The Effects of Stress Type, Vowel Identity, Baseline f_0, and Loudness on the Relative Fundamental Frequency of Individuals With Healthy Voices

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Summary: Objective. Relative fundamental frequency (RFF) has been investigated as a possible acoustic measure to assess laryngeal tension. This study aimed to identify possible factors in RFF stimuli (stress type, vowel identity, baseline f_0, and loudness) that might also affect RFF values.

Methods. Fifteen speakers with healthy voices produced short RFF stimuli (vowel-/f/-vowel; eg, /ɑfɑ/) in different conditions. They produced the stimuli with three different stress types and four different vowels. Participants also produced stimuli in three different baseline f_0 conditions and three different loudness conditions. The mean RFF and within- and between-subject standard deviation (SD) of RFF were estimated for each stimuli condition.

Results. Stress type had a statistically significant effect on RFF means and within-subject SDs with a large effect size ($P < 0.001$). A significant but small effect of vowel identity was observed: onset 1 RFF values from /ɑ/ were higher than onset 1 RFF values from /u/ ($P < 0.01$). Baseline f_0 had a significant effect on RFF values with a medium effect size ($P < 0.05$). Loudness did not have any significant effect on RFF, but onset 1 RFF values produced with soft voice showed an unexpectedly high between-subject SD.

Conclusions. This evidence suggests that stress type is the most important factor to consider in RFF measurement. We also conclude that RFF may be somewhat resistant to vowel variation and small differences in baseline f_0 and loudness, which may be beneficial in clinical settings.

Key Words: Relative fundamental frequency—Acoustic measurement—Voice assessment—Laryngeal tension—Strain.

INTRODUCTION

Excessive laryngeal tension, often perceived as a strained voice, is a common feature of voice disorders. Clinical assessment of voice disorders currently relies primarily on subjective measures, particularly auditory perception, and strained voice quality has not been well-correlated with any acoustic measures.[1,2] Recently, relative fundamental frequency (RFF) has been investigated as a possible acoustic correlate of strained voice quality. RFF quantifies changes in fundamental frequencies (f_0) during voicing offset and onset during the production of sonorant-voiceless consonant-sonorant constructs (Figure 1).[3,4] In healthy voices, f_0 usually decreases slightly before the voiceless consonant and increases immediately after it.[5] However, it has been hypothesized that baseline tension in the larynx in individuals with excessive laryngeal tension may decrease the extent of the short-term f_0 increases during voiceless consonant production. Thus, RFF of individuals with laryngeal tension has been hypothesized to be lower than those with healthy voices.[3,6] RFF's potential to detect laryngeal tension has been supported by several studies: RFF values were significantly lower in participants with vocal hyperfunction,[3,7–9] Parkinson's disease,[4,10,11] and adductor spasmodic dysphonia[12] compared to the values of individuals with healthy voices. Additionally, individuals with vocal hyperfunction showed significant increases in their RFF values after successful voice therapy sessions, with post-therapy values trending toward values of typical speakers.[6,7]

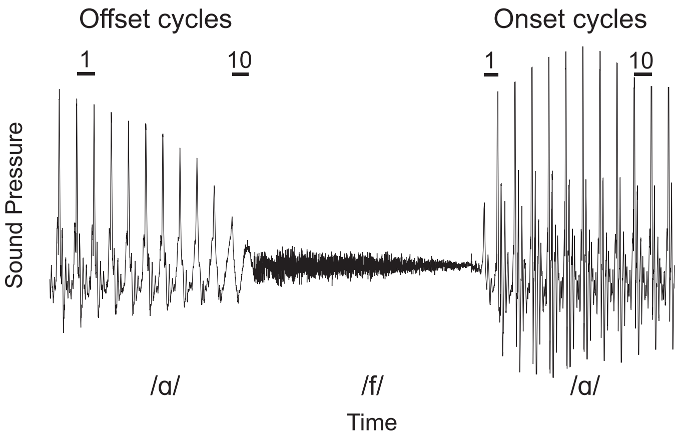

FIGURE 1. An example acoustic waveform of a sonorant-voiceless consonant-sonorant. The offset cycles and onset cycles 1 and 10 are labeled.

Because RFF has exhibited potential for detecting and quantifying laryngeal tension, studies also have attempted to explicitly increase its precision and efficiency as a measure. To improve the precision of RFF estimation, Lien et al in 2014 examined the effect of phonetic context on RFF and found that simple vowel-voiceless consonant-vowel (VCV) utterance stimuli (eg, /ɑfɑ/) resulted in lower within-subject variability than sentence stimuli, and that

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using the voiceless fricative consonants /f/ and /ʃ/ resulted in lower within-subject variability than voiceless stop consonants.[13] More recently, to reduce the subjectivity and operator effort in manual RFF estimation, Lien et al in 2017 developed an automated algorithm to estimate RFF more objectively and efficiently.[14]

Previous studies on RFF have published RFF values of both individuals with healthy voices and individuals with voice disorders related with vocal hyperfunction, compiling approximate ranges of RFF values for each group. However, there are some discrepancies between the studies in their exact RFF ranges for healthy and disordered voices. One potential reason for these discrepancies could be that some of the recent studies that used short utterance stimuli (e.g., /ifi/) also used an automated algorithm to estimate RFF. Lien et al. found that the automated algorithm resulted in slightly lower RFF values than manual estimation.[14] Another potential reason is that the short utterances have not been controlled for syllable stress, vowel identity, baseline f_0, or loudness in previous studies. It is unknown how these factors may contribute to RFF values. Therefore, the current study aimed to determine the effects of syllable stress, vowel identity, baseline f_0, and loudness on RFF estimation using the current automated algorithm.

Syllable stress

Syllable stress may have a substantial effect on RFF when estimated from the two-syllable VCV stimuli. Stressed syllables are typically produced with more vocal effort than unstressed syllables.[15] Since RFF is inversely related to vocal effort,[16,17] RFF values measured on stressed syllables may be lower than unstressed syllables. Different syllable stresses also have different f_0 contours, which could result in variable baseline laryngeal tension depending on f_0. Higher f_0 would be caused by higher baseline tension, reducing the tension-mediated increases of f_0 (lower RFF). Different contours could also result in variable reference f_0 values, which are used in normalizing RFF values. To determine the effect of syllable stress on RFF, in the current study, we compared the RFF stimuli produced in three different stress types: stress on the first vowel ("stress first"), stress on the second vowel ("stress second"), and with both vowels produced with the same pitch without particular stress on either vowel ("stress same"). Because unstressed vowels are likely to have less vocal effort, decreased $f_{0,}$ and lower reference f_0s, which all could result in higher RFF values, we hypothesized that the "stress first" type would have the highest onset RFF values. Regarding RFF variability, we hypothesized that the "stress same" type would have the lowest within- and between-subject variability because this type would have the most consistent vocal effort and f_0 contour compared to other stress types.

Vowel identity

At the phonemic level in short utterance stimuli, vowel identity may also be an important factor in RFF estimation. In the previous studies with sentences or short utterances, researchers have included a variety of vowel combinations into RFF stimuli, although vowel identity may have a substantial effect on RFF values. Different vowels have different intrinsic f_0s, which could affect the degree of f_0 changes during the voiceless consonant production. For example, high vowels such as /i/ have a higher intrinsic f_0 than low vowels such as /ɑ/, with a mean difference of 1.65 semitones (ST).[18] The different intrinsic f_0 of each vowel would represent different baseline vocal fold tension, and this difference could result in different degrees of f_0 change during voiceless consonant production: high vowels with greater baseline vocal fold tension would have less f_0 change compared to low vowels with less baseline tension. Thus, we hypothesized that stimuli with high vowels (/i, u/) would result in lower RFF values than stimuli with low vowels (/ɑ, ə/).

Baseline f_0

Similarly, as the hypothesis of vowel identity on RFF was primarily based on the baseline f_0 on RFF, we also explicitly studied the effect of baseline f_0 on RFF values. Because the baseline f_0 is related to higher vocal fold tension, higher baseline f_0s would be more likely to have higher vocal fold tension, which would lower the f_0 increases during RFF stimuli production. Thus, we hypothesized that RFF values would be lower for stimuli produced with higher baseline f_0s compared to those produced with lower baseline f_0s.

Loudness

Lastly, loudness may also affect RFF estimation as it is partially controlled by laryngeal tension mechanisms. Loudness is controlled by combinations of modifications to the vocal tract, laryngeal tension, and respiratory system.[19] Thus, when a louder voice is used to produce RFF stimuli, a speaker may have a higher laryngeal tension, and this could result in lower RFF mean values. To study the effect of loudness, we compared RFF stimuli produced in soft, comfortable, and loud voices with the hypotheses that loud production would have lower RFF mean values and higher within- and between-subject variability than soft and comfortable voices.

In summary, the effects of stress type, vowel identity, baseline f_0, and loudness on RFF values and variability were evaluated in healthy individuals.

METHODS

Participants

Fifteen healthy participants, aged 19–29 years (11 women; mean = 21.9 years, standard deviation [SD] = 3.9), were recruited and reported no history of speech, language, and hearing disorders. Participants scored normally on Voice Handicap Index and Reflux Symptom Index. The Voice Handicap Index and Reflux Symptom Index subjectively evaluate the degree of voice handicap and laryngopharyngeal reflux, respectively.[20,21] Participants completed written consent to participate in compliance with the Boston University Institution Review Board.

Experimental tasks

RFF stimuli

We aimed to evaluate factors in RFF short utterance stimuli that could affect RFF estimation: syllable stress type, vowel identity, baseline f_0, and loudness.

Syllable stress and vowel identity. The effects of syllable stress and vowel identity on RFF were examined with three syllable stress types and four different vowels. Three types of syllable stress were included in this study: stress on the first vowel ("stress first"), stress on the second vowel ("stress second"), and same stress on both vowels ("stress same"). Stressed vowels were expected to have the mixture of higher pitch and intensity and longer duration than unstressed ones did, and the "stress same" type required participants to produce both vowels with the same pitch and intensity. Under each stress type, the four stimuli were included with four different vowels (/ɑfɑ/, /əfə/, /ifi/, /ufu/).

Baseline f_0. The effect of the baseline f_0 was tested with RFF stimuli produced with each individual's comfortable, low, and high baseline f_0. The individual comfortable baseline f_0 was determined from each participant's recording of sustained /ɑ/ with their comfortable voice using Praat acoustic software.[22] The low baseline f_0 was set to be 3 ST below their comfortable baseline f_0, and the high baseline f_0 was set to be 3 ST above the comfortable baseline f_0. The difference of 3 ST was chosen to create relatively large change in f_0 that participants could still produce. Sample tones of comfortable, low, and high baseline f_0 were generated and played with Madde synthesizer.[23] We played each tone to participants, and they produced the stimuli /əfə/ with the "stress same" type with the pitch they heard. The stimulus /əfə/ with the "stress same" type was chosen because we had hypothesized it to be the least variable among vowels and stress types.

Loudness. The effect of loudness was tested with the RFF stimulus /əfə/ with the "stress same" type, produced with soft, comfortable, and loud voice. The degree of loudness was not assigned but rather determined by participants, similar to clinical instructions for soft and loud voice.[24] Participants were asked to decrease loudness without whispering for soft voice, and raise loudness as if to be heard across a room for loud voice. Sound pressure level was estimated offline by calibrating the microphone with a test tone from an electrolarynx (TruTone Artificial Larynx, Griffin Laboratories, Temecula, California) and a sound pressure meter (CM-150, Galaxy Audio, Wichita, Kansas) placed 7 cm from the mouth.

RFF stimuli recording

The experimenter instructed participants on how to pronounce the different syllable stresses and vowels before recording. Participants also listened to sample recordings of stimuli with all four vowels under each stress type. Opposite gender recordings were played in an attempt to prevent mimicking of pitch. (However, our *post hoc* analysis revealed that roughly two-thirds of participants produced an average f_0 that was within +/− 1 ST of the octave below or octave above of the average f_0 of the speakers in the instructional recordings.) After learning the stimuli, participants were fitted with a head-mounted microphone (WH20, Shure, Niles, Illinois), placed 7 cm from the mouth and 45° from the midline. Their voices were recorded with SONAR Artist (Cakewalk, Chicago, Illinois) with a 44.1-kHz sampling frequency in a sound-treated booth.

The order of stress type and vowel was pseudorandomized to eliminate potential order effects. The order of baseline f_0 and loudness was not randomized because producing high or loud voice can physiologically affect the next production, so the order was set to be comfortable, low, and high for baseline f_0, and comfortable, soft, and loud for loudness. Each stimulus under each category (eg, /ɑfɑ/ with "stress first" or /əfə/ with soft voice) was produced nine times because RFF means were previously found to be stable when averaged over at least six productions.[12] Thus, participants produced a total of 36 productions under one stress type (four vowel stimuli × nine times), and they moved on to the next stress type. They produced stimuli 108 times during the different stress type and vowel portion of the experiment and 27 times each in the baseline f_0 and loudness portions. This resulted in a total of 162 productions. The recording took approximately 10 minutes. In addition, when participants occasionally pronounced stimuli with the wrong stress type or vowel, the experimenter asked them to produce them again. The experimenter also asked participants to repeat any stimulus with clear glottalization or with extremely short vowel productions, as these do not allow RFF estimation.

Data Analysis

RFF was estimated using an automated RFF estimation algorithm[14] in *MATLAB* (version R2015b, MathWorks, Natick, Massachusetts). The automated RFF algorithm identifies the voiced cycles before and after the consonants, estimates the periods and the instantaneous f_0 for each cycle, and calculates RFF with RFF equation, $ST = 39.86 \times \log_{10}(f_0/\text{reference } f_0)$. The algorithm automatically rejects any recorded stimuli that lack sufficient periodic cycles or contain glottalization, which can affect the accurate f_0 estimation. We focused our analysis on offset cycle 10 and onset cycle 1 RFF values because they are farthest away from stable vowel cycles.[3,17]

From nine RFF values estimated (less in the case of any rejections) from the nine iterations of each stimulus condition, offset cycle 10 and onset cycle 1 RFF means and within-subject SDs were calculated. The within-subject SD demonstrates each stimulus condition's reproducibility. The between-subject SD of each stimulus condition was also calculated with individual RFF mean values of all participants. The between-subject SD demonstrates the variability across the speakers producing one stimulus type.

Statistical Analysis

Statistical analysis was performed in *SPSS* (version 24.0, IBM Corp., Armonk, New York). Two-way analysis of variances (ANOVA) with stress type and vowel identity as man effects were performed for RFF means and within-subject SDs of both offset 10 and onset 1 cycles calculated from the different stress type and vowel identity trials. The interaction effect between stress type and vowel identity was also examined from the two-way ANOVA results. A one-way ANOVA was performed on the data from the different baseline f_0 trials, and another one-way ANOVA was performed on the data from the different loudness trials. Effect sizes were calculated as a partial eta squared (η_p^2), and Tukey *post hoc* tests were performed as appropriate. A predetermined level of statistical significance ($P < 0.05$) was used.

RESULTS

Stress type and vowel identity

Significant effects of stress type were found for both offset 10 and onset 1 RFF mean values, with medium and large effect sizes of 0.10 and 0.31, respectively ($P < 0.001$; Table 1). *Post hoc* tests revealed that for offset 10, the “stress first” stimuli had lower mean values than the “stress second” stimuli, and the mean values of the “stress same” stimuli were not significantly different from the other stress types (Figure 2; Stress Type). For onset 1, the “stress first” stimuli had the highest values, the “stress second” stimuli had the lowest, and all values were significantly different from one another. RFF within-subject SDs showed significant effects of stress type in onset 1 with a large effect size of 0.31 ($P < 0.001$). *Post hoc* testing revealed that for onset 1, the “stress same” stimuli had the lowest within-subject SDs (Figure 3; Stress Type). With respect to vowel identity, no significant effect was found for mean offset 10 RFF values, but a significant effect was found for mean onset 1 RFF with a small effect size of 0.07 ($P = 0.01$; Table 2); as expected, RFF values from high vowels were generally lower than values from low vowels and RFF values from /ɑ/ and /u/ were significantly different from one another (Figure 2; Vowel Identity). Although vowels did not have a significant effect on the within-subject SD, there was a trend for the vowel /ə/ to have the lowest within-subject SD compared to other vowels (Figure 3; Stress Type). There was no significant interaction between stress type and vowel identity for RFF means and within-subject SD.

Baseline f_0

Baseline f_0 was shown to be a significant factor for both offset 10 and onset 1 RFF mean values with medium effect sizes ($\eta_p^2 = 0.14$ and 0.18; $P = 0.05$ and 0.01), but not for within-subject SDs (Table 2). *Post hoc* testing revealed that in both offset 10 and onset 1, the low baseline f_0 condition had the highest RFF mean values, and the high baseline f_0 condition had the lowest (Figure 2; Baseline f_0).

Loudness

Loudness was not a significant factor for RFF offset 10 and onset 1 mean values or within-subject SDs (Figure 2 and 3; Loudness). Although there was no significant effect of loudness, onset 1 RFF mean values for soft voice had an unusually wide range of RFF values (Figure 5).

Between-subject SD

The between-subject SD (Figure 4) was the lowest in the “stress same” type for both offset 10 and onset 1, and it was very similar across different vowels. The comfortable baseline f_0 condition had the lowest between-subject SD. The soft voice condition had a high between-subject SD (Figure 4 and Figure 5).

DISCUSSION

Since RFF is a possible objective measure of laryngeal tension, we evaluated the effects of different factors on short RFF stimuli, including syllable stress type, vowel identity, baseline f_0, and loudness. We found significant effects of stress type, vowel identity, and baseline f_0 on RFF means and a significant effect of stress type on RFF within-subject SD. We did not find a significant effect of loudness, although we found a high between-subject variability with soft voice production.

TABLE 1.
Results of Two-way ANOVAs on RFF Mean and Within-subject Standard Deviation from Stress Type and Vowel Identity Trials

Factors	Source	RFF Cycle	F	P	η_p^2
Stress type	**Mean**	**Offset 10**	**8.8**	**<0.001**	**0.10**
		Onset 1	**49.5**	**<0.001**	**0.38**
	Within-subject SD	Offset 10	1.1	0.30	0.01
		Onset 1	**35.4**	**<0.001**	**0.31**
Vowel identity	**Mean**	Offset 10	0.1	0.94	<0.01
		Onset 1	**4.2**	**0.01**	**0.07**
	Within-subject SD	Offset 10	1.4	0.25	0.03
		Onset 1	1.0	0.40	0.02
Interaction	Mean	Offset 10	0.3	0.96	0.01
		Onset 1	0.4	0.90	0.01
	Within-subject SD	Offset 10	0.8	0.59	0.03
		Onset 1	1.2	0.32	0.05

Significance is bolded $P < 0.05$.

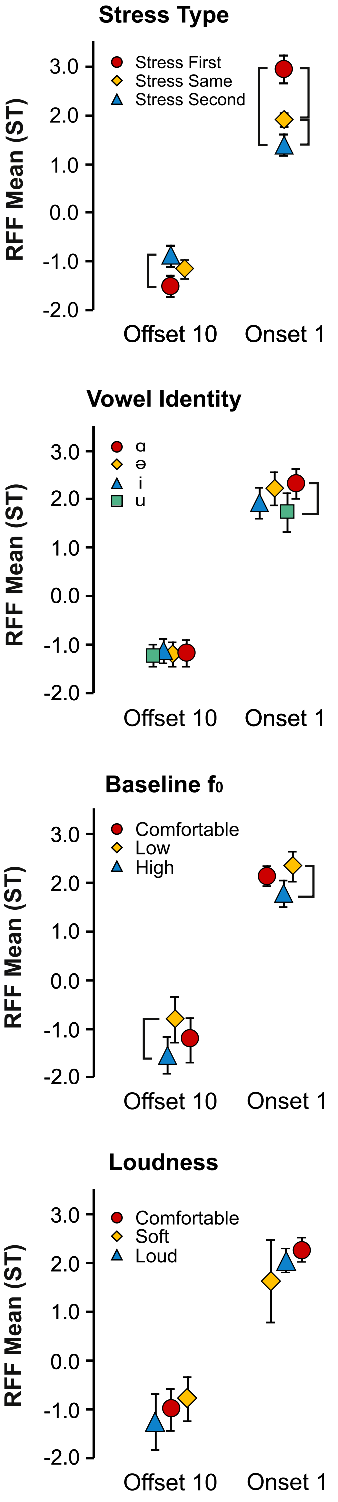

FIGURE 2. RFF offset 10 and onset 1 mean values from different conditions in each factor. Brackets indicate significant differences ($P < 0.05$). Error bars indicate the 95% confidence intervals for the means.

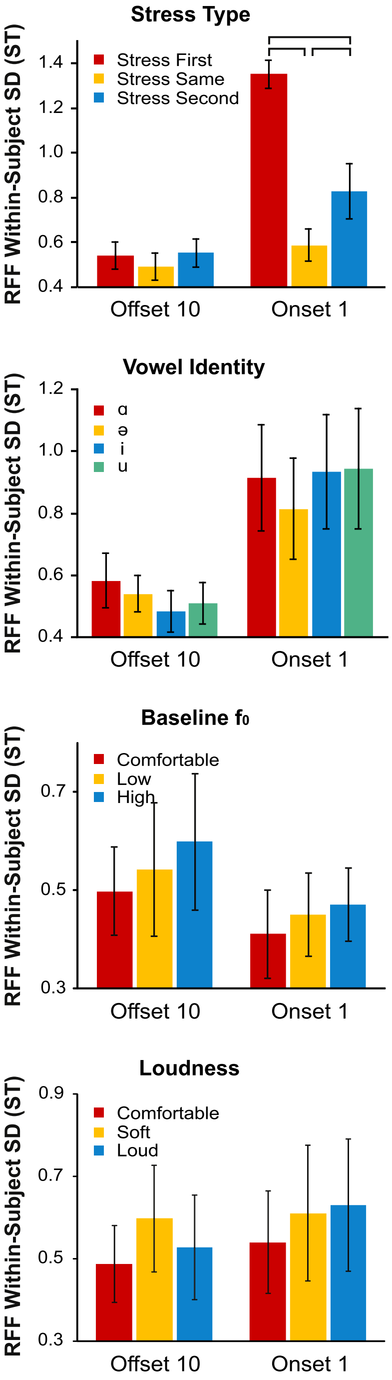

FIGURE 3. RFF offset 10 and onset 1 within-subject standard deviation from different conditions in each factor. Brackets indicate significant differences ($P < 0.05$). Error bars indicate the 95% confidence intervals for the means.

Stress type

As expected, stress type was a significant factor in both offset 10 and onset 1 RFF mean values. The "stress first" stimuli resulted in lower RFF values of offset 10 cycles than the other stress types, and the "stress second" stimuli resulted in the lowest onset 1 RFF. The results showed that when the first vowel in the syllable is stressed, offset 10, right after the first vowel, had lower RFF values, and when the second vowel is stressed, onset 1, right before the second vowel, had lower RFF values. Cycles closer to the stressed syllables seem to have lower RFF values, which is indicative of increased laryngeal tension, due to increased vocal effort and elevated pitch during stressed vowels.[15]

TABLE 2.
Results of One-way ANOVAs on RFF Mean and Within-subject Standard Deviation from Baseline f_0 and Loudness Trials

Factors	Source	RFF Cycle	F	*P*	η_p^2
Baseline f_0	**Mean**	**Offset 10**	**3.34**	**0.05**	**0.14**
		Onset 1	**4.66**	**0.02**	**0.18**
	Within-subject SD	Offset 10	0.76	0.47	0.04
		Onset 1	0.59	0.56	0.03
Loudness	Mean	Offset 10	1.08	0.35	0.05
		Onset 1	1.62	0.21	0.11
	Within-subject SD	Offset 10	1.04	0.36	0.05
		Onset 1	0.48	0.63	0.00

Significance is bolded $P < 0.05$.

Stress type may be one of the possible reasons for the discrepancy noted between RFF values in previous studies. Previous studies have used the Rainbow Passage to extract RFF stimuli from running speech, making the RFF samples consistent and predictable in their syllable stress. For example, common RFF stimuli from the Rainbow Passage[3,6] are "ev**er fi**nds" and "l**ooking for**": "/ər/-/f/-/aɪ/" would be produced with "stress second," "/ʊ/-/k/-/ɪŋ/" with "stress first," and "/ɪŋ/-/f/-/ɔr/" with "stress same." Thus, the sentence stimuli from the previous studies likely contain a balance of stress types. Conversely, for short utterance stimuli, based on a review of our own datasets, we suspect that speakers might have used the "stress second" more than other stress types. This is consistent with RFF onset values that are lower than those from the sentence stimuli.

The "stress same" stimuli had the lowest RFF within-subject SDs, as expected. However, one drawback of encouraging equal stress on each syllable is the increased likelihood of the task being chanted or sung by participants. We advise that specific instructions be given to speakers to perform equal stress on each syllable in a normal speaking voice so as not to lose the ecological validity of the normal variations in natural speech. Overall, our findings confirm that stress patterns should be controlled during RFF measurement, as different stress patterns ultimately affect RFF values and add to within-subject variability.

Vowel identity

We predicted that vowel identity would have a significant effect on RFF values due to intrinsic pitch. Our results indicated that there was no significant effect of vowel identity in offset 10 RFF values, but there was a significant effect in onset 1 RFF values, with a small effect size. The mean f_0 difference between /a/ and /u/, produced with "stress same," was found as only 0.3 ST, which may be a negligible difference. As the actual f_0 differences between high and low vowels were so small, we now suspect that the intrinsic pitch may not be a major reason for the effects of vowel identity that were found. Another possible physiological explanation is the acoustic impedance of the vocal tract. High vowels /i, u/ have higher vocal tract acoustic impedance due to a more constricted vocal tract than low vowels. When the acoustic impedance becomes high enough, the vocal tract can affect the source and can lead to less stable vocal fold vibration through nonlinear source-filter coupling.[25] Less stability of vocal fold vibration in high vowels may be related to our result that high vowels result in lower onset RFF values. However, the small effect size may indicate that vowel identity may not be a major factor that affects RFF values.

Baseline f_0

We found a significant effect of baseline f_0 in onset 1 RFF mean values with a medium effect size. The *post hoc* test revealed that RFF values from the low baseline f_0 condition were significantly higher than RFF values from high baseline f_0 condition. However, RFF values from the comfortable baseline f_0 condition did not significantly differ from RFF values from the low or high conditions. The participants produced RFF stimuli with 3 ST above and below the comfortable baseline f_0 for the high and low baseline f_0 trials. Thus, it could be inferred that a 3-ST difference may not have been large enough to affect RFF values. These findings are consistent with our hypothesis that a higher baseline f_0 would result in a smaller change in f_0 (smaller RFF values) during voiceless consonant production in a VCV context than a lower baseline f_0 due to increased vocal fold tension. In addition, our results may also imply that a small difference in baseline f_0 (eg, +/− 3 ST) may not affect RFF values, and that RFF may be resistant to minor variation in baseline f_0.

Loudness

Our hypothesis that loud voice production would have lower RFF values was not supported by the results. The loudness variations in our study seemed to be appropriate: we found a mean increase from comfortable to loud voice of 6.0 dB (SD = 2.5 dB). This increase is similar to the 6.3- to 8.1-dB increase from comfortable to loud voice found in a recent study, which resulted in changes in acoustic perturbation measurements.[26] However, participants in our study may have used other methods to raise loudness instead of increasing laryngeal tension. Hirano et al[27] found that at low-to-medium intensities, the intrinsic laryngeal muscles played a key role controlling the intensity in voicing, but in

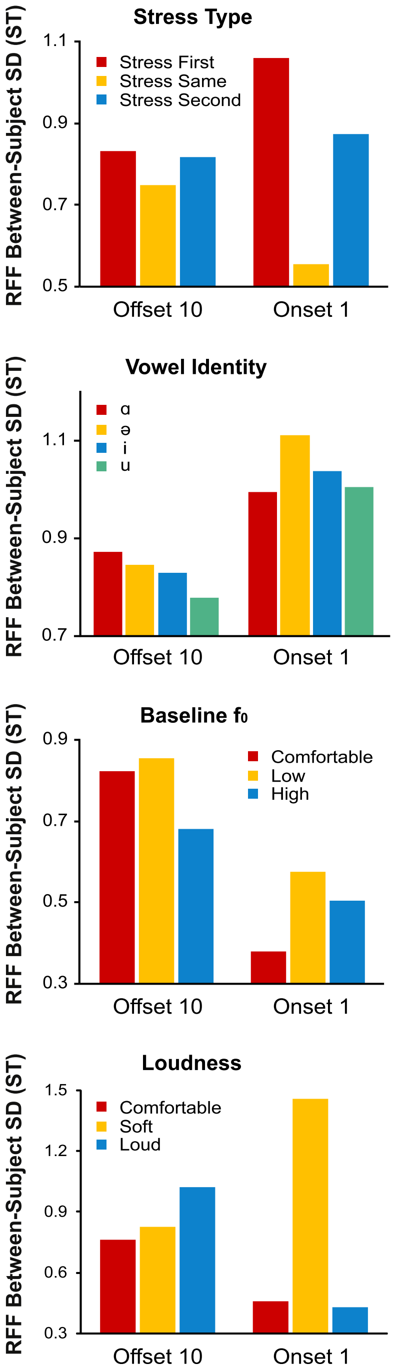

FIGURE 4. RFF offset 10 and onset 1 between-subject standard deviation from different conditions in each factor. The standard deviation was calculated with participants' mean values of each condition, so only one value is obtained for each conditions.

a high-intensity condition, the subglottal pressure was the primary contributor to the increase in vocal intensity. Although we did not find a significant effect of loudness on RFF means, this finding may support that minor differences in loudness would not affect RFF results.

Interestingly, onset 1 RFF values from soft voice productions showed a large range of RFF values (Figure 5) and high between-subject SD (Figure 4; Loudness). Soft voice, in a previous study,[28] also resulted in higher between-speaker variability in perturbation measures (eg, jitter and shimmer). Brockmann et al in 2008 attributed the finding to the fact that soft voice is produced with a higher glottal open quotient and lower intrinsic muscle tension, which results in more variable mucosa cover vibration of the vocal folds.[28] Brockmann et al further suspected that this mucosa cover variability in soft voice might track subtle laryngeal tension differences in functional voice disorders. Their explanation may also apply to our findings of variation in RFF during soft voice. Our results support a possible clinical value of analyzing RFF measurements during soft voice productions.

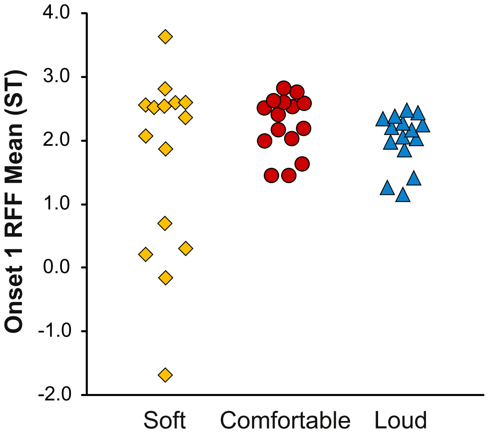

FIGURE 5. Individual onset 1 RFF values as a function of loudness in ST. These values are from the same data in Figure 2 (Loudness, Onset 1). This figure is to highlight a wide range of values resulted in soft voice compared to other loudness.

Clinical translation of findings

From the findings of the current study, we can extend the RFF stimuli recommendations of Lien et al.[13] Lien et al recommended a uniform utterance with a fricative consonant, such as /ʃ/ or /f/. We further recommend that RFF stimuli are produced with equal stress across the syllables based on our findings that stress type has a significant effect and the "stress same" had the lowest within-subject SD. Stress type should be consistent especially when RFF is used to track progress during therapy sessions. Comfortable pitch and loudness are recommended, but minor variations are acceptable.

Limitations and future directions

One limitation of this study is that sentence stimuli were not included. Even though prior studies showed that sentence stimuli resulted in higher SDs compared to short utterance stimuli,[13] sentence stimuli may still be valuable because of their high external validity. We recommend future studies to examine sentence stimuli with controlled stress types in RFF instances.

Another limitation of this study is that our results represent only healthy voices, not disordered voices. Individuals with disordered voices may respond differently to the factors in RFF stimuli, so we do not know yet what the best RFF stimuli are for all voice types. Future studies should examine these factors in individuals with disordered voices to enhance the stimuli for clinical use.

CONCLUSIONS

We sought to improve the reliability of RFF estimation by determining which factors in short RFF stimuli can affect RFF values. Stress type, vowel identity, and baseline f_0 all showed significant effects on RFF mean values, although with different effect sizes. We recommend that, among other factors, stress type should be controlled due to its large effect on RFF; we recommend using the "stress same" type in clinical practice and future research due to its low within-subject SD. Our results also suggest that minor differences in pitch and loudness would be less likely to affect RFF values, a possible strength of RFF as a clinical measure.

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