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Vocal Fry and Vowel Height in Simulated Room Acoustics

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Abstract

Purpose: The purpose of this study was to investigate the influence of room acoustics in the relationship between vowel height and vocal fry.

Methods: Cross-sectional study. Participants (college students, $n=40$). Participants read the first six sentences of the Rainbow passage under nine simulated room acoustic conditions. Using two words with low vowels (act, pot) and two words with high vowels (shape, strikes) preceding voiceless stop, the presence/absence of vocal fry was assessed using an automatic detection script. Generalized estimation equations were used to investigate the relationship between percentage of vocal fry, vowel height and room acoustics.

Results: The percentage of vocal fry was significantly higher for the low height vowels compared with the high height vowels ($\beta=1.21$; $SE=0.35$), and with pink background noise present ($\beta=0.89$; $SE=0.35$) compared with the condition without artificial noise added.

Conclusion: The results of this study indicate that young college students are more likely to produce fry phonation when producing low height vowels under pink background noise condition compared with no noise conditions and high height vowels. This result is of special interest for voice clinicians when designing therapy plans and vocal assessment protocols with fry like components.

Keywords

vocal fry; vowel height; background noise; reverberation time

1 INTRODUCTION

Although *persistent* use of vocal fry may be associated with a reduction in voice quality [1, 2]; *sporadic* production of vocal fry has a linguistically meaningful value in languages like English where it has been recognized as one of the several acoustic cues to indicate the end of paragraphs and sentences [3]. Moreover, in the clinical settings, fry phonation is a well-

known technique used in the treatment of different voice disorders, such as psychogenic voice problems, muscle tension dysphonia, and cleft palate, among others [4].

As a vocal register, vocal fry may be characterized considering its perceptual, physiological, and acoustic characteristics. Fry phonation may be perceptually determined as a creaky sound with a rough vocal quality [5]. From the physiological point of view, the production of vocal fry involves a low cricothyroid and interarytenoid muscle activity, and a high thyroarytenoid activity [6]. Concerning the acoustic characteristics, previous authors have reported fundamental frequencies far below during fry phonation compared with modal voice (between 18 Hz and 65 Hz) [6–8].

Due to the prevalent use of vocal fry in normal linguistic contexts as well as its use in voice therapy, there is a need of additional work to assess which factors influence the production of this vocal register. This is one of the motivations for the present study, where we want to explore the variable production of vocal fry, and which individual and environmental factors affect its occurrence.

Previous reports have suggested that this “epidemic” use of vocal fry may be associated with two social influences. First, the use of vocal fry by the media and celebrities who used this vocal register in their conversational and singing voice (imitation patterns). Second, the use of vocal fry among friends and colleagues that may incur social acceptance benefits (identification patterns) [9, 10]. However, since voice production is a multidimensional phenomenon, the production of vocal fry may be also affected by individual and environmental factors.

Concerning the individual factors that influence the use of vocal fry, the literature is sparse, and with contradictory results. For instance, some studies suggested higher occurrence of vocal fry among females compared with males [3, 11], whereas previous studies did not [12]. In regards with language-related factors, two studies have assessed the influence of linguistic and speech variables in the production of vocal fry suggesting the influence of intermediate factors, such as dialect and locations in the utterance [3], and the height of the vowels [13] in an increased production of this vocal register.

In regards with the environmental factors that could influence the use of vocal fry, it would be expected those factors be similar to the conditions where talkers adjust their speech characteristics due to their communication environment (room reverberation time, noise, communication partner) [14–17]. Previous research has reported that speech level (SPL) decreases under more reverberant conditions [18, 19]. Pasquale et al (2011) confirmed this effect on loud voice but not on modal phonation. Nevertheless, there is little knowledge about the influence of room acoustics in the production of fry phonation. Regarding the effect of background noise on vocal fry, two previous studies have informed a decrease in the production of vocal fry as an effect of noise [20, 21]. However, there is still a need to understand the combined effect of room acoustics and speech material (for example, vowel height) in the production of vocal fry. However, there is little knowledge about the influence of room acoustics in the relationship between vowel height and vocal fry. Such information may contribute to identify how the production of vocal fry change in relation with both the

speech material and the acoustic conditions of the environments, which may contribute in the design of treatment procedures that involve vocal fry to improve different voice production's mechanisms [22].

To address these gaps, a cross-sectional study was conducted with the main aim of investigating how the relationship between vowel height and vocal fry is influenced by room acoustics. With this purpose, two specific aims were determined: (1) to assess the differences in percentage of vocal fry between high/low vowels, and (2) to investigate if room acoustics intermediate the relationship between vowel height and vocal fry. Such information would be useful to linguists studying its use in spoken communication as well as for clinicians who may use it in voice therapy contexts.

2 METHODS

2.1 Design and Participants

The results presented in this manuscript are based in a cross-sectional study. The cross-sectional design implies that information of the outcome (vocal fry) and the exposure (vowel height and room acoustics) was collected simultaneously (at the same point in time) [23]. A total of 40 American English native speakers (22 females and 18 males) with a mean age of 22 years old (range between 20 and 25 years old) participated in this study. All the participants had normal hearing (250Hz – 8000 Hz <20dB), and no self-reported voice complaints the day of the experiment. Participants read aloud the first six sentences of “The Rainbow Passage” (a standardized text in English) [24] under nine different “virtual-simulated” acoustic conditions. This study is focused on the analysis of vocal fry in relation with vowel height in connected speech. All participants gave written informed consent to participate in this study. The Michigan State University Human Research Protection Program approved this study.

2.2 Data collection procedures

2.2.1 Voice samples—The analyzed speech material consisted of four words from the first paragraph of “The Rainbow Passage”. The four words included vowels preceding a voiceless stop. Among the four words, two words contained low height vowels (act, pot) and two words with high height vowels (shape, strikes). The targeted vowels were /æ/, /ɒ/, /eɪ/, and /aɪ/. The paragraph spoken repeatedly in nine different simulated acoustic conditions (detailed below). The order of the nine conditions was randomized aiming to balance for any (short-term) vocal fatigue over the duration of the tasks, as well as to control for any unknown confounding variables relating to task order.

Since in “The Rainbow Passage”, the words containing low height vowels were at the end of the sentence, and words with high height vowels at the beginning, the relationship between vocal fry and vowel height could be confounded by the position of the target word in the text. The bias may be entered because production of vocal fry is more likely at the end of the sentence. In order to assess the influence of the location of the target words (initial vs. final) in the relation between vocal fry and vowel height, 22 participants (12 females and 10 males) read eight sentences that contained four words including vowels preceding a

voiceless stop. Four sentences contained the words at the beginning of the production, whereas the other four sentences contained the words at the end.

2.2.2 Simulated room acoustics—The nine “virtual-simulated” acoustic conditions consisted of three different reverberation times and three background noise settings. The mid-frequency reverberation times were 0.4 s (Low), 0.8 s (Medium) and 1.2 s (High). These three time responses were defined based in previous studies that report average reverberation times of 0.4 s for an anechoic room, 0.78 s for a semi-reverberant room, and 2.37 s for a reverberant room [25]. The average reverberation time (T30) for combined 500 Hz and 1 kHz octave bands, were determined for each of the three simulated environments [26]. In the low T30 condition, the average was 0.49, in the medium was 0.90 s, and 1.35 s in the high T30 condition. The three background noise conditions were: (1) without artificial noise - about 25 dBA at the participant’s ears; (2) with artificial classroom non-semantic babble noise at about 61 dBA at the participant’s ears; and (3) with artificial pink noise at about 61 dBA at the participant’s ears.

The simulations and recordings were conducted in a double walled sound isolation booth (2.5×2.75 m and $h = 2$ m) with a mid-frequency reverberation time of 0.05 seconds and a trend over the octave band almost flat. The background noise in the room was 25 dBA. Figure 1 shows the setup of the experiment.

2.2.3 Equipment—An omnidirectional microphone placed at a fixed distance of 30 cm from the mouth (M2211, NTi Audio, Tigards, OR, USA) was used for the recording of the voice samples. The microphone output was split in two. The first output was for the direct digital recording of the voice (44,100 Hz) with an external soundboard (UH-7000 TASCAM, Teac Corporation, Montebello, CA, USA) connected to a personal computer (PC) running Audacity 2.0.6 (SourceForge, La Jolla, CA). The second output was for creating the virtual acoustic environment. For the virtual environment, the direct microphone output was combined with one of three noise types (played from the PC) using a digital mixer (MultiMix 8 USB FX 8, Alesis, Cumberland, RI, USA). Additionally, the voice and noise mixed signal was digitally processed to add reverberation using a real-time effect processor (MX400, Lexicon, South Jordan, UT, USA) and played back to the participant using headphones (SRH840, Shure, Niles, IL, USA). The level of playback in the headphones was set to match the level of the voice at the ears of the participants. This level was set using a Head and Torso Simulator with Mouth Simulator (HATS, 45BC KEMAR, G.R.A.S. Sound & Vibration, Holte, Denmark). Playing a pink noise from the mouth, the levels recorded (1) by the ears of the HATS while wearing the headphones and (2) by a microphone located close to the ears of the HATS, were matched adjusting the gain of the digital mixer. The result was that the participants were acoustically immersed in a simulated environment, which included their own voice.

2.2.4 Percentage of automatically detected vocal fry—The calculation of the percentage of automatically detected vocal fry was performed in two steps. First, we used an analysis technique for the automatic detection of vocal fry in the four targeted vowels from the selected words of the Rainbow Passage (act, pot, shape, strikes). The script for the automatic detection of vocal fry was implemented using Matlab and Statistics Toolbox

Release 2014b (The MathWorks, Inc., Natick, Massachusetts, United States). The technique for the automatic detection of vocal fry identifies local power peaks for obtaining glottal pulse candidates, checks for periodicity properties, and evaluates a similarity measure between neighboring glottal pulse candidates for deciding the possibility of being vocal fry pulses. More detailed information about the automatic detection of vocal fry has been reported in [27]. Second, we calculated the percentage of vocal fry in each word. The percentage of vocal fry was calculated as the ratio of the duration of the segments recognized as vocal fry and the duration of the full voice sample (multiplied by 100). Finally, the four words were clustered into two groups, those containing low height vowels and those with high height vowels.

2.3 Statistical Analysis

All statistical analyses were performed using SPSS 21 (IBM Corporation). First, differences in percentage of automatically detected vocal fry under the nine different acoustic conditions were assessed by General Linear Model Repeated Measures (GLM). GLM is an advisable analysis of variance when the same measurement is made several times on each subject. Second, normality of the dependent variable (percentage of vocal fry) was assessed using the Shapiro-Wilk test. Since the distribution of the percentage of automatically detected vocal fry was non-normal, we used the Box Cox Transformation [28] with a lambda of 0.10 to normalize the data. Once transformed the dependent variable was used as normally distributed for all further analysis. Third, Generalized Estimating Equations (GEEs) were used to determine whether vowel height and room acoustic parameters were associated with the *transformed* percentage of vocal fry. For the independent variables, those with a p-value lower than 0.20 in the univariate analyses were included in the multivariate analysis in order to avoid residual confounding [29], and were only retained when the p-value reached the conventional level of significance of 0.05. The magnitude of the association was expressed by the beta (β) and its standard error (SE).

3 RESULT

3.1 Vocal fry and vowel height

In total, 40 American college students with normal hearing and without currently self-reported voice complaints completed the study. The mean percentage of vocal fry among the students in high height vowel was 0.12 (SE= 0.05), whereas in low height vowel was 1.49 (SE= 0.22). Table 1 shows that the highest mean percentage of vocal fry in low height vowels was under pink noisy conditions (1.79%).

Figure 2 shows the mean percentage of vocal fry clustered by vowel height (low vs. high) and location in the sentence (begin vs. end). Results of the Mann-Whitney U test show that production of vocal fry was significantly higher in low vowels compared with high vowels. As shown in Figure 2, production of vocal fry was more frequent on low vowels located at the end of the sentences compared with low vowels produced at the beginning of the sentence.

3.2 Factors associated with percentage of vocal fry

Table 2 shows the factors that were found to be associated with the transformed percentage of vocal fry in univariate and multivariate linear regression analyses. The univariate analysis shows no significant association of either gender or age on the production of vocal fry. The multivariate analysis shows that, after adjustment for all variables that were statistically significant in the univariate analysis (vowel height, background noise and reverberation time), the transformed percentage of vocal fry was significantly higher for the low height vowels ($\beta = 1.21$; $SE = 0.35$), and with pink background noise present ($\beta = 0.89$; $SE = 0.35$). Assessment of the interaction between vowel height and room acoustics showed a tendency among the participants to produce more vocal fry on low height vowels under medium reverberation time conditions (Figure 3). Figure 4 shows a trend to produce more vocal fry on low vowels when speaking in pink background noise. Nevertheless, none of these interactions was statistically significant.

4 .DISCUSSION

In this study, we investigated the relationship between background noise, reverberation time and vowel height in the production of vocal fry among 40 college student native speakers of American English. Our findings indicate a statistically significant effect of background noise and vowel height in the production of vocal fry.

The results of this study suggest a higher production of vocal fry in low height vowels compared with high height vowels, which is in line with previous research that reported low vowels were more likely to be creaky than high vowels [13]. Previous studies have indicated an inverse relationship between jaw opening and both fundamental frequency of vowels (intrinsic fundamental frequency) and loudness [30]. Therefore high height vowels such as [i] and [u] are inclined to be produced with higher fundamental frequencies than low vowels such as [a] and [o] [31, 32]. From a clinical point of view, it seems likely that the action of the jaw lowering produce a retraction of the hyoid reducing the length of the vocal tract [33] and a reduction of the longitudinal tension of the vocal folds [34]. This situation may facilitate the production of vocal fry. Nevertheless, most of the studies have been performed either on isolated vowels or focused on the effects of emotions in the speech prosody. The results of the present study on vowels embedded in reading speech are in agreement with Lim et al (2006) who also reported a higher fundamental frequency when the magnitude of the jaw opening decreases in vowel production.

Although the results on the relationship between the different speech articulators on the vocal source are not surprising, understanding them is still important for vocal clinicians for designing more efficient therapy plans.

Particularly interesting were the findings on background noise, vowel height and vocal fry since previous studies have not assessed the effect of noise on the production of vocal fry in different vowel height. One previous study in this same population showed that participants were more likely to be perceptually identified producing vocal fry when they were speaking under noisy conditions [35]. Moreover, participants were slightly less likely to be perceptually identified with vocal fry when they spoke under noisy conditions with babble

noise (OR=0.5) than with pink noise (OR=0.4). However, Cantor-Cutiva et al (2017) did not investigate the combined effect of both room acoustics and speech material (vowel height). Since previous research has reported a significant effect of vowel height [13], and background noise in the production of vocal fry, our hypothesis was a lower occurrence of vocal fry when speakers produced high height vowels under noisy conditions.

It was found that when compared to the condition without artificial noise added, words which contained low height vowels ($\beta=1.21$) and were spoken under pink noise ($\beta=0.89$) condition were produced with around 2% more fry. This result is partially unexpected, but a possible explanation for this combined effect may be the increased opening of the jaw during a louder production of low height vowels. It has been widely demonstrated that under noisy conditions the voice level tends to increase (Lombard reflex) [36]. One of the techniques to raise the vocal loudness is to increase the mouth opening by lowering the jaw [37], and low height vowels are produced with lowered jaw. Previous studies have reported that the Lombard effect may also generate a change in speaking rate, probably as a mechanism to improve intelligibility. Therefore, under noisy conditions, speakers tend to speak louder but also slowly [38]. This tendency may lead to differences in lip and jaw kinematics. Therefore, it can be hypothesized that there is a coadjutant effect of jaw opening that influence the production of vocal fry. Our hypothesis is that under pink background noise condition, participants were speaking slower enough that the muscular tension generated to increase the loudness of the voice was compensated by the muscle action for lowering the jaw to produce the low height vowels, and therefore the production of vocal fry was higher. Nevertheless, since in our study, we did not perform physical examinations of the phonatory system, future research is needed to corroborate this hypothesis.

Although small effect (around 2%), information of the influence of vowel height and background noise on the production of vocal fry is of interest for clinicians. These results may help voice pathologist during the voice therapy planning, where speech material and room acoustics may be taken into account. For example, when during the voice therapy the speech-language pathologist (SLP) aims to increase the production of vocal fry, the clinician might use words with low height vowels to facilitate the production of fry. moreover, the SLP might develop therapy sessions using pink noise as auditory stimuli. In contrast, if the objective of the therapy is to avoid vocal fry (e.g., patients changing Male-to-Female Transsexual Voice [39] or with vocal fatigue [40]), the SLP might conduct the therapy in rooms with low background noise, and including activities with high height vowels.

A limitation of this study was the cross-sectional nature that prevents insights into causality of the reported associations. Hence, we do not know in which time-window the production of either low vowels or under noisy conditions will result in vocal fry. A second limitation is the cross-section of vocally healthy college-age participants limits our ability to generalize the results to a wider age range participant.

5. CONCLUSIONS

From this study, two factors were found to be associated with an increased percentage of vocal fry. The percentage of vocal fry was significantly higher for the low height vowels

compared to the high height vowels and with pink background noise present, compared to the condition without artificial noise added. This information is of special interest for voice clinicians to be considered while designing therapy plans and vocal assessment protocols.

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Figure 1.
Setup for recording and creating the virtual environment

Figure 2.
Percentage of vocal fry by vowel height and location of the target word in the sentence

Figure 3.
Percentage of vocal fry by vowel height and reverberation time

Figure 4.
Percentage of vocal fry by vowel height and background noise

Table 1.

Percentage of Vocal Fry by room acoustics

Room Acoustics	Vocal Fry Percentage			
	High Vowel Height		Low Vowel Height	
	Mean	SE	Mean	SE
<i>Background Noise</i>				
No Noise	0.25	0.15	1.15	0.38
Babble Noise	0.08	0.07	1.55	0.41
Pink Noise	0.03	0.03	1.79	0.35
<i>Reverberation Time</i>				
Low RT (0.4 s)	0.24	0.13	1.36	0.31
Medium RT (0.8 s)	0.12	0.10	1.59	0.44
High RT (1.2 s)	0.00	0.00	1.54	0.37

RT= Reverberation Time

Table 2.Room acoustic factors associated with *transformed* percentage of vocal fry in low and high vowels

Variable	Univariate analysis		Multivariate analysis	
	Beta	SE	Beta	SE
<i>Individual factors</i>				
Female gender	-3.52	7.68		
Age	-1.41	3.63		
Vowel Height (low/high)	0.86 [*]	0.30	1.21 [*]	0.35
<i>Room Acoustics</i>				
Noise (Babble/No noise)	0.06	0.29	0.07	0.27
Noise (Pink/No noise)	0.68 ⁺	0.37	0.89 [*]	0.35
Reverberation Time (Medium/Low)	1.05 ⁺	0.57	-0.24	0.31
Reverberation Time (High/Low)	0.79 ⁺	0.57	-0.22	0.26

*
p<0.05;⁺
p<0.20

Low Reverberation Time = 0.4 s; Medium Reverberation Time= 0.8 s; High Reverberation Time = 1.2 s