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Research paper

Effects of hearing aid amplification on voice F0 variability in speakers with prelingual hearing loss☆

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ABSTRACT

To investigate the audio-vocal feedback responses of (F0) to hearing amplification in severe-to-profound prelingual hearing loss (SPHL) using power spectral analysis of F0 contour of sustained vowels. Sustained phonations of vowel/a/of seventeen participants with SPHL were acquired with and without hearing-aid amplifications. The vocal intensity was visually fed back to the participants to help controlling the vocal intensity at 65–75 dBA and 85–95 dBA. The F0 contour of the phonations was extracted and submitted to spectral analysis to measure the extent of F0 fluctuations at different frequency ranges. The results showed that both high vocal intensity and hearing-aid amplification significantly improved voice F0 control by reducing the low-frequency fluctuations (low-frequency power, LFP, 0.2–3 Hz) in F0 spectrum. However, the enhanced feedback from higher vocal intensity and/or hearing amplification was not adequate to reduce the LFP to the level of a normal hearing person. Moreover, we found significant and negative correlations between LFP and supra-threshold feedback intensity (phonation intensity − hearing threshold level) for the frequencies of 500–2000 Hz. Increased vocal intensity, as well as hearing-aid amplification, improved voice F0 control by reducing the LFP of F0 spectrum, and the subtle changes in voices could be well explored using spectral analysis of F0.

1. Introduction

Human phonation is closely and reflexively monitored by audio-vocal system, and there is an important feedback, the so-called audio-vocal feedback, linking the two systems with the purpose of producing and maintaining a steady and desired vocalization. The feedback is conducted by a neural loop consists of auditory system, phonatory system, and central nervous system. This feedback is usually a negative one acting to maintain a stable vocal performance and can be classified in the domains of intensity, frequency, and temporal feedback according to the acoustic characteristics. Lombard effect is featured with the increase of a speaker's vocal intensity in response to the noises (Egan, 1975; Pick et al., 1989) and is a typical example of audio-vocal feedback related with the adjustment of vocal intensity. Moreover, the studies of delayed auditory feedback revealed disrupted speech fluency, increased vocal intensity, decreased speaking velocity, and articulation problems (Black, 1951; Fairbanks, 1955; Fairbanks and Guttman, 1958; Zanini et al., 1999). All these studies showed the evidence of auditory feedback in temporal domain. Apart from intensity and temporal feedback, voice fundamental frequency (F0) is also feedback controlled by auditory feedback mechanism. In the studies of pitch-shift reflex (PSR), F0 showed a bi-directional compensatory response to the pitch-shift stimulus in order to adjust F0 to a desired level (Burnett et al., 1998; Hain et al., 2001; Larson et al., 2000). The responses of PSR are another example of audio-vocal reflex in frequency domain.

Deviant speech/voice physiology of abnormal vocal fold tension and articulation was discovered in the children with moderate-to-severe sensorineural hearing loss (SNHL) who had diminished auditory input and feedback (Higgins et al., 2005). Besides, in these

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Abbreviations: ANOVA, analysis of variance; F0, vocal fundamental frequency; HFP, high-frequency power; LFP, low-frequency power; LSD, least significant difference; MFP, middle frequency power; PSR, pitch-shift reflex; RAP, relative average perturbation; SNHL, sensorineural hearing loss.

☆ Example software of power spectral analysis of F0 can be retrieved by Email or the following link http://lgs.myweb.hinet.net/Articles/F0V%20Demo.htm.

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subjects, the poor speech perception skills may be associated with an abnormally high vocal fundamental frequency (Higgins et al., 2005). Interestingly, the high F0 of the pre-implanted subjects with SNHL decreased significantly to the normative values after cochlear implantation (Hamzavi et al., 2000; Higgins et al., 2003; Kishon-Rabin et al., 1999; Langereis et al., 1998). Moreover, the variability of F0 such as frequency perturbations and standard deviation of F0 (pitch sigma) of the subjects with hearing loss was greater than that of the normally-hearing controls (Bolfan-Stosic and Simunjak, 2007). However, elevated F0 or increased variability of F0 does not necessarily means an impaired hearing of the vocalizing subject. A voluntarily high-pitch phonation and the disordered vocal fold vibrations will make a phonation similar to that of a hearing-impaired subject. Instead, an exclusive measurement of the phonatory changes related with hearing loss might be used to study the audio-vocal feedback and even to estimate hearing loss.

Recently, the spectral analysis of F0 was used to evaluate the F0 responses of audio-vocal feedback. The analysis needs to acquire a sustained voice, usually a vowel of longer than several seconds, and then retrieves all F0s of the voice. A contour of F0 is then obtained using signal processing of interpolation, re-sampling, and cent conversion. Thereafter, Fourier transformation is used to get the power spectrum of the F0 contour which decomposes the fluctuations of F0 by different frequencies. Using this method, a significant increase of low-frequency (0.2 Hz $\sim$ 3 Hz) F0 modulations was revealed when the auditory input was attenuated by binaural noise masking (Lee et al., 2004). Moreover, the amplitude of low-frequency F0 modulations was also significantly reduced when the test subjects raised their phonation intensity (Lee et al., 2007), and the low-frequency F0 modulations of the subjects with post-lingual sensorineural hearing loss (SNHL) were significantly greater than those of the subjects without hearing loss (Lee, 2012; Lee and Lin, 2009) at comfortable speech level. The low-frequency modulations of F0 are related with the auditory input for audio-vocal feedback and may be used to evaluate the F0 responses of this feedback and even to estimate the degree of hearing loss (Lee, 2012; Lee and Lin, 2009).

In the subjects with prelingually severe-to-profound SNHL, the hearing amplification with a hearing aid is widely used for audiological rehabilitation. But the hearing aids usually do not provide adequate amplification to compensate the severity of hearing loss, and commonly there presents a certain degree of abnormalities and delayed development in the spoken language. However, among the children with cochlear implants, the ones with better speech perception abilities could present with a lower variability of voice quality in perceptive-auditory analysis (Coelho et al., 2009). Nonetheless, for the subjects with moderate-to-profound hearing loss, and the speech/voice production abilities including vocal fold vibrations were still abnormal even in the ones having good to excellent oral communication skills, and the physiological assessments were not able to show a significant difference between aided and unaided vocalizations (Higgins et al., 1994). The voice changes related to hearing amplification may be too subtle and remain undetectable using the traditional physiological assessments for the hearing-impaired. However, in our previous research, even though the jitter was not able to show a significant change in different auditory status of audio-vocal feedback, the significant amplitude change of F0 modulations could be sensitively measured by power spectral analysis of F0 (Lee, 2012; Lee et al., 2004, 2007). Besides, the modulations of F0 responding to a hearing amplification remains unclear in the hearing-impaired. Therefore, we used this analysis to investigate the F0 of the phonations with different vocal intensities in the participants with prelingually severe-to-profound SNHL and especially to explore the phonations with and without hearing amplification. The results were also compared with our previous research to know more about the F0 responses of aided and unaided audio-vocal feedback in SNHL.

2. Materials and methods

2.1. Participants

Sixteen participants (9 males and 7 females) with prelingually severe-to-profound hearing loss were recruited from the Hard of Hearing Association in this study. The participants aged from 16 to 36 years with a median of 22 years. The onsets of hearing loss were all less than 3 years old and the participants all used the air-conduction hearing aid for hearing amplification. The average hearing thresholds (500 Hz, 1000 Hz, and 2000 Hz) of the better ear of all participants were 70 dB HL or worse. They had no medical history of neurological deficits, speech disorders, experience of training as a singer, or a recent upper respiratory infection. The study procedures were approved by the Institutional Review Board of National Yang Ming University (IRB-960014), and the written informed consents were obtained from all participants.

2.2. Sampling of voice

The participants were requested to start a steady-as-possible vocalization of vowel/a/(tone 1) for more than 5 s following a hand signal. Vowel [a] has the first formant frequency of around 600–800 Hz and the second formant of around 1000–1200 Hz. The phonations were controlled in the low-intensity range of 65 dBA to 75 dBA and in the high-intensity range of 85 dBA to 95 dBA using a real-time sound intensity monitor. Meanwhile, the phonations were made separately without or with wearing hearing aid, and all participants use air-conduction hearing aid for amplification. The mean aided hearing threshold levels of the participants (68 dB HL) were significantly better than the unaided mean hearing threshold levels (90 dB HL) ($p < 0.01$, paired sample t-test). Overall, there were four conditions of phonation for each participant including low-intensity phonation with hearing amplification (Aided-Low-Int), high-intensity phonation with hearing amplification (Aided-High-Int), low-intensity phonation without hearing amplification (Unaided-Low-Int), and high-intensity phonation without hearing amplification (Unaided-High-Int). To avoid an occlusion effect, the participants took off the hearing aids in Unaided-Low-Int and Unaided-High-Int conditions. Two steady phonations were recorded for each phonation condition, and the analytic results of the phonations were averaged to represent the results of the phonation condition.

The phonations of Unaided-Low-Int and Unaided-High-Int were arranged in random but were sampled as a group of phonations without hearing amplification. The phonations of Aided-Low-Int and Aided-High-Int were also arranged in random but were sampled as a group of phonations with hearing amplification. The two groups of phonations were also sampled randomly. The audibility of the phonations was acquired using a questionnaire at the end of each phonation. The vocal intensity signals were acquired from the sound level meter (TES-1350A TES Electrical Electronic Corp., Taipei, Taiwan) which was calibrated using the 1-kHz pure tone of 94-dB SPL. The intensity of signals was digitally sampled at the rate of 100 Hz and was real-time displayed as a visual bar on a laptop to assist the phonation control. The voice recordings were made in a quiet room with the background noises of less than 40 dBA. The voice signals were collected using a dynamic microphone (TES-1350A TES Electrical Electronic Corp., Taipei, Taiwan) at a distance of 15 cm in front of the participants' lips. The voices were digitally sampled at the rate of 44.1 kHz using the Realtek High Definition Audio sound adapter and were stored in a 16-bit digital