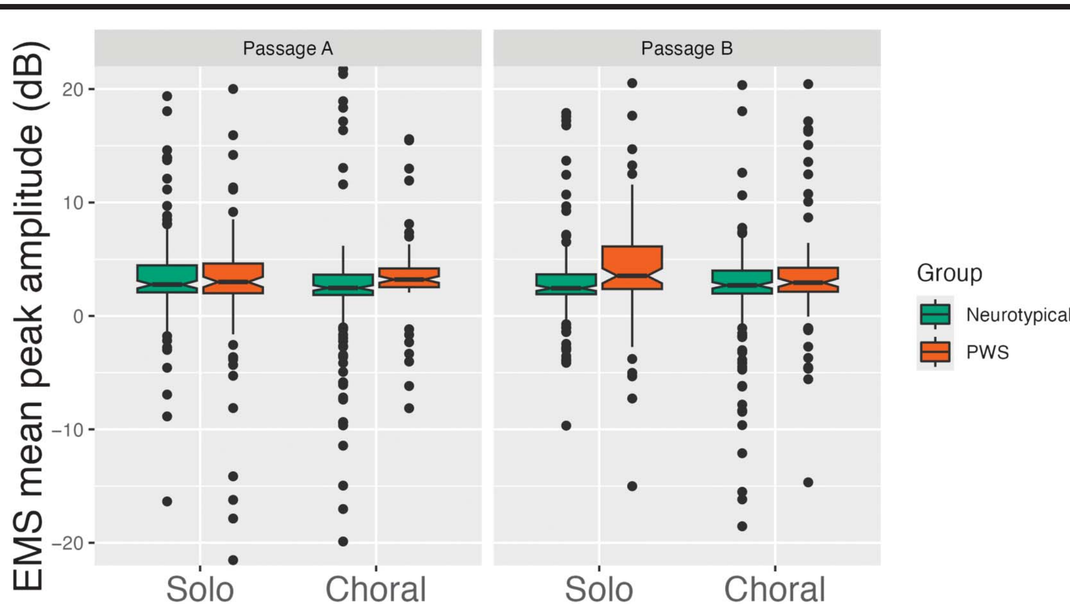


chorally: In this case, PWS's peak frequency was significantly higher than controls. During choral speech, neurotypical controls spoke with a mean peak frequency of 0.46, while participants with a stutter read with a mean peak frequency of 0.58.

EMS Peak Amplitude

Boxplots of the data (see Figure 3) suggested that peak amplitude was slightly more variable in the solo condition than in the choral condition for both groups. However, there

Figure 3. Boxplot showing the consistency of the dominant rhythm (EMS mean peak amplitude) with which each group read each passage in the solo and choral conditions. Each box represents the interquartile range, with a horizontal line showing the median value. Whiskers extend to 1.5 times the interquartile range. Boxes are color coded by participant group (green = neurotypical, orange = people who stutter). EMS = Envelope Modulation Spectrum.



were no significant effects of condition (β = 0.56, *SE* = 4.38, t = 0.13, p = .90), group (β = −0.58, *SE* = 5.02, t = −0.12, p = .91), or any significant condition by group interaction (β = −0.12, *SE* = 7.06, t = 0.02, p = .99); the adjusted r squared value for the model was −0.004.

Stuttering Frequency

As previously reported in Meekings et al. (2023), PWS's fluency increased when they spoke chorally (β = 3.96, *SE* = 0.41, t = 9.66, p < .001). As peak amplitude did not significantly differ between conditions, we did not test for a correlation between this metric and stuttering frequency. However, linear mixed modeling revealed that fluency was significantly predicted by mean peak frequency (β = −1.72, *SE* = 0.42, t = −4.07, p < .001, conditional r^2 = .07, marginal r^2 = .02). The relationship between stuttering frequency and mean EMS peak frequency is shown in Figure 4 below.

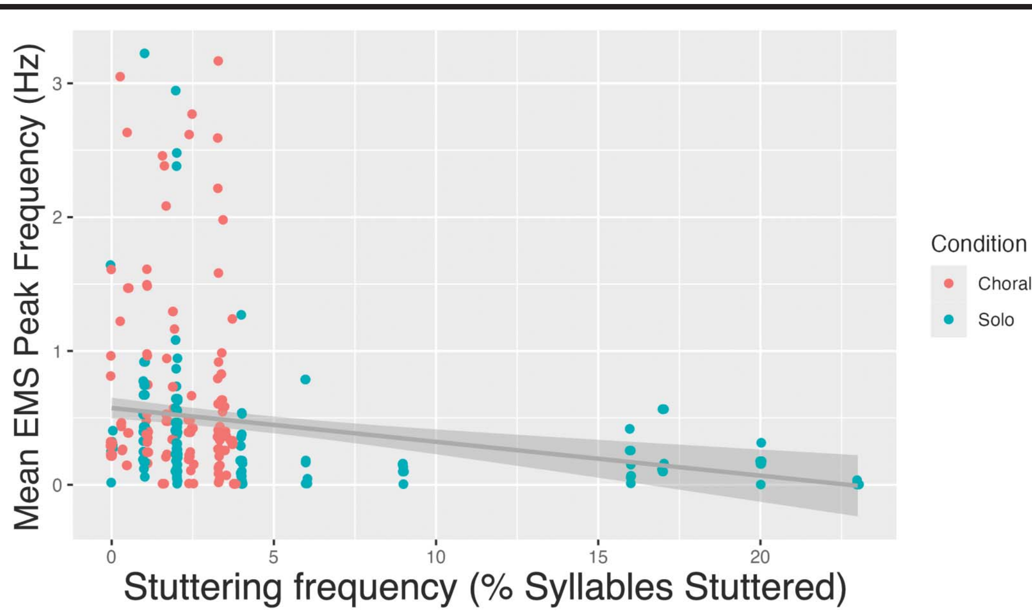
Discussion

Dechamma and Maruthy (2018) and Meekings et al. (2023) both found that choral speech in participants with a stutter was associated with an increase in both fluency and mean peak frequency across multiple octave bands, compared to solo speech. This suggested a relationship between speech rhythm and fluency that might support the hypothesis that PWS use their partner's speech as a rhythmic guide during choral reading. However, our data suggest that the choral speech rhythm of neurotypical talkers is significantly different to that of PWS. Moreover, reading chorally affects these populations in opposite directions: peak frequency is higher during choral reading than solo speech in PWS, but the reverse is true for neurotypical talkers. The choral speech rhythm of PWS is similar to the solo speech of neurotypical controls but very different from neurotypical choral speech.

We interpret these results as indicating that fluency induced during choral reading may not be caused by imitating typical speakers' choral vocal patterns. That is, the change in speech rhythm does not cause the change in fluency; rather, the change in fluency causes the change in speech rhythm. This could be, for example, because PWS use learned or automatic fluency techniques when talking on their own, and these techniques (e.g., sound elongation, soft onsets, or slowed speech rhythm) result in a lower EMS peak frequency. When fluency is induced during choral speech, there is no longer any need to use these techniques and thus EMS peak frequency increases.

However, there are some limitations to our findings. Because only one side of the interaction was recorded in the original experiment with PWS, we were unable to compare their speech rhythm directly with that of their partner, meaning that we cannot assess the degree or directionality of convergence in the PWS-experimenter dyads. Instead, we have compared the choral speech behavior of typical talkers and PWS when paired with a

Figure 4. Stuttering frequency for each disfluent participant (in percentage syllables stuttered) plotted against their mean EMS peak frequency (averaged across all octave bands, in Hz). Dots are color coded by condition (red = choral, blue = solo). Shaded area indicates 95% confidence interval around the line of best fit. EMS = Envelope Modulation Spectrum.



neurotypical partner. Looking at participants' behavior independent of that of their partner allowed us to control for the possibility that talkers' speech converges during choral reading not because the PWS is converging with the neurotypical talker, but because the neurotypical talker is converging with the PWS. Previous research has found that neurotypical speakers make rhythmic changes during choral speech, which make the perceptual centers of their speech more predictable, and that these changes are typically consistent between participants (Cummins, 2009), so we expect neurotypical participants and experimenters to use approximately the same speech rhythm when reading the same passage chorally. However, it may be that typical speakers adopt a different rhythmic strategy when reading chorally with someone who stutters, or that the specific experimenters who partnered with PWS in this study had higher than average peak frequency, meaning that the PWS did in fact converge to their partner. Alternatively, the task instructions might prompt participants to speak with greater rhythmicity, even if they do not copy their partner's speech rhythm, and this more consistent rhythm might be sufficient to induce fluency in and of itself. In this experiment, we used EMS mean peak amplitude to assess the degree to which participants used a consistent speech rhythm. We found no significant differences between conditions or groups. This is surprising, as previous research does suggest that choral speech is more predictable rhythmically than solo reading.

Future research could investigate other measures of rhythmic consistency. Additionally, it would be informative to compare choral speech convergence between neurotypical-neurotypical pairs, neurotypical-PWS pairs and contrast both groups' convergence with a live speaker to convergence with recorded speech, to establish to what extent each partner contributes to convergence during choral speech. A further limitation is that because PWS's data were originally collected as part of a behavioral pretest for a larger experiment, while the control data were collected later at a different institution, this led to some small differences in equipment and experimental setup, which may have affected the results, although every effort was made to ensure a comparable testing environment and matching technical specifications between sets of equipment.

One experimental difference, which may have affected the results, is the choice of partner. Neurotypical participants were paired with other neurotypical participants, who were of equivalent social status and had limited previous experience of choral speech. Participants who stutter were paired with one of four experimenters, who had read the passage before and had more experience with choral reading. Previous research has found that, typically, participants are able to read chorally in close synchrony almost immediately, even if they have no prior experience of the task. Moreover, practicing a passage only marginally changes choral speech behavior, while prior experience with choral speech does not affect performance (Cummins, 2003; O'Dell et al., 2010). However, because the experimenter might have been perceived as the dominant partner because they ran the experiment and had experience doing the task, this may have caused the PWS to converge more to the experimenter than vice versa (Gregory & Webster, 1996).

In general, evidence for the motor timing theory of stuttering is mixed. Although there are many effective fluency-enhancing situations that appear to work by inducing a regular speech rhythm, many other interventions such as altered auditory feedback and masking noise have no obvious rhythmic effect. Additionally, although many authors have found increased kinematic variability or differences in movement initiation and timing (Frisch et al., 2016; Loucks & De Nil, 2006; Wiltshire et al., 2021) that are reduced when PWS are provided with an external rhythmic stimulus (Franke et al., 2023; Wiltshire et al., 2023), other studies have found no difference between the motor skills of PWS and neurotypical controls (Max & Yudman, 2003; Smith & Kleinow, 2000; Zelaznik et al., 1994).

If fluency is not caused by copying neurotypical speech rhythm, it could be that it is instead induced by some other property of choral speech. Another mechanism that has been hypothesized to explain the effect of fluency-enhancing situations including choral speech is that many of them occlude the sound of the talker's voice, preventing them from using auditory feedback to guide their utterances. However, evidence for this theory is also mixed, with studies finding opposing results (Garnett et al., 2022; Meekings et al., 2020).

It is also possible that PWS do converge to their partner's speech rhythm during choral reading but to a different feature. We chose EMS peak frequency to investigate as this measure is correlated with fluency during choral reading in PWS. However, recent work suggests that neurotypical talkers synchronize vowel onsets closely during choral speech and has identified a specific amplitude envelope correlated with this (MacIntyre et al., 2022), which may provide a better measure to investigate rhythmic behavior during this task.

Research into conversational alignment more generally demonstrates that while participants do often adapt to their partner's speech behavior during conversational interaction, there is individual variation in the precise feature that talkers align with (e.g., Eijk, 2023). In our work, there was considerable variance in all participants' speech rhythm during the passage reading in both choral and solo conditions. Stuttering is also a heterogeneous disorder (SheikhBahaei et al., 2023), and this is reflected in our results: Participants with a stutter had a wide range of stuttering severities. It is possible that individuals, and individual dyads, adopt different strategies during choral reading. It may therefore be informative to look at individual patterns of speech adaptation between dyads during choral speech. Overall, however, our results demonstrate that choral reading affects neurotypical talkers and PWS in diametrically opposing ways, suggesting that the fluency-inducing effect of choral reading in PWS may not be attributable to participants copying their neurotypical partner's speech rhythms.

Author Contributions

Sophie Meekings: Conceptualization (Lead), Data curation (Lead), Formal analysis (Lead), Project administration (Equal), Investigation (Equal), Visualization (Lead), Funding acquisition (Lead), Writing – original draft (Lead). **Lotte Eijk:** Investigation (Equal), Project administration (Equal), Writing – review & editing (Lead). **Stefany Stankova:** Investigation (Equal), Data curation (Supporting). **Santosh Maruthy:** Conceptualization (Supporting), Resources (Supporting), Software (Supporting). **Sophie Kerttu Scott:** Supervision (Lead), Investigation (Supporting).

Data Availability Statement

The data sets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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