Altered Auditory Feedback in Teachers: A Preliminary Investigation

Charles J. Nudelman, Mary M. Flaherty, and Pasquale Bottalico, *Champaign, llinois*

Abstract: Purpose. Due to the elevated vocal risks of university professors and the possible relationship between auditory-motor integration and voice disorders, the current study was designed to explore the effects of altered auditory feedback via bone conduction on voice production measures in university professors.

Methods. A total of 43 hours of voice recordings across 32 university classes were collected from two vocally healthy college professors through voice dosimetry. During their classes, the professors experienced either the real-time altered auditory feedback or a condition without altered auditory feedback. The voice dosimetry recordings from all classes were processed to calculate the sound pressure level values, fundamental frequency values, and the time dose. The effects of the altered auditory feedback conditions on these voice acoustic parameters were analyzed and compared with the conditions without altered auditory feedback.

Results. The altered auditory feedback conditions resulted in significantly decreased sound pressure level values and time dose for both professors when comparing the altered auditory feedback conditions to the conditions without altered auditory feedback. The altered auditory feedback effects were larger for the male professor compared with the female professor. Additionally, the male professor demonstrated significantly decreased fundamental frequency values when comparing the altered auditory feedback conditions to the conditions without altered auditory feedback, while the female professor did not.

Conclusions. This study provides evidence that altered auditory feedback provided via bone conduction through an altered auditory feedback device resulted in statistically significant improvements in the voices of two college professors.

Key Words: Altered auditory feedback—Bone conduction—Voice production—Teachers..

INTRODUCTION

Individuals who speak extensively for their occupation are referred to as occupational voice users,[1] and about one-third of working adults in the United States are members of this category.[2] Teachers are occupational voice users, and they have been shown to have a high prevalence of voice disorders (up to 65%).[3,4] Within this group, university professors comprise a subgroup, which, to date, has been the subject of research in the field of speech science.

Among other differences from the broader population of teachers, professors have distinct job responsibilities. Their students are older and ostensibly more academically inclined, and their classes take place in a distinct academic culture.[5-8] Despite these differences from other teachers, professors remain at significant risk for voice disorders, and evidence indicates that up to 73.8% of university professors have voice-related complaints.[9] A recent systematic review clarified that about 41% of professors meet the criteria for a voice disorder.[5] University professors' occupational demands at baseline are associated with increased emotional distress, stress, and burnout.[10-12] With the addition of a health problem such as a voice disorder, professors' job performance and quality of life are significantly degraded.[9,13-15] Considering this phenomenon, voice research aims to produce translational findings aimed at informing innovative and ecologically valid habilitative interventions to be employed in the classroom. As occupational voice users, university professors' job responsibilities involve increased vocal demands (eg, teaching/lecturing for prolonged durations in classrooms, lecture halls, and/or auditoria[16]). Voice demands incur a vocal demand response, which is defined as a manner of voicing produced by an individual in an attempt to respond to a perceived vocal demand within a communication scenario.[17] For teachers specifically, hyperfunctional vocal demand responses—ie, higher-than-normal physical forces during habitual voice use in daily life[18]—contribute to a high prevalence of hyperfunctional voice disorders. For example, among different disorders within the category of hyperfunctional voice disorders, teachers have high rates of vocal fold nodules.[19-24]

Despite the known prevalence of vocal hyperfunction within teachers and university professors, clinical voice interventions remain primarily rehabilitative in nature (ie, a focus on regaining lost skills or functioning[25]), as opposed to habilitative in nature (ie, a focus on preventative efforts to reduce the likelihood that functioning will be lost). The primary voice-related habilitative recommendation provided by clinicians for teachers is to use personal voice amplification systems while teaching.[26-31] However, one study has empirically demonstrated that personal voice amplification devices actually worsen voice-related outcomes in teachers, ostensibly due to the relationship

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From the Department of Speech and Hearing Science, University of Illinois Urbana-Champaign, Champaign, llinois.

Address correspondence and reprint requests to Pasquale Bottalico, Department of Speech and Hearing Science, University of Illinois Urbana-Champaign, Champaign, Illinois. E-mail: pb81@illinois.edu

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between amplification devices and increased classroom noise (a risk factor for voice disorders).[32] One potential ecologically valid habilitative tool for teachers and university professors focuses on auditory-motor integration during voice production.

Recent research has provided empirical evidence supporting the use of real-time auditory feedback devices as effective habilitative tools in clinical practice. Maladaptive voice production in individuals with vocal hyperfunction is hypothesized to occur (at least partially) due to alterations in auditory-motor integration[33-37] and altered auditory feedback (AAF) can ostensibly address this issue. In addition to voice disorders, AAF has demonstrated efficacy in improving fluency in individuals who stutter (eg,[38,39]) and intelligibility for individuals with Parkinson's disease (eg,[40]). Additionally, AAF technology may serve as an augmentative tool to improve speech and voice outcomes within the domain of telemedicine, as teleconferencing technology itself may significantly influence speech (eg,[41]). One promising area of real-time AAF employs bone conduction.[42,43]

Sound waves are converted to neural impulses through both bone conduction and air conduction.[44] Bone conduction involves mechanical vibration to the bones of the skull, whereas air conduction involves transformation of the auditory sound wave into a mechanical signal within the middle ear. Regardless of the pathway, the mechanical vibrations are converted into neural impulses within the cochlea.[45,46] Typically, research investigating AAF has relied on air conduction feedback through the use of over-ear headphones.[47,48] However, bone conduction may be a better alternative, especially for teachers, as there is no occlusion of the users' ears. This would allow teachers to hear their students while receiving real-time AAF.

There is one commercially available AAF device that uses bone conduction to improve speech and voice outcomes. Forbrain®, developed by Sound For Life Limited (Soundev) in Luxemburg (model UN38.3, Europe, http://www.forbrain.com) uses a pair of bone conductors and a microphone to provide a speaker with real-time AAF. Research measuring the effects of the Forbrain® device reports significant improvements in CPPS and spectral tilt for 32 adult healthy speakers using the device[42] and significant improvements in self-reported vocal fatigue, sound pressure level (SPL) values, and spectral moments of the long-term average spectrum for 20 adult healthy speakers using the device.[49] According to its patent registration,[50] Forbrain® implements a two-band filter that applies one of two settings to the voice input. These two settings are activated by the input sound energy at 1 kHz over a time window of integration ranging 10-200 ms. The resulting output is altered in its frequency spectrum by the two-band filter and is then delivered through bone conduction headphones to the temporal bones.[42] As described previously, the Forbrain® device has been empirically tested and its use has resulted in improved voice quality with two samples of healthy speakers. Moreover, a simplified version of bone conduction AAF (without the two-band filtering) was demonstrated to significantly improve the voice quality of speakers with voice disorders[43] and healthy speakers.[49] The Forbrain® device may have merit as a habilitative tool for clinical care of the voice, however, it has yet to be studied within a sample of occupational voice users such as professors.

Due to the elevated vocal risk associated with university professors and the potential relationship between auditory-motor integration and vocal health, this study aimed to explore the impact of AAF, provided by the Forbrain® device, on voice production during teaching. Specifically, the study aimed to determine how this feedback might influence voice parameters compared with a non-AAF condition. Given the high vocal risk involved and the need for controlled conditions, this preliminary investigation was conducted with two participants to gather initial data and assess the feasibility and reproducibility of the methodology before scaling up to a larger study. The hypothesis was that the professors' voice parameters would indicate an increased risk for abnormal voice production in the non-AAF conditions compared with the AAF conditions.

MATERIALS AND METHODS

Two university professors (41 and 42 years) were enrolled in the study. One of the participants reported their sex as female and one as male. Both participants were self-described as conversationally proficient American English-speaking adults. Participants identified themselves as Non-Hispanic White. With protocol approval from the University of Illinois Urbana-Champaign Institutional Review Board (IRB # 18179), speech samples of the professors were recorded via voice dosimetry during a total of 32 lectures (about 43 total hours)—thus, each professor was recorded during 16 of their lectures. The lectures were conducted in the same classroom, with the same cohort of 65 students. The classroom has a surface area of 184 m^2, a height of 4 m, and a reverberation time (T_{30}) between 500 and 1000 Hz of 1.2 seconds. Each professor alternated the condition (AAF versus non-AAF) they experienced during their lecture, starting with the non-AAF condition and then wearing the Forbrain® device and receiving AAF during the subsequent lecture. They continued this pattern until 16 lectures were completed. In other words, during eight of their lectures, the professors received real-time AAF via the Forbrain® device, and during the other 8 of their lectures, they did not receive any AAF (non-AAF condition). The effects of the AAF conditions on 1) SPL values, 2) fundamental frequency (f_o) values, and 3) the mean time dose (Dt%) were evaluated.

Equipment

The real-time AAF was provided via a standard headset of the Forbrain® device. The headset was provided at no cost by the manufacturer. As previously outlined, Forbrain® implements a two-band filter that applies one of two

FIGURE 1. The Forbrain® device (left) and placement (right).

settings to the voice input: 1) a setting that raises low frequencies (100-800 Hz, +12 dB) and dampens high frequencies (800-15 000 Hz, −12 dB) when the input signal energy at 1 kHz exceeds −56 dBV for a trigger time between 10 and 50 ms. 2) A setting that performs the opposite (ie, dampens low frequencies ranging 100-800 Hz and raises high frequencies ranging 800-15 000 Hz) when the input signal at 1 kHz drops below −66 to −70 dBV for a holding time between 20 and 200 ms. The resulting output is altered in its frequency spectrum by the two-band filter and is then delivered through bone conduction headphones to the temporal bones.[42,50] The Forbrain® device and placement are displayed in Figure 1.

The professors' voice signals were recorded through a voice dosimeter that was self-assembled by the authors, called the do-it-yourself (DIY) voice dosimeter. The dosimeter consists of a Roland R-07 Portable Audio Recorder (Roland Corporation)[51] attached to a contact microphone (Lsgoodcare) via a 3.5-mm headphone splitter (to separate the microphone and headphone inputs). The dosimeter has been validated in a prior work for mean SPL, mean f_o, and mean cepstral peak prominence smoothed (CPPS)[52] and has been found to be comparable to previously available commercial voice dosimeters. This dosimeter can record either two or four stereo tracks. When recording two stereo tracks, the sampling rate is 44.1/48/88.2/96 kHz. When recording four stereo tracks, the sampling rate is 44.1/48 kHz. The bit depth for wave formats are 16/24 bits. The Roland R-07 uses a microSD memory card with SDHC182 format compatibility and can record up to approximately 15 hours depending on the specifications, capacity, and conditions of the battery used (Roland, n.d.). The placement of the voice dosimeter's contact microphones is based on previous evidence which indicates that a voice signal is measured most accurately via contact microphones when they are placed laterally on the neck, inferior to the major horns of the hyoid bone, specially, at the level of the thyrohyoid space.[53,54] The dosimeter device is displayed in Figure 2.

Procedure

Following the recommendations of Hillman et al[55] and Švec and Granqvist[56], individual calibration was performed prior to each recording session in a sound-attenuating double-walled Whisper Room (interior dimensions: 226 × 287 cm and h = 203 cm). Reverberation time (T_{30}) was measured for mid-frequencies to be 0.07 seconds in the Whisper Room and ambient noise equal to 25 dB(A). The calibration of the voice dosimeter consisted of comparing the SPL of a sustained /a/ vowel and reading passage produced with a normal vocal effort measured with the voice dosimeter and with an M2211 microphone (NTI Audio, Tigards, OR), which was selected due to its status as a Class-1 microphone[57]. For the calibration, the participants were instructed to sustain an /a/ vowel and then to read aloud the first six sentences of "The Rainbow Passage," a standardized text in English[58] using a normal vocal effort level (ie, 60 dB(A) at 1 m [ISO 9921]). This normal vocal effort level was confirmed in terms of its dB levels during the first calibration phase via a Lingwaves II SPL meter (WEVOSYS234 hardware [IEC Type 2, ANSI S1.4 Type 2]). Both the sustained vowel and reading task were recorded simultaneously via the voice dosimeter and the M2211 microphone.

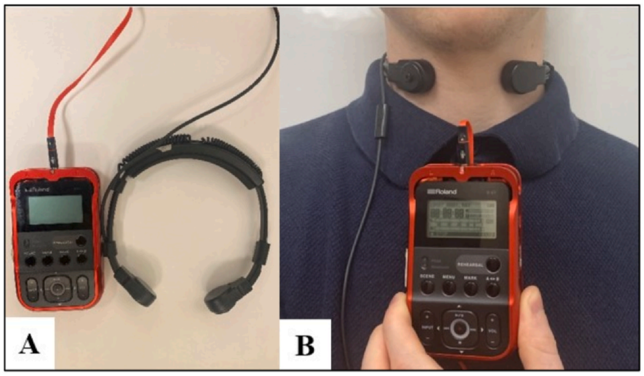

FIGURE 2. The do-it-yourself (DIY) voice dosimeter device (A) and placement (B).

Description of acoustic voice parameters

The SPL of the voice is a measure of the physical amplitude of the sound escaping from the upper airway and is broadly referred to as the intensity of the voice signal. Intensity is a measure of power per unit of area (the units for intensity are watts/m^2). Intensity is related to the psychological construct of loudness, and it is apparent that sound intensity diminishes with increasing distance from the sound source (eg,[59]). The formula[60] for acoustic intensity is

$$I = \frac{\bar{\mathscr{P}}}{4\pi R^2}$$

where $\bar{\mathscr{P}}$ is the time-averaged power emitted by the source and R is the radius from the sound source to the receiver. SPL is an expression of intensity in the logarithmic units of decibels (dB) and is in reference to the standard reference pressure of 20 μPascals. The formula[60] for SPL is

$$SPL = 20 \quad \log_{10}\frac{P}{P_0}dB$$

Here, P refers to the pressure of the acoustic source and P_0 represents the standard reference pressure.

The f_o of a voice signal represents the number of vocal fold oscillations each second, and correlates to the perceived pitch of a voice. Pitch perception is a psychophysical process, however, it is perceived as the greatest common denominator of the harmonics (ie, the f_o of the harmonic series[61]). As previously mentioned, the f_o of a voice signal is derived from the oscillation rate of the vocal folds. If one approximates the vocal folds to a vibrating string, the formula[62] for fundamental frequency can be written as

$$f_o = \frac{1}{2L}\sqrt{\frac{\sigma}{\rho}}$$

where L is the length of the oscillating vocal fold tissues, σ is the longitudinal stress in the vocal fold tissues, and ρ is the density of the vocal fold tissues. The stiffness and mass of the vocal fold tissues also influence the f_o of vocal fold oscillation and these factors should be considered when performing a more comprehensive evaluation of f_o.

Phonation time (Dt%) reflects the percentage of vocal fold vibration during a period of measurement[63,64] and is calculated as the ratio of the voiced frames of a speech recording over the total recording duration. According to Titze et al[65] , the formula for time dose calculation is

$$D = \int_0^{t_p} k_v \, dt \ seconds$$

in which t_p is the recording time and k_v is the voicing unit step function defined as

$$k_v = \begin{cases} 1 \ for \ voicing \\ 0 \ for \ nonvoicing \end{cases}$$

These acoustic voice parameters are objective indicators that a voice disorder may develop when speaking for a prolonged period of time at high levels.

Voice processing and statistical analysis

All participant recordings were processed to extract the SPL, f_o, and Dt%. These acoustic voice parameters were selected to encompass traditional indicators of vocal loading.[17] The recordings were processed with MATLAB R2023b (Mathworks, Natick, MA) and Praat 6.0.13 (Netherlands). Specifically, a custom MATLAB script was applied to estimate the SPL values of the voiced speech signals. This script included the MATLAB function detectVoiced,[66] which extracted (a) the signal's energy and (b) its spectral centroid every 50 ms for the duration of the recorded signal. From these two features, dynamic thresholds were applied in order to detect voiced segments and remove unvoiced segments. The f_o of the speech signals was estimated with Praat using the autocorrelation method and the following settings: time step = 0.05 seconds, pitch floor = 50 Hz, very accurate = yes, pitch ceiling = 500 Hz, and the standard values for the other settings (silence threshold, voicing threshold, octave cost, octave-jump cost, and voiced/unvoiced cost). Finally, the Dt% was estimated with Praat using the command "To Pitch (ac)," which creates a pitch object from every selected sound object within the Praat window. The following parameters were used for the Dt% analysis: 0.05 second as the time step, 50 Hz as the pitch floor, 15 as the maximum number of candidates, 0.03 as the silence threshold, 0.45 as the voicing threshold, 0.0025 as the octave cost, 0.35 as the octave-jump cost, 0.20 as the voiced/unvoiced cost, and 500 Hz as the pitch ceiling. Subsequently, the voiced frames and the total number of frames were calculated and inputted into a table, from which the ratio of voiced frames to total frames was computed. For all acoustic voice parameters, summary statistics were calculated to evaluate the uncertainty of their mean error. Prior to calculating the summary statistics, the interquartile technique was employed to remove outliers.[67]

Statistical analyses were conducted using R version 4.2.0 (R Core Team[68]). The SPL and f_o response variables were statistically analyzed using generalized additive models (GAMs) with integrated smoothness estimation fitted by restricted maximum likelihood. These models are extensions of generalized linear models that replace the traditional linear predictor with an additive predictor, and the traditional linear form with a sum of smoothed function (ie, estimated using a scatterplot smoother). GAMs were selected for the present dataset, as they allow for nonlinear relationships between predictors and the response variables, are appropriate for likelihood-based regression, and are completely automatic.[69] For parametric coefficients, the GAM outputs included the estimates of the fixed-effects coefficients, the standard error associated with the estimate, the test statistic (t), and the P value. For the smoothed terms, the GAM outputs included effective degrees of freedom (edf), reference degrees of freedom (Ref.df), F value, and P value.

The analyses of Dt(%), were statistically analyzed using linear mixed-effect (LME) models, which were fitted by restricted maximum likelihood. Models were selected on the basis of the Akaike information criterion (the model with the lowest value being preferred). The LME output included the estimates of the fixed-effect coefficients, the standard error associated with the estimate, the degrees of freedom (df), the test statistic (t), and the P value. The Satterthwaite method was used to approximate degrees of freedom and calculate P value.

RESULTS

For each participant, a total of two GAMs (for the SPL and F_O response variables) and one LME (for the DT(%) response variable) were conducted for the following response variables. The structure of each GAM and LME is displayed in Table 1.

TABLE 1.
Code Structure for Each Statistical Model Including the Response Variable and Model Itself

Response variable	Model
SPL	gam(SPL ~ condition + smoothtime + smoothtime by condition)
F_o	gam(F_o ~ condition + smoothtime + smoothtime by condition)
DT(%)	lmer(Dt ~ condition + (1 | ID))

SPL

To assess the effects of the condition (with AAF versus non-AAF) on SPL during teaching, for each participant, a GAM was fitted with three predictors: (1) condition, (2) time (with integrated smoothness estimation), and (3) time (with integrated smoothness estimation) by condition. Of note, the smooth time variable was modeled such that it varies with levels of the condition (AAF) variable. In other words, it models how the relationship between time and SPL changes depending on the presence of AAF.

For the male participant, the model revealed that the presence of AAF had statistically significant effects on SPL. Specifically, SPL values were 5.5 dB lower ($P < 0.001$) during the AAF condition compared with the non-AAF condition. The model also revealed that time exhibited a significant ($P = 0.001$) nonlinear effect on SPL ($F(1,1) = 86.2$) as time progressed, regardless of AAF condition. Finally, there were statistically significant ($P < 0.001$) nonlinear relationships between time and SPL for both AAF conditions (non-AAF condition: (F(8,9 = 127.1) and AAF condition [$F(9,9) = 106.2$)]. The results of this model are listed in Table 2.

In summary, the model reveals that for the male participant, the AAF condition significantly reduces SPL by approximately 3 dB compared with the non-AAF condition. Additionally, there is a significant interaction between time and condition, with complex, nonlinear relationships between time and SPL under both AAF and non-AAF conditions, with the AAF condition exhibiting a more pronounced and complex time effect. This suggests that the male participant's vocal control in response to AAF evolves more dynamically over time than in the non-AAF condition.

For the female participant, the model revealed that the presence of AAF had statistically significant effects on SPL. However, the effect of AAF was smaller compared with the male participant. Specifically, SPL values were approximately 2 dB lower ($P < 0.001$) during the AAF condition compared with the non-AAF condition. The model also revealed that time does not have a significant overall effect on SPL when not considering AAF condition ($P = 0.952$), although there were also statistically significant ($P < 0.001$) nonlinear relationships between time and SPL within both AAF conditions (non-AAF condition: $F(8,8) = 5.43$ and AAF condition: $F(8,8) = 26.59$). The results of this model are listed in Table 3.

In summary, the model shows that SPL is lower in the AAF condition, and time has a nonlinear effect on SPL, but the nature of this effect depends significantly on the auditory feedback condition (AAF or non-AAF). The interaction between time and the AAF conditions appears to drive changes in SPL over time, with significant differences in how time affects SPL in each AAF condition.

Figure 3 shows the smoothed trend of SPL in decibels (dB) over the time of the 80-minute lectures (in minutes) for the male (top) and the female (bottom) participants, under two different auditory feedback conditions: non-AAF and AAF. The two curves represent the predicted SPL value at a specific time based on the GAM.

Fundamental frequency

To assess the effects of the condition (with AAF versus non-AAF) on f_o during teaching, a GAM was fitted with three predictors: (1) condition, (2) time (with integrated smoothness estimation), and (3) time (with integrated smoothness estimation) by condition. Of note, the smooth time variable was modeled such that it varies with levels of the condition (AAF) variable. In other words, it models how the relationship between time and f_o changes depending on the presence of AAF.

TABLE 2.
GAM Model Output With SPL as the Response Variable and Condition, Time (With Integrated Smoothness Estimation), and Time (With Integrated Smoothness Estimation) by Condition as Fixed Factors, for the Male Participant

Male SPL (dB): parametric coefficients				
Fixed factors	Estimate (dB)	Std. error (dB)	*t*	*P*
(Intercept)	74.6	0.02	3754.7	< 0.001***
Condition: AAF	–3.2	0.03	–108.1	< 0.001***
Male SPL (dB): smoothed terms				
Fixed factors	edf	Ref.df	*F*	*P*
smoothTime	1	1	86.2	0.001**
smoothTime, by AAFCondition	9	9	106.2	< 0.001***
smoothTime, by non-AAFCondition	8	8	127.1	< 0.001***

Significance codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1.

TABLE 3.
GAM Model Output With SPL as the Response Variable and Condition, Time (With Integrated Smoothness Estimation), and Time (With Integrated Smoothness Estimation) by Condition as Fixed Factors, for the Female Participant

Female SPL (dB): parametric coefficients				
Fixed factors	Estimate (dB)	Std. error (dB)	*t*	*P*
(Intercept)	76.73	0.02	3486.1	< 0.001***
Condition: AAF	–1.95	0.03	–58.1	< 0.001***
Female SPL (dB): smoothed terms				
Fixed factors	edf	Ref.df	*F*	*P*
smoothTime	2	2	0.05	0.952
smoothTime, by AAFCondition	8	8	5.43	< 0.001***
smoothTime, by non-AAFCondition	8	8	26.59	< 0.001***

Significance codes: 0 “***” 0.001 “**” 0.01 “*” 0.05 “.” 0.1.

For the male participant, the model revealed that the presence of AAF had statistically significant effects on f_o. Specifically, f_o values were 4.6 Hz lower ($P < 0.001$) during the AAF condition compared with the non-AAF condition. The smoothed term for time suggests a slightly nonlinear effect of time on the response variable overall. However, this effect is not significant ($P = 0.861$), indicating that time alone does not significantly affect the response variable without considering the interaction with AAF. When considering the smoothed term for time by AAF condition, the model suggests a complex, highly nonlinear relationship between time and the response in the non-AAF condition ($P < 0.001$) and a nonsignificant nonlinear relationship between time and the response in the AAF condition ($P = 0.268$).

In summary, the model shows that while AAF has a significant impact on f_o for the male participant (reducing it by 4.6 Hz), the effect of time is only significant in the non-AAF condition, where it exhibits a complex, nonlinear relationship. In contrast, within the AAF condition, time does not play a significant role in changing f_o. The results of this model are listed in Table 4.

For the female participant, the model revealed that f_o was slightly higher (0.54 Hz) in the AAF condition compared with the non-AAF condition. Even if this effect was likely too small in magnitude to be clinically significant, it was statistically significant ($P = 0.002$). The smoothed term for time suggests a slightly nonlinear effect of time on f_o overall. However, this effect is not significant ($P = 0.658$), indicating that time alone does not significantly affect the response variable without considering the interaction with AAF. When considering the smoothed term for time by AAF condition, the model suggests a complex, highly nonlinear relationship between time and the response in both AAF conditions ($P < 0.01$).

In summary, while the presence of AAF has a small but significant effect on the female participant's f_o, time interacts with the AAF condition in a more complex way, significantly influencing the response in both AAF and non-AAF conditions. The results of this model are listed in Table 5.

Figure 4 shows the smoothed trend of fundamental frequency (f_o) in decibels (Hz) over the time of the 80-minute lectures (in minutes) for the male (top) and the female (bottom) participants, under two different auditory feedback conditions: Non-AAF and AAF. The two curves represent the predicted f_o value at a specific time, based on the GAM.

Time dose

To assess the effects of the condition (with AAF versus non-AAF) on DT(%) during teaching, an LME was fitted with one predictor: (1) condition, and participant ID as the random factor. The model revealed that the presence of AAF had statistically significant effects on DT(%). Specifically, DT(%) values were approximately 4% lower ($P = 0.041$) during the AAF condition compared with the non-AAF condition. The results of this analysis are displayed in Table 6 and Figure 5.

DISCUSSION

This study examined the effects of AAF provided by the Forbrain® device on acoustic voice outcomes for university professors while teaching. The hypothesis was that the professors' voice parameters would reflect increased risk for aberrant voice production during the non-AAF conditions compared with the AAF conditions. This hypothesis was confirmed by the results of the statistical analyses. The main findings of the analyses indicate that receiving AAF feedback while teaching resulted in significant decreases in SPL and Dt% compared with the non-AAF condition in both participants. Additionally, a significant decrease in f_o was demonstrated by the male participant when comparing the AAF condition with the non-AAF condition. Increases in SPL, Dt%, and f_o serve as an indicator aberrant vocal demand responses, which are defined as manners of voicing produced by an individual in

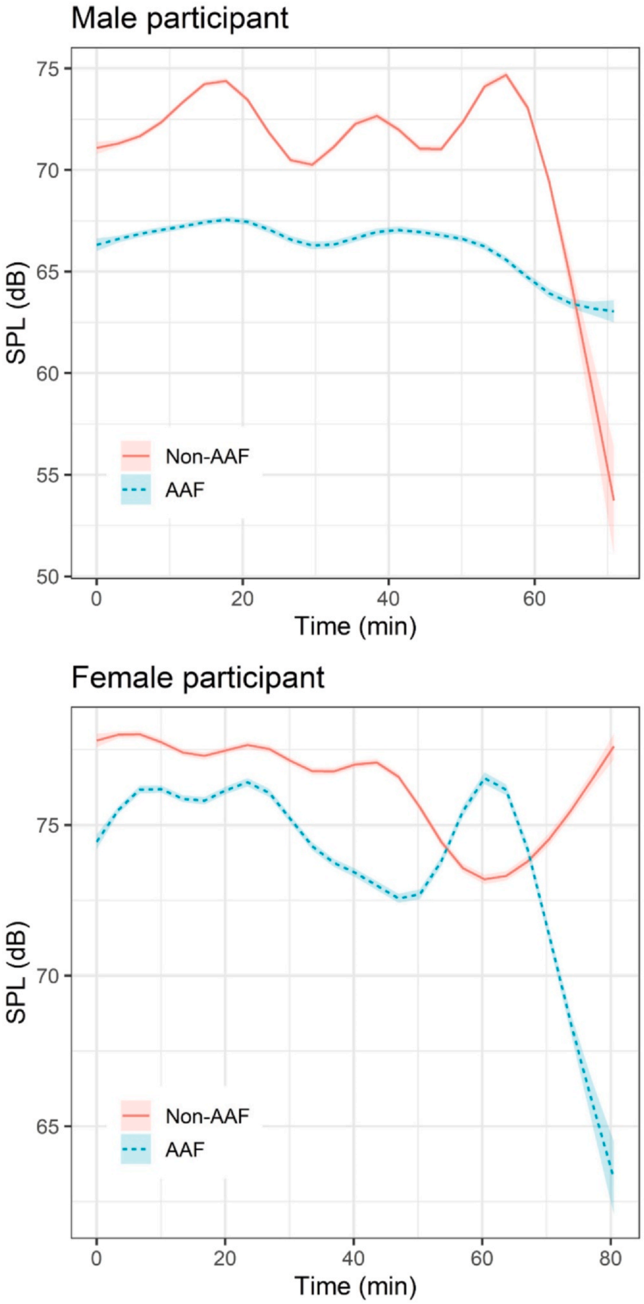

FIGURE 3. Smoothed trend of the predicted sound pressure levels (using GAM) for each condition over time for the male (top) and female (bottom) participants.

an attempt to respond to a perceived vocal demand.[17] The results reinforce the possibility that bone conduction AAF via the Forbrain® device can reduce the acoustic correlates of vocal fatigue in university professors. This possibility is explored for each response variable in the remaining discussion paragraphs.

The analyses revealed that SPL values were approximately 3 and 2 dB lower ($P < 0.001$) during the AAF condition compared with the non-AAF condition for the male and female participants, respectively. Additionally, there were statistically significant ($P < 0.001$) nonlinear relationships between time and SPL for both the non-AAF and AAF conditions for both participants. This indicates that as teaching sessions progressed, SPL changed in a nonlinear fashion, suggesting fluctuations in vocal intensity over time during both conditions. In other words, the nonlinear effects captured by the GAM model underscore the dynamic nature of SPL changes over time for the professors, and these changes were possibly influenced by their classroom environment and the presence of AAF. Of note, the female participant demonstrated increasing SPL levels during the last 20 minutes of her lectures during the non-AAF conditions. However, this trend was the opposite during AAF conditions, as she demonstrated a decrease of approximately 15 dB, on average, during the final 20 minutes of her lectures when receiving AAF.

As a measure, the SPL of the voice is the physical amplitude of the sound escaping from the upper airway and is broadly referred to as the intensity of the voice signal.[70] In the context of vocal health, SPL reflects the general extent of the laryngeal forces (ie, mechanical and aerodynamic[71-73]). Previous research has indicated that changes in SPL ranging from 0.8 to 2.0 dB (SPL) are correlated with significant accumulations of vocal loading during a workday.[28,74] In the present study, SPL was significantly lower while the professors received AAF feedback. This indicates that vocal loading was possibly reduced due to the feedback. Regardless of the condition, there was a notable increase in SPL across the professors starting approximately 70 minutes into each lecture. This was reflected in the statistically significant results of the GAM analysis. This, too, might indicate that vocal loading was experienced regardless of condition while the professors were teaching, however, the AAF feedback may have provided a protective factor to this loading, as the overall SPL values were significantly reduced during the AAF condition compared with the non-AAF condition.

The analyses revealed that f_o values were approximately 5 Hz lower ($P < 0.001$) during the AAF condition compared with the non-AAF condition for the male participant. However, f_o values were approximately 0.5 Hz higher ($P = 0.002$) during the AAF condition compared with the non-AAF condition for the female participant. The model also revealed statistically significant ($P < 0.001$ [male] and $P = 0.008$ [female]) nonlinear relationships between time and f_o for both the male and female participants during AAF conditions. Additionally, the model demonstrated that, for the female participant, there was a statistically significant ($P < 0.001$) nonlinear relationship between time and f_o for the non-AAF condition. Altogether, this indicates that as teaching sessions progressed, f_o changed in a nonlinear fashion for both participants during the AAF conditions. However, for the female, f_o also changed in a nonlinear fashion during the non-AAF conditions. Broadly, the nonlinear effects captured by the GAM model underscore the dynamic nature of f_o changes over time, possibly influenced by the teaching environment and the presence of AAF.

It is hypothesized that increased vocal effort results in increased f_o (Solomon[75]), and overall, increased f_o

TABLE 4.
GAM Model Output With F_o as the Response Variable and Condition, Time (With Integrated Smoothness Estimation), and Time (With Integrated Smoothness Estimation) by Condition as Fixed Factors, for the Male Participant

Male F_o (Hz): parametric coefficients

Fixed factors	Estimate (Hz)	Std. error (Hz)	*t*	*P*
(Intercept)	167.5	0.11	1506.6	< 0.001***
Condition: AAF	–4.6	0.16	–28.05	< 0.001***

Male F_o (Hz): smoothed terms

Fixed factors	edf	Ref.df	*F*	*P*
smoothTime	2	2	0.14	0.861
smoothTime, by AAFCondition	9	9	10.18	< 0.001***
smoothTime, by non-AAFCondition	3	4	1.12	0.268

Significance codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1.

TABLE 5.
GAM Model Output With F_o as the Response Variable and Condition, Time (With Integrated Smoothness Estimation), and Time (With Integrated Smoothness Estimation) by Condition as Fixed Factors, for the Female Participant

Female F_o (Hz): Parametric coefficients

Fixed factors	Estimate (Hz)	Std. Error (Hz)	*t*	*P*
(Intercept)	216.8	0.12	1862.1	< 0.001***
Condition: AAF	0.54	0.18	3.0	0.002**

Female F_o (Hz): smoothed terms

Fixed factors	edf	Ref.df	*F*	*P*
smoothTime	1	2	0.3	0.658
smoothTime, by AAFCondition	7	8	2.6	0.008**
smoothTime, by non-AAFCondition	7	8	5.4	< 0.001***

Significance codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1.

contributes to mechanical loading of the vocal fold tissues,[73] which increases a speaker's risk for experiencing a voice disorder. Moreover, there is a known relationship between SPL and f_o, as increasing one's SPL will increase subglottal pressure, and thus, increase vocal fold tension.[76] Ultimately, this increase in vocal fold tension will result in raised f_o for speakers (Black[77]). The present study revealed that AAF may have influenced this relationship in the female participant. That is, while the female demonstrated a large SPL decrease (by approximately 15 dB) during the final 20 minutes of her lectures, her f_o increased. Recent behavioral research involving a cohort of professors further suggests that an increase in f_o may be indicative of heightened vocal fatigue (Cantor-Cutiva et al[78]). Similar to the results surrounding SPL, the results of the present analyses surrounding f_o indicate that the AAF feedback may have provided a protective factor to vocal loading for both participants. For the male, both f_o and SPL were decreased during the AAF condition. For the female, the results depict a possible effect of AAF on the known relationship between subglottal pressure and vocal fold tension. That is, despite the female participant's increased f_o during the AAF conditions, her SPL was significantly reduced when compared with the non-AAF condition.

It is interesting to consider the differences among the participants in f_o. For the male, as time progressed, the trends in f_o were qualitatively different depending on condition. As seen in Figure 4, during the non-AAF condition, the male participant's f_o is relatively consistent. This is contrasted by the variable f_o throughout the non-AAF condition and the sharp increase starting at around 60 minutes into each class. The female participant's f_o was variable for both conditions with noticeable peaks and valleys for the AAF condition. It is possible that these f_o changes align with the professors' vocal fatigue symptoms. That is, in response to perceived increases in vocal fatigue, the professors may have attempted to alter their f_o. Conversely, for the male participant, it is possible that these f_o changes did not occur during the AAF condition (1)

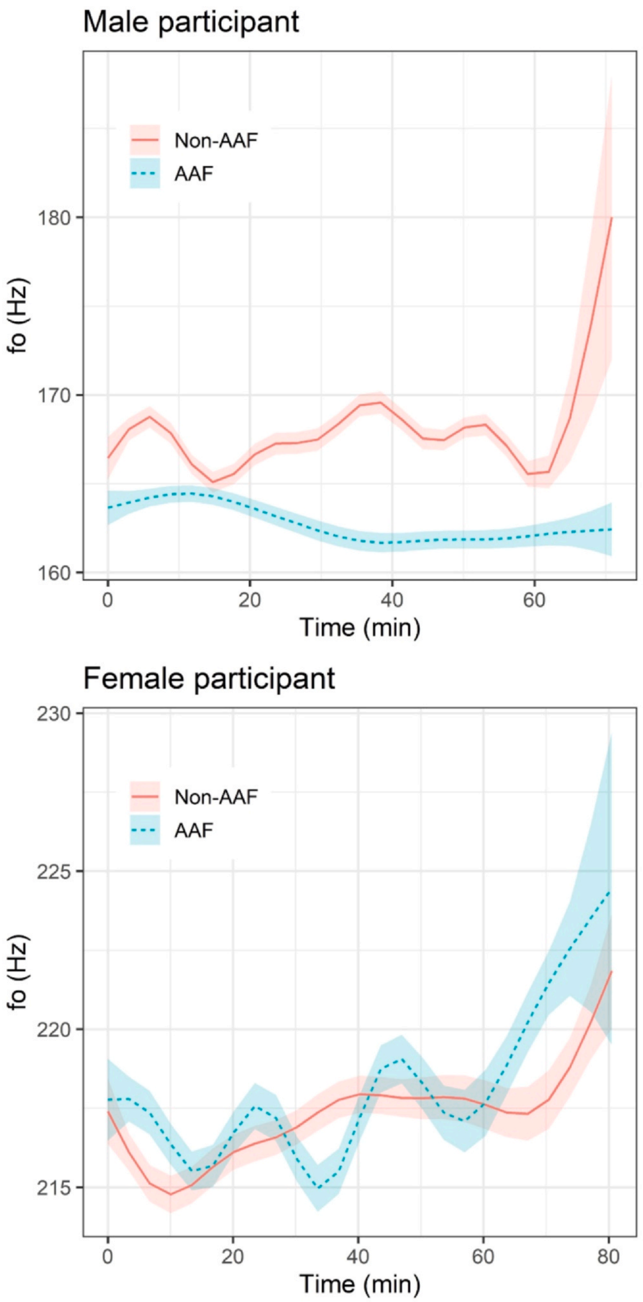

FIGURE 4. Smoothed trend of the predicted fundamental frequency (using GAM) for each condition over time for the male (top) and female (bottom) participants.

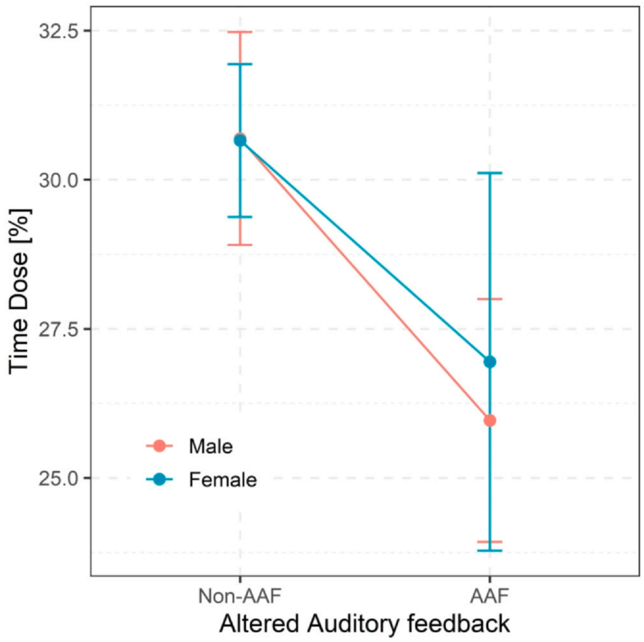

FIGURE 5. Mean and standard error of time dose for each condition by participant.

because he was not experiencing comparable levels of vocal fatigue, or (2) the AAF altered his vocal responses to perceived vocal fatigue.

The analyses revealed that Dt% values were approximately 4% lower ($P = 0.041$) during the AAF condition compared with the non-AAF condition. Dt% is a measure of vocal loading, as it reflects the percentage of vocal fold vibration during a period of measurement.[63,64] It is calculated as the ratio of the voiced frames of a speech recording over the total recording duration, and thus, the higher the Dt%, the greater a speaker's duration of voicing. It has been hypothesized that an increased time dose may be a factor contributing to vocal fatigue[79] and voice disorders themselves.[80] Prior research involving teachers and professors has demonstrated that when voice disorders are present, Dt% tends to be higher, by magnitudes of approximately 4%-9% (eg,[64,81,82]). The present study's Dt% results, when considered in light of these prior findings, support the aforementioned possibility that AAF provides a protective factor to vocal loading.

TABLE 6.
LME Model Output With Dt (%) as the Response Variable and Condition, as the Fixed Factor

Dt (%)

Fixed factors	Estimate (%)	Std. error (%)	Df	*t*	*P*
(Intercept)	30.7	1.3	16	22.9	< 0.001***
Condition: AAF	–4.2	1.9	16	–2.2	0.041*

Significance codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "." 0.1.

Limitations

An important limitation of this study is that it enrolled only two research participants. Clearly, studies involving more professors with varying levels of teaching experience, different class sizes, and varying classroom types are further needed to clarify the effects of AAF on voice-related outcomes. There are many known factors that influence teachers' voice production within classrooms, including classroom noise,[83,84] classroom temperature,[85] and possibly the size and fullness of the classroom.[86,87] However, these classroom-related factors were not assessed in the present study and could have confounded the results. Additionally, the outcome measures selected in the present study may not represent the most precise objective indicators that a voice disorder may develop. SPL, f_o, and Dt% have been utilized as univariate acoustic voice parameters to determine teachers' risk for developing a voice disorder (eg,[88]), however, more fine-grained acoustic measures such as CPPS[89] and multivariate objective measures (eg, the Daily Phonotrauma Index[90–93]) may serve as more nuanced indicators of a forthcoming voice disorder. Furthermore, the present study investigated only real-time voice acoustic parameters, and thus, the study lacked the perceptions (ie, self-reported outcomes) of the professors and it also lacked long-term effects of the AAF on voice. In this respect, the results of the present study can be considered introductory.

CONCLUSION

Overall, the present study targeted the elevated vocal risk of university professors and the possible relationship between auditory-motor integration and impaired voice production. The results demonstrate that bone conduction feedback via the Forbrain® device while teaching significantly decreased the SPL, f_o, and Dt% in two professors compared with teaching without the Forbrain® device. Increases in each of these acoustic voice parameters have been previously demonstrated to indicate increased vocal fatigue, and in some cases, the presence of a voice disorder. Thus, the present results suggest that the Forbrain® device reduced the acoustic correlates of vocal fatigue in these two university professors.

Author Contributions

P.B. conceived the experiment, P.B., M.F., and C.J.N. conducted the experiment, P.B. analyzed the results, and C.J.N. wrote and prepared the original draft. All authors reviewed the paper.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships that may be considered as potential competing interests: Pasquale Bottalico reports equipment, drugs, or supplies were provided by SOUND FOR LIFE. In particular, the device Forbrain was provided free of charge by SOUND FOR LIFE. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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