JSLHR

Research Article

Changes in Relative Fundamental Frequency Under Increased Cognitive Load in Individuals With Healthy Voices

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Purpose: The purpose of this study was to determine the effect of cognitive load on relative fundamental frequency (RFF) in individuals with healthy voices.
Method: Twenty adults with healthy voices read sentences under different cognitive load conditions. Each sentence contained color terms printed in colored ink, creating an embedded Stroop task. Participants read the ink color in which a word was printed, rather than the color term itself. Sentences with mismatched ink colors and printed words constituted an increased cognitive load. RFF, an acoustic correlate of laryngeal tension, was calculated for the 10 voicing cycles preceding (i.e., offset) and following (i.e., onset) voiceless consonants. Repeated measures analyses of variance were constructed to assess the effects of RFF cycle, cognitive load, and their interaction on mean RFF offset and onset.
Results: There was a significant effect of cognitive load condition on RFF offset. There was no significant effect of condition on RFF onset nor significant interaction between cycle and condition on RFF onset or offset values.
Conclusion: Reduced mean RFF offset may indicate an increase in laryngeal muscle tension during a cognitively demanding task.

The sympathetic division of the autonomic nervous system is known to respond to stress conditions, including cognitively demanding tasks (Bear et al., 2007). This arousal of the autonomic nervous system under increased cognitive load has been shown to affect several characteristics of speech articulation, including rate (Lively et al., 1993), lip kinematics (Dromey & Benson, 2003; Kleinow & Smith, 2006), production accuracy (MacPherson, 2019), and fluency (Weber & Smith, 1990). These changes are thought to be driven by the reallocation of neural resources when cognitive demands are relatively high (Dromey & Benson, 2003), with implications for speech motor control.

Cognitive load has also been shown to affect voice production. Several studies have documented changes in mean fundamental frequency (F0), F0 variation, sound pressure level, and frequency and amplitude perturbation (e.g., jitter and shimmer) under increased cognitive load. Results across these studies are inconsistent, however. For example, researchers have found F0 to increase (Boyer et al., 2018; Mendoza & Carballo, 1998; Perrine & Scherer, 2020; Ruiz et al., 1996; Scherer et al., 2002), decrease (Dietrich, 2008; Streeter et al., 1983; Van Lierde et al., 2009), and remain unchanged (Lively et al., 1993; MacPherson et al., 2017) with cognitive loading. Variable results have also been found for F0 variation (Boyer et al., 2018; Lively et al., 1993), sound pressure level (Lively et al., 1993; MacPherson et al., 2017), and perturbation measures (Boyer et al., 2018).

It may be that acoustic correlates of voice quality are more sensitive to cognitive stressors than are measures of frequency and amplitude. Boyer et al. (2018) found harmonic-to-noise ratio (HNR) to vary significantly with cognitive load during a word list recall task. As the number of words increased, so did HNR. HNR was not a significant predictor of cognitive load, however. The authors stated that, given the relationship between HNR and vowel type, voice quality measures independent of vowel type, such as low-to-high spectral energy ratio (LHR), may be stronger predictors of mental load.

Likewise, MacPherson et al. (2017) found LHR and cepstral peak prominence (CPP) to be significant predictors of cognitive load in speakers with healthy voices. In their study, speakers showed an increase in CPP and a decrease

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Editor-in-Chief: Julie Barkmeier-Kraemer

Received March 26, 2020
Revision received November 19, 2020
Accepted January 6, 2021
https://doi.org/10.1044/2021_JSLHR-20-00134

Disclosure: *Cara E. Stepp has received consulting fees from Altec, Inc./Delsys, Inc., companies focused on developing and commercializing technologies related to human movement. Stepp's interests were reviewed and are managed by Boston University in accordance with their conflict of interest policies. The other author has declared that no other competing interests existed at the time of publication.*

in LHR when speaking under increased cognitive load. Decreased LHR can be indicative of increases in higher frequency harmonics or higher frequency noise relative to low frequency harmonics. However, given that the decreases in LHR were accompanied by increases in CPP, the authors interpreted these results as indicating that the speakers may have used a more pressed voice with more energy in higher harmonics in the cognitively demanding condition. This explanation is consistent with the finding that autonomic arousal is associated with increased activation of intrinsic laryngeal muscles (Helou et al., 2013, 2018). Thus, voice changes in response to cognitive load may result from the increase in laryngeal muscle tension that occurs during autonomic arousal. Additional research is needed, however, to determine that it is in fact this increased tension that is driving these changes in acoustic metrics of voice quality. Establishing this relationship would provide support for the use of acoustic measures to identify increased laryngeal tension, with applications for the assessment and treatment of muscle tension-related voice disorders, such as vocal hyperfunction.

Relative fundamental frequency (RFF) has shown promise as an acoustic correlate of laryngeal muscle tension (Park & Stepp, 2019b; Roy et al., 2016; Stepp et al., 2010). RFF is an acoustic measure of changes in F0 during transitions between voiced and voiceless segments. Individuals with vocal hyperfunction, a disorder characterized by excessive laryngeal tension (Hillman et al., 1989), typically have lower RFF values than do speakers with healthy voices (Heller Murray et al., 2017; Roy et al., 2016; Stepp et al., 2010). Lower RFF values relative to speakers with healthy voices have also been found in individuals with other disorders associated with laryngeal tension or rigidity, namely, adductor-type laryngeal dystonia (Eadie & Stepp, 2013) and Parkinson's disease (Goberman & Blomgren, 2008; Stepp, 2013). Finally, RFF values are reduced relative to baseline when individuals with healthy voices purposefully phonate with increased strain (Lien et al., 2015). We might therefore expect RFF values to decrease during voice production under increased cognitive load, when the autonomic nervous system is aroused and there is greater tension in the laryngeal muscles, consistent with a more pressed style of phonation.

Thus, the purpose of this study was to determine the effect of increased cognitive load on RFF in individuals with healthy voices. Cognitive load during speech production was manipulated using a modified, sentence-level Stroop task (Stroop, 1935). Stroop tasks are designed to measure the inhibition of cognitive interference in the presence of mismatched stimuli (Scarpina & Tagini, 2017), in this case, color terms printed in colored ink within sentences read aloud by participants. We hypothesized that RFF values for these speakers with healthy voices would decrease when cognitive load increased.

Method

Participants

Participants were 20 young adults with healthy voices (10 women, 10 men; age range: 18–22 years, M = 20.2 years, SD = 1.4 years) selected from an existing database of voice recordings at Boston University. No participant reported a history of communication disorder or cognitive disorder. Participants passed a color blindness screening[1] (Ishihara, 2011) and a pulsed-tone hearing screening at a minimum threshold of 30 dB at octaves from 125 to 8000 Hz. All participants provided written consent in accordance with the Boston University Institutional Review Board.

Procedure

Participants were recorded while reading aloud sentences that contained an embedded Stroop task and sequences of voiced–voiceless–voiced phonemes as necessary for measuring RFF (see Appendix for list of sentences). All acoustic recordings were collected in a sound-treated room at Boston University using a head-mounted microphone (Shure WH20) with a sampling rate of 44.1 kHz.

The Stroop task was used to manipulate cognitive load during voice production, as in previous studies (Kleinow & Smith, 2006; MacPherson, 2019; MacPherson et al., 2017; Ruiz et al., 1996). Participants read 12 sentences, each containing a sequence of four color terms printed in colored ink (e.g., "Then our pal gave blue, purple, brown, and red new posters to us"). All other words were printed in black. The first six sentences constituted the congruent condition, in which the color terms and colored ink matched (e.g., "blue" printed in blue ink). The remaining six sentences constituted the incongruent condition, in which there was a mismatch between the color terms and colored ink (e.g., "red" printed in blue ink). In both conditions, participants were instructed to say the color of the ink in which the word was printed, not the printed word itself. Thus, cognitive load was at a typical level during the congruent condition and at an increased level during the incongruent condition.

The congruent condition always preceded the incongruent, with no break in between. Laryngeal responses to autonomic arousal may persist for several minutes after removal of a stressor (Helou et al., 2013). A fixed condition order was thus necessary to ensure that autonomic arousal induced during the incongruent condition did not interfere with measures collected during the congruent condition.

Each condition contained three carrier sentences that were repeated twice, with each repetition having a different sequence of color terms. Although the printed color terms differed between the congruent and incongruent conditions, the colored ink was the same. Thus, the target production for each set of six sentences was identical across conditions. When participants erred during the production of a sentence, they were informed of the error and asked to repeat the sentence. Long pauses or substantial slowing of speech were not corrected during recording but were evaluated during analysis to determine usability of productions (see

[1]Two participants were not administered the color blindness screening, as this task was added to the recording procedure after these participants completed the study. Neither participant reported a history of color blindness or difficulty perceiving the ink colors during the study.

Acoustic Analysis section). The sentences had a Flesch Reading Ease score of 85.6 and thus were expected to be easy to read (Flesch, 1948).

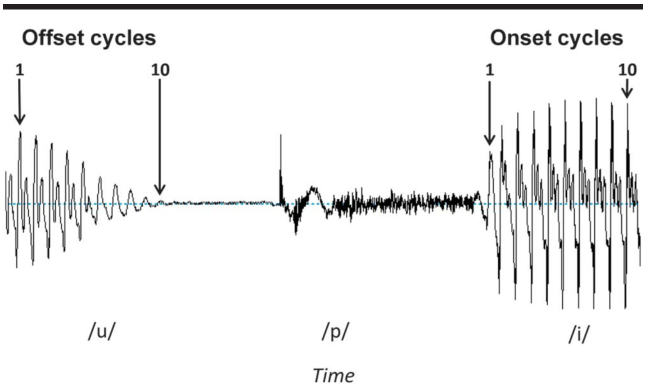
Each sentence included in the Stroop task also contained sequences of phonemes necessary for RFF analysis. Such sequences included two voiced sonorants with an intervening voiceless obstruent (e.g., /ɝpæ/ in "our pal" and /upoʊ͡/ in "new posters"). RFF tokens were distributed throughout the sentence so that each one contained at least one RFF token before, within, and after the embedded Stroop task (i.e., the color terms). Each sentence contained four to seven RFF sound sequences, for a total of 68 possible RFF tokens per condition (34 offset and 34 onset).

Acoustic Analysis

RFF is an acoustic measure of changes in F0 in the 10 voicing cycles immediately preceding and following a voiceless consonant. While algorithms for automatic RFF calculation have been recently developed (Lien et al., 2017; Vojtech et al., 2019), the connected speech stimuli used in this study mandated manual analysis of RFF in Praat (Boersma & Weenink, 2015).

Manual calculation of RFF began with the identification of the voicing cycle closest to the voiceless consonant—that is, the last of the voicing offset cycles and the first of the voicing onset cycles (see Figure 1). The pulse function in Praat was then used with standard pulse settings to calculate the period of each of the 10 offset and onset cycles. Pitch settings were adjusted as needed to achieve proper tracking of F0 and thus alignment of the displayed pulses with the cycle already identified as the last offset or first onset cycle. Praat's pulse listing provided timestamps for this cycle and the 10 preceding (offset) or following (onset) cycles. The timestamps were used to calculate the period of each cycle. The period of each cycle was inverted to calculate instantaneous F0. The instantaneous F0 was then converted to semitones (ST) relative to a reference F0 from the steady state of the voiced segment (i.e., the first offset or last onset cycle; see Equation 1).

Figure 1. Acoustic waveform of a sonorant—voiceless consonant—sonorant sequence from the phrase "blue, pink." Offset and Onset Cycles 1 and 10 are labeled.



$$RFF(\mathrm{ST}) = 39.86 \times \log_{10}\left(\frac{cycle\ f_o}{reference\ f_o}\right). \quad (1)$$

RFF tokens were rejected if any of the following were present during the production (number [percent] of rejections): voicing of the voiceless segment (1,053 [39%]); glottalization, or vocal fry, which is characterized by relatively low F0, low amplitude, and tightly approximated vocal folds (Colton et al., 2011; 138 [5%]); short voiced segment (< 10 voicing cycles; 125 [4%]); long pauses between phonemes (> 250 ms; 86 [3%]); failure to reach steady state during the voiced segment (51 [2%]); word errors (7 [0.2%]); or presence of background noise (1 [0.03%]). The resulting data set included at least seven usable RFF tokens per type (onset, offset) for each speaker and condition (M = 14.5 tokens), thus adhering to the minimum of six tokens recommended for reliable RFF measurement (Eadie & Stepp, 2013).

Differences in the rate of speech between congruent and incongruent conditions were also measured for each participant. Total duration of each sentence in the congruent condition was measured and compared to its counterpart in the incongruent condition. The purpose of this calculation was to identify any substantial slowing of speech during the incongruent condition. In the case of a substantial rate decrease, we could not be confident that the intended effect of increased cognitive load had been achieved. The criterion for rejection of a sentence was a difference in duration between congruent and incongruent conditions greater than four seconds. This cutoff corresponded to the authors' perception of substantially reduced speaking rate when evaluating Stroop task recordings from a larger database of recordings. Rejection criteria corresponding to shorter differences in duration (i.e., 3.5 s and 3.0 s) were considered, but neither had an effect on the resulting data set or statistical results so the original criterion was maintained. No productions were rejected based on this criterion; the mean difference between productions in the congruent and incongruent conditions was 0.44 s (SD = 0.64 s, range: 0–3.41 s).

The F0 traces were extracted from Praat for each sentence in each condition after visual inspection of Praat's pitch tracking. Pitch settings were adjusted as needed to ensure proper tracking. Mean F0 for each subject was calculated for each condition.

Intra- and interrater reliability of RFF analysis was assessed by repeating 15% of samples for re-analysis. The lead author reanalyzed these repeated samples several months after the initial analysis, and a second researcher independently analyzed these samples. Pearson product–moment correlation coefficients showed high intrarater (r = .98) and interrater (r = .91) reliability.

Statistical Analysis

The resulting number of RFF tokens used in the statistical analysis was 1,143 (588 in the congruent condition, 555 in the incongruent condition). Repeated-measures two-way analyses of variance (ANOVAs) were constructed to measure the main effects of RFF cycle (1–10) and condition (congruent, incongruent) on mean RFF offset and mean RFF onset and to measure the interaction between cycle and condition. Effect sizes for significant effects and interactions were calculated as partial eta squared (η_p^2). As a post hoc explanatory analysis, a repeated-measures two-way ANOVA was also constructed to measure the main effect of condition on mean F0. Statistical analyses were conducted in Minitab (Version 18, Minitab, Inc.).

Table 1. Results of two-way analysis of variance on mean offset relative fundamental frequency values.

Effect	*df*	η_p^2	*F*	*p*
Cycle	9	.10	4.25	< .01*
Condition	1	.01	5.21	.023*
Cycle × Condition	9	NS	0.55	.836

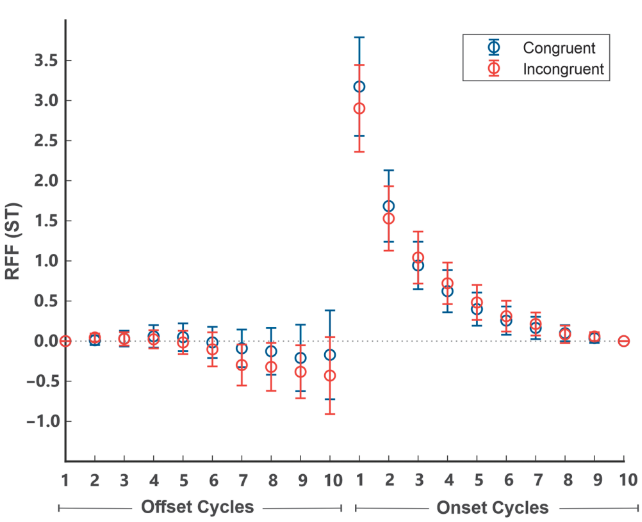
Note. NS = not significant.
*Significant at $p < .05$.

Results

Mean RFF values by cognitive load condition are shown in Figure 2. In the congruent condition, mean RFF offset at cycle 10 was −0.17 ST and mean RFF onset at Cycle 1 was 3.24 ST. In the incongruent condition, mean RFF offset at Cycle 10 was −0.42 ST, and mean RFF onset at Cycle 1 was 2.90 ST.

The results of two-way ANOVAs on mean RFF offset and mean RFF onset values are shown in Tables 1 and 2, respectively. There was a small but significant effect of cognitive load condition ($p = .023$, $F = 5.21$, $\eta_p^2 = .01$) on mean RFF offset. Mean RFF offset values were reduced under increased cognitive load. There was also a significant effect of cycle on mean RFF offset with medium effect size ($p < .001$, $F = 4.25$, $\eta_p^2 = .10$) and on mean RFF onset with large effect size ($p < .001$, $F = 151.38$, $\eta_p^2 = .79$). Mean RFF values of cycles closest to the voiceless consonant differed significantly from those nearer the center of the vowel. Specifically, RFF of offset cycles nearest the voiceless consonant were lower than earlier cycles, and RFF of onset cycles nearest the voiceless consonant were greater than later cycles. There was no significant effect of condition on RFF onset, nor significant interactions between cycle and condition on onset or offset RFF values.

Figure 2. Mean relative fundamental frequency (RFF) in congruent (blue markers) and incongruent (red markers) conditions. ST = semitones.



To better illustrate the change in RFF offset between congruent and incongruent conditions at an individual participant level, the difference between the sum of all RFF offset values in each condition was calculated in ST (see Figure 3). Twelve participants (60%) demonstrated a decrease in RFF offset in the incongruent condition, as indicated by a negative difference in RFF offset between conditions. Eight participants (40%) demonstrated an increase in RFF offset in the incongruent condition, or a positive difference between conditions.

Results of the post hoc explanatory analysis of F0 demonstrated no significant effect of condition on F0 ($p = .155$, $F = 2.20$). Thus, there was no significant difference in mean F0 between the congruent and incongruent conditions.

Discussion

The purpose of this study was to determine the effect of cognitive load on RFF in speakers with healthy voices. Cognitive load did indeed have a small but significant effect on RFF offset, but no significant effect was found for RFF onset.

Comparison With the Literature

Mean RFF values for young adults with healthy voices speaking under typical cognitive load in this study are consistent with those in earlier research (Robb & Smith, 2002; Stepp et al., 2010). The pattern of RFF changes during transition into and out of the voiceless consonant (see

Table 2. Results of two-way analysis of variance on mean onset relative fundamental frequency values.

Effect	*df*	η_p^2	*F*	*p*
Cycle	9	.79	151.38	< .01*
Condition	1	NS	0	.994
Cycle × Condition	9	NS	0.60	.795

Note. NS = not significant.
*Significant at $p < .05$.

Figure 3. Change in relative fundamental frequency (RFF) during offset cycles between congruent and incongruent conditions. Change was calculated as the difference between sums of RFF offset values in incongruent and congruent conditions. ST = semitones.

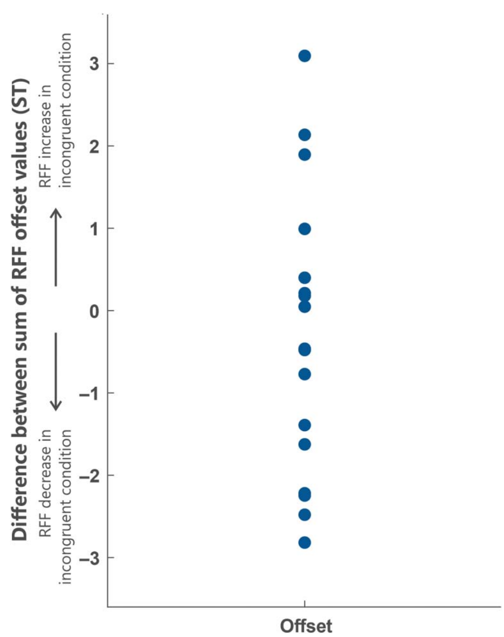


Figure 2) appears to be typical of young speakers with healthy voices. Specifically, RFF during offset cycles was relatively flat at around 0 ST with a slight decrease in RFF at the devoicing transition. RFF at voicing onset was relatively high at around 3 ST, followed by a sharp decrease over onset cycles. This same pattern, as well as mean values for manually measured RFF, has been documented in young speakers with healthy voices in previous work (Robb & Smith, 2002; Roy et al., 2016; Stepp et al., 2010), with one exception (Watson, 1998) in which there was a slight increase in offset RFF just before the voiceless consonant.

Mean offset RFF values were lower relative to those in the congruent condition when cognitive load increased. This increased cognitive load is associated with autonomic arousal (MacPherson et al., 2017) and thus an expected increase in laryngeal tension (Helou et al., 2018, 2013). This finding is consistent with previous work showing lower RFF values among individuals with disorders associated with increased laryngeal tension or rigidity (Eadie & Stepp, 2013; Goberman & Blomgren, 2008; Heller Murray et al., 2017; Roy et al., 2016; Stepp, 2013; Stepp et al., 2010). RFF values in these populations varied from −0.52 to −2.20 ST for RFF offset and from 1.10 to 2.60 ST for RFF onset. Of note, mean RFF values in this study fell outside of these ranges, with mean offset RFF at −0.42 ST and mean onset RFF at 2.90 ST. Thus while increased cognitive load was associated with a reduction in RFF in the study sample, these values remained within the range of speakers with healthy voices.

RFF as a Correlate of Laryngeal Tension

The stressor used in this study, increased cognitive load, has been shown to instigate autonomic nervous system arousal (Bear et al., 2007), with related effects on voice quality (MacPherson et al., 2017) and laryngeal muscle tension (Helou et al., 2018, 2013). While the changes in voice quality that have been observed under increased cognitive load —increased CPP and decreased LHR (MacPherson et al., 2017)—are suggestive of greater laryngeal tension, such as that used during pressed phonation, this link has not previously been established. The findings of this study, in which a small but significant reduction in mean RFF offset was observed under increased cognitive load, provide additional evidence that acoustic changes in voice under this condition are likely driven by increased laryngeal tension.

These results are consistent with a growing body of literature suggesting that RFF is an acoustic correlate of laryngeal tension. Previous work has demonstrated that RFF is decreased in individuals with voice disorders associated with increased laryngeal tension, including vocal hyperfunction (Heller Murray et al., 2017; Roy et al., 2016; Stepp et al., 2010), adductor-type laryngeal dystonia (Eadie & Stepp, 2013), and Parkinson's disease (Goberman & Blomgren, 2008; Stepp, 2013). RFF has also been shown to decrease when individuals with healthy voices deliberately increase strain during voice production (Lien et al., 2015). While in this study, the effect of cognitive load was small and only significant for RFF offset, these results align with previous findings.

The lack of a significant effect of cognitive load on RFF onset, where such an effect was found for RFF offset, warrants further discussion. Other studies have also shown that offset and onset RFF values do not always show the same effects (Eadie & Stepp, 2013; Heller Murray et al., 2017, 2020). This difference is accounted for in the model of RFF proposed by Stepp et al. (2011) and updated by Heller Murray et al. (2017). In this model, RFF values result from the relative contributions of baseline vocal fold tension, aerodynamic factors, and abductory factors. Differences in baseline vocal fold tension, as between individuals with and without vocal hyperfunction, are associated with disparate effects of decreased pressure across the glottis (i.e., aerodynamic factors; Ladefoged, 1967) and length of vibratory periods (i.e., abductory factors; Watson, 1998), thus resulting in differences in RFF values.

In the revised model proposed by Heller Murray et al. (2017), the specific type of laryngeal tension present —longitudinal or transverse—may also contribute to differences in RFF values. The authors suggested that individuals with vocal hyperfunction demonstrate increased longitudinal tension as a result of increased activity of the cricothyroid (Jaiswal, 2011; Stevens, 1977) or vocalis muscles (Hirano, 1974), or as a result of stretching related to higher laryngeal posturing (Stevens, 1977). Individuals with phonotraumatic vocal hyperfunction also demonstrate increased transverse tension, with the vocal folds more tightly adducted (Hillman et al., 1989). Heller Murray et al. (2017)

suggest that both patterns of increased tension—longitudinal only and combined longitudinal and transverse—result in decreased RFF values. However, they proposed that the effect of longitudinal tension alone would be smaller, particularly for RFF onset values. Increased longitudinal tension results in incomplete vocal fold adduction at voicing onset, thus extending the time during which aerodynamic factors are in effect (Heller Murray et al., 2017). The result is that the expected tension-related decrease in RFF values at voicing onset is mitigated by an expected increase driven by corresponding changes in aerodynamic effects.

Interpreting the results of this study within this revised model of RFF suggests that speakers with healthy voices may increase longitudinal tension of the vocal folds under increased cognitive load without any significant change in transverse tension. Such a pattern of RFF changes between typical and increased cognitive load would be similar to the pattern of RFF changes previously seen between speakers with and without nonphonotraumatic vocal hyperfunction (Heller Murray et al., 2017). An increase in F0 under cognitive load would provide further support for this interpretation, as greater longitudinal tension would be expected to induce an increase in F0. While previous studies have documented F0 increases under cognitive load (Boyer et al., 2018; Mendoza & Carballo, 1998; Perrine & Scherer, 2020; Ruiz et al., 1996; Scherer et al., 2002), no such effect was identified in this study. Thus, this interpretation is offered with some caution, as further study of the relationship between cognitive load and laryngeal tension is needed. Future study of the impacts of autonomic arousal in individuals with nonphonotraumatic vocal hyperfunction may also help clarify these findings.

Clinical Implications

Despite the prevalence of vocal hyperfunction among voice clinic patients (Roy, 2003), assessment of this disorder still relies primarily on subjective evaluation based on patient complaints, perceptual assessment, and laryngeal exam. A reliable, objective measure to identify the presence and severity of excessive laryngeal tension has not yet been found. RFF has shown promise as a reliable acoustic correlate of laryngeal muscle tension (Park & Stepp, 2019b; Roy et al., 2016; Stepp et al., 2010). The relationship between cognitive load—a factor known to induce laryngeal tension—and RFF in this study aligns with work supporting the use of RFF as an indicator of laryngeal tension.

A few points of caution are warranted, however. First, a decrease in RFF between the congruent and incongruent conditions was observed in some participants, but not all. This finding is illustrated in Figure 3. Whereas 60% of participants (n = 12) showed an expected decrease in RFF in the incongruent condition, several participants (40%; n = 8) showed a change in the opposite direction. Second, the manual analysis of RFF necessary for this study entailed a time commitment that is prohibitive in a clinical setting. Automation of RFF calculation (see Lien et al., 2017; Vojtech et al., 2019) is thus key to the viability of RFF analysis as a clinical tool. Finally, the number of tokens rejected as unusable for RFF calculation (54% of the total sample) demonstrates the need to use specific stimuli for RFF analysis. While connected speech samples were required for cognitive load manipulation in this study, voice samples collected to measure RFF for clinical purposes should adhere to recommendations regarding phonetic context (Lien et al., 2014) and stress pattern (Park & Stepp, 2019a) that improve reliability of RFF analysis.

Limitations and Future Directions

This study sought to determine the effect of cognitive load on voice production in speakers with healthy voices. As all participants were young adults, aged 18–22 years, these results may not be generalizable to adults across the life-span. In fact, cognitive load has been shown to affect speech motor control differently in older adults (MacPherson, 2019), and thus its effects on RFF in an older population may differ. All participants were speakers with healthy voices. Future research should compare the effects of cognitive load on RFF in individuals with and without voice disorders, particularly disorders characterized by increased laryngeal tension. The vocal health status of participants was determined by self-report. Participants did not undergo a clinical evaluation by a laryngologist. It is thus possible that the study sample included participants with undiagnosed voice disorders. Participant scores on voice-related self-assessment instruments, however, suggest that this is unlikely; all participants scored ≥ 95 on the Voice-Related Quality of Life (Hogikyan & Sethuraman, 1999) or ≤ 25 on the Voice Handicap Index (Jacobson et al., 1997).

Finally, neither laryngeal tension nor autonomic arousal was directly measured. Autonomic arousal was assumed to have taken place under increased cognitive load, as has been demonstrated by others (MacPherson et al., 2017), but was not confirmed with physiologic measures. Because autonomic arousal was not directly measured, a strict task order—congruent followed by incongruent condition—was maintained across subjects. While this prevented carryover of the effects of autonomic arousal from one condition to the other, order effect could not be assessed. Future work would benefit from a counterbalanced condition order while incorporating a sufficient break between conditions to ensure return to baseline autonomic function or confirming autonomic status with physiologic measures. Research confirming increased laryngeal tension via videostroboscopic assessment could also help contextualize these findings.

Conclusions

RFF offset decreased under increased cognitive load in individuals with healthy voices. This reduction in mean RFF offset values suggests an increase in laryngeal muscle tension during a cognitively demanding task, as would be expected under conditions of autonomic nervous system activation. This finding provides further support for RFF as a measure of laryngeal tension, with applications for diagnosis and treatment of hyperfunctional voice disorders.

Acknowledgments

This work was supported by Grant DC015570 (awarded to C. E. S.) from the National Institute on Deafness and Other Communication Disorders. The authors thank Samantha Shank for her assistance with data analysis.

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Appendix

Stroop Task Sentences

Congruent condition sentences

Then our pal gave **blue**, **purple**, **brown**, and **red** new posters to us.
Later Marie painted **red**, **blue**, **pink**, and **green** for two paintings in a row.
Her friend Lee potted **gray**, **purple**, **green**, and **orange** new poppies for his mother.
Then our pal gave **orange**, **blue**, **purple**, and **green** new posters to us.
Later Marie painted **blue**, **pink**, **orange**, and **brown** for two paintings in a row.
Her friend Lee potted **green**, **gray**, **pink**, and **red** new poppies for his mother.

Incongruent condition sentences

Then our pal gave **red**, **brown**, **purple**, and **blue** new posters to us.
Later Marie painted **green**, **pink**, **blue**, and **red** for two paintings in a row.
Her friend Lee potted **orange**, **green**, **purple**, and **gray** new poppies for his mother.
Then our pal gave **blue**, **orange**, **green**, and **purple** new posters to us.
Later Marie painted **orange**, **brown**, **blue**, and **pink** for two paintings in a row.
Her friend Lee potted **gray**, **purple**, **green**, and **orange** new poppies for his mother.