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Reducing Vocal Fatigue With Bone Conduction Devices: Comparing Forbrain and Sidetone Amplification

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ABSTRACT

Purpose: Altered auditory feedback research aims to identify methods to strengthen speakers' awareness of their own voicing behaviors, diminish their perception of vocal fatigue, and improve their voice production. This study aims to compare the effects of two bone conduction devices that provide altered auditory feedback.

Method: Twenty participants (19–33 years old, age: *M* [*SD*] = 25.5 [3.85] years) participated in a vocal loading task using a standard Forbrain device that provides filtered auditory feedback via bone conduction and a modified Forbrain device that provides only sidetone amplification, and a control condition with no device was also included. They rated their vocal fatigue on a visual analog scale every 2 min during the vocal loading task. Additionally, pre- and postloading voice samples were analyzed for acoustic voice parameters.

Results: Across all participants, the use of bone conduction–altered auditory feedback devices resulted in a lower vocal fatigue when compared to the condition with no feedback. During the pre- and postvoice samples, the sound pressure level decreased significantly during feedback conditions. During feedback conditions, spectral mean and standard deviation significantly decreased, and spectral skew significantly increased.

Conclusion: The results promote bone conduction as a possible preventative tool that may reduce self-reported vocal fatigue and compensatory voice production for healthy individuals without voice disorders.

Across the life span, approximately 30% of the population will experience impairments in voice production, resulting in a voice disorder (Roy et al., 2004, 2005), and currently, approximately 7%–17% of the population is experiencing a voice disorder (Behlau et al., 2012; Lyberg-Åhlander et al., 2019; OECD, 2014). One of the most commonly treated voice disorders is vocal hyperfunction (Bhattacharyya, 2014; Coyle et al., 2001; Herrington-Hall et al., 1988; Zhukhovitskaya et al., 2015), which can be defined as excessive perilaryngeal musculoskeletal activity during phonation (Oates & Winkworth, 2008). In certain occupational groups who use their voice extensively (e.g., teachers, physicians, salespeople), well over 50% of the workforce has obvious anatomical signs of vocal hyperfunction upon examination of their vocal folds (Tavares & Martins, 2007). Within this group of highly prevalent voice disorders, a possible underlying factor is sensorimotor integration. Sensorimotor integration can be defined as the integration of auditory, visual, and somatosensory information with motor actions—in this case, the motor actions of voice production (Machado et al., 2010).

Recent evidence indicates that individuals with specific types of voice disorders display distinct vocal responses in relation to their auditory perception (Castro et al., 2022; Hillman et al., 2020; Stepp et al., 2017; Weerathunge et al., 2022; Ziethe et al., 2019). This grouping of abnormal vocal responses (coined "auditory–motor phenotype"; Abur et al., 2021; Weerathunge et al., 2022)

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is hypothesized to contribute to the pathophysiology of hyperfunctional voice disorders (Castro et al., 2022; Hillman et al., 2020; Stepp et al., 2017; Ziethe et al., 2019). This auditory–motor phenotype originated from behavioral studies in which patients with voice disorders were presented with intensity-, formant-, or pitch-altered feedback of their voice in real time during phonation tasks (e.g., Abur et al., 2018; X. Chen et al., 2013; Houde et al., 2019; Naunheim et al., 2019). Through this methodology, patients' vocal responses were analyzed in an effort to understand the relationship between sensorimotor integration and their voice disorder. Among the symptoms of hyperfunctional voice disorders, vocal fatigue is commonly the first to appear (Mahalingam et al., 2021; Nanjundeswaran et al., 2019). Given that hyperfunctional voice disorders are most common among occupational voice users and that vocal fatigue symptoms may be tied to differences in voice production (e.g., Fujiki et al., 2021, 2022; Kang et al., 2020; Milbrath & Solomon, 2003; Nanjundeswaran et al., 2017; Shembel & Nanjundeswaran, 2022), it would be informative to explore possible solutions to the auditory–motor phenotype that is influencing the development of voice disorders in this population.

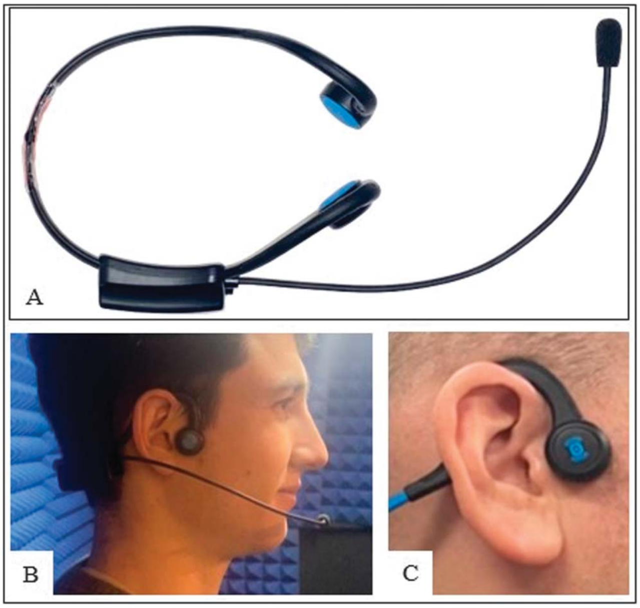
Real-time altered auditory feedback (AAF) is one tool that has been studied in order to better understand voice disorders and contribute to biofeedback paradigms that could address the auditory–motor phenotype present in those with hyperfunctional voice disorders. Typically, AAF is presented in the daily lives of users through headphones, including traditional air-conduction headphones (Pelegrín-García & Brunskog, 2012; Sierra-Polanco et al., 2021) and, more recently, bone conduction headphones (Escera et al., 2018; Nudelman, Codino, et al., 2022).

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 (Henry & Letowski, 2007). Both the mechanical vibrations from bone conduction and air conduction are eventually converted into neural impulses within the cochlea (Békésy, 1932; Lowy, 1942). In terms of real-time AAF to be delivered in daily life, bone conduction may be a better option, especially for occupational voice users, as there is no occlusion of their ears. This would allow for speakers to hear their communication partner and the ambient sound environment, simultaneously, while receiving real-time AAF for their voices. Alternatively, air-conducted AAF would fully cover the ears, making it difficult for occupational voice users to hear their communication partners.

There is one commercially available AAF device that uses bone conduction to improve speech. Forbrain, developed by Sound for Life LTD (Soundev) in Luxembourg (Model UN38.3; http://www.forbrain.com), uses a pair of bone conductors and a microphone to provide a speaker with real-time AAF. According to its website and patent registration, the Forbrain device is ergonomically designed to fit all head sizes comfortably. The device is displayed in Figure 1.

Research measuring the effects of the Forbrain device reports significant improvements in cepstral peak prominence smoothed (CPPS) and spectral tilt for 32 adult healthy speakers using the device (Escera et al., 2018). Based on the perceptual correlates of CPPS and spectral tilt, these results imply that the use of the Forbrain device contributes to a more harmonic/less breathy (Heman-Ackah et al., 2002; Hillenbrand & Houde, 1996) and more resonant (Maryn et al., 2010) voice signal. According to its patent registration (Guajarengues & Lohmann, 2015), Forbrain implements a two-band filter, which (from the perspective of the current authors) creates a slightly noticeable perception of altered voice quality (i.e., increased brightness of tone) for the user. The two-band filter applies one of two settings to the voice input, and these two settings are activated by the input sound energy at 1 kHz over a time window of integration ranging from 10 to 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 (Escera et al., 2018). Moreover, a simplified version of bone conduction AAF (without the two-band filtering) was demonstrated to significantly improve the voice quality of speakers with

Figure 1. Overhead view of the Forbrain device (A), with placement of the headset (B) and one of the two bone conductors (C).



voice disorders (Nudelman, Codino, et al., 2022. This simplified device uses sidetone amplification (amplified playback of one's own voice; Garnier et al., 2010; Laukkanen et al., 2004; Tomassi et al., 2023). Sidetone amplification elicits the Fletcher effect, which is a reflexive phenomenon of decreasing vocal loudness (sound pressure level [SPL]) by 1 dB SPL for each 2- to 3-dB SPL increase in auditory feedback; Fletcher, 1918; Lane & Tranel, 1971). To the authors' knowledge, the slim body of work on the Forbrain device and the other study regarding bone conduction represent the current evidence that has examined AAF devices that use bone conduction. Thus, comparing the existing bone conduction devices may be useful, as these devices ostensibly offer more ecological validity (given that the user's ears remain uncovered/unoccluded compared to air-conduction AAF) and may be useful in future clinical biofeedback paradigms, especially in occupational voice users. Moreover, examining AAF provides insights into the higher order mechanisms of planning and producing speech (Weerathunge et al., 2022). Research in this domain has provided critical information regarding how speakers detect and correct errors in their speech. Specifically, this area of research provides insights about the sensorimotor integration process. For example, experimental AAF studies examining pitch alteration (Hain et al., 2001) and/or delayed auditory feedback (Chon et al., 2013; Hain et al., 2001; Stuart & Kalinowski, 2015) have successfully determined the efficiency and sensitivity of participants' auditory feedback control system, which is responsible for correcting errors in voice production (e.g., Behroozmand et al., 2012; Burnett et al., 1998; Kim & Larson, 2019; Larson & Robin, 2016; Liu & Larson, 2007; Scheerer & Jones, 2018).

Outside of the bone conduction studies, AAF research related to voice production has primarily been examined in daily life using self-reported symptoms as proxies for impaired voice production, especially in occupational voice users (Cantor Cutiva et al., 2013; Martins et al., 2014; Nair et al., 2021). However, alterations in voice production secondary to AAF can be more objectively quantified in laboratory settings through vocal loading tasks (VLTs), which aid in understanding how speakers without voice disorders respond vocally to challenging scenarios (Kelchner et al., 2006; Solomon & DiMattia, 2000; Stemple et al., 1995). A systematic review examined VLTs within the literature and concluded that loud and prolonged reading is the most common task (Fujiki & Sivasankar, 2017). Recent VLTs have measured objective and subjective indicators of vocal fatigue using VLTs that involved between 10 and 60 min of loud reading (Echternach et al., 2020; Free et al., 2021; Lei et al., 2020; Xue et al., 2019), and recently, 60 min of loud singing was employed in a VLT study (Devadas et al., 2023). Prior VLTs have induced vocal fatigue by incorporating external acoustic input (i.e., increased background noise; Bottalico et al., 2016; Cipriano et al., 2017; Herndon et al., 2019; Whitling et al., 2015), increasing duration of voice use and intensity of voice production, and adjusting speech patterns so that they are unnatural to the speakers (e.g., Buekers, 1998; Enflo et al., 2013; Fujiki et al., 2017; Kelchner et al., 2006; Nudelman et al., 2021; Remacle et al., 2012; Stemple et al., 1995; Vilkman et al., 1999; Yiu & Chan, 2003; Yiu et al., 2013).

AAF research aims to identify and validate methods to improve speakers' awareness of their own voicing behaviors, diminish their perception of vocal fatigue, and improve their acoustic voice parameters. This study aims to compare the effects of AAF provided by two bone conduction devices to a control condition. The two bone conduction devices are (a) sidetone amplification via a modified Forbrain device and (b) Forbrain's filtered auditory feedback. Specifically, these devices will be compared through a VLT in terms of acoustic voice parameters derived from the long-term average spectrum (LTAS) produced by healthy participants and their subjective self-ratings of vocal fatigue. We hypothesize that the AAF devices will result in improvements in compensatory voice production (e.g., reduced SPL, decreased mean of the LTAS) and a lower slope of increase in vocal fatigue during the VLT, as compared to the control conditions.

Materials and Method

This study employed a single VLT (consisting of three AAF conditions), which was completed within a single session lasting approximately 1 hr. Twenty participants (19–33 years old, age: *M* [*SD*] = 25.5 [3.85] years) were enrolled in the study and were recruited through sequential convenience sampling. Ten of the participants were male, and 10 were female. All the participants were self-described as conversationally proficient American English–speaking adults. Their ethnicities per self-report were "Caucasian" (*n* = 6), "Asian–Pacific Islander Native" (*n* = 2), "Hispanic–Latino" (*n* = 10), and "Black–African American" (*n* = 2).

Inclusion criteria for this study were being over the age of 18 years; passing a hearing screening; and reporting no history of voice, speech, language, or hearing disorders. The hearing screenings were pure-tone audiometry tests performed by a certified speech-language pathologist. Hearing loss was considered present when bilateral thresholds were greater than 20 dB HL at octave frequencies from 500 to 4000 Hz. A voice disorder was considered present when a participant met at least one of the following criteria: (a) Vocal Handicap Index-10 score above 11 (Arffa et al., 2012; Sund et al., 2023), (b) Voice-Related

Quality of Life score above 91.25 (Behlau et al., 2016), or (c) Voice Fatigue Index score greater than or equal to 24.47 for Factor 1, 6.90 for Factor 2, or less than or equal to 7.71 for Factor 3 (Nanjundeswaran et al., 2015). No participants were excluded from the study.

With protocol approval from the University of Illinois at Urbana–Champaign Institutional Review Board (IRB No. 18179), speech samples of each participant were recorded during a VLT in three different AAF conditions. The recordings were performed in a soundproof double-walled whisper room (interior dimensions: 226 × 287 × 203 cm). Reverberation time (T30) was measured for mid-frequencies (500–2000 Hz) to be 0.07 s in the whisper room, and background noise was equal to 25 dBA. The effects of the type and level of external auditory feedback on the following five outcome measures were evaluated:

1) The amount of self-reported vocal fatigue on a visual analog scale (VAS), which has been associated with alterations in acoustic voice parameters and psychosocial voice impairment in healthy occupational voice users (Castillo-Allendes et al., 2023).

2) SPL values, a measure of the voice signal's physical magnitude (Baken & Orlikoff, 2000) that is related to the amplitude of the sound escaping from the upper airway. SPL is broadly referred to as the intensity of the voice signal.

3) Spectral mean of the LTAS (LTAS_mean), which reflects the average value of the LTAS distribution. The presence of spectral energy above 5000 Hz is a strong predictor of dysphonic voice quality (Hartmann & von Cramon, 1984); thus, a lower LTAS_mean value reflects better voice quality.

4) Standard deviation of the LTAS (LTAS_SD), which describes the variance of the spectral distribution, with lower variance indicating better voice quality (Tanner et al., 2005).

5) Skewness of the LTAS (LTAS_skew), which describes positive or negative tilt of the LTAS. Positive skewness results in a "tail" of values extending to the right of the bell curve, which moves the overall shape of the spectrum toward lower frequencies. Negative skewness results in the opposite (i.e., tail extending to the left of the bell curve). There remains a lack of consensus surrounding LTAS_skew as an indicator of voice quality, with some studies indicating no significant influences on voice (e.g., Tanner et al., 2005) and others indicating significant associations with dysphonic voice quality (e.g., Hillenbrand & Houde, 1996).

Of note, LTAS_mean, LTAS_SD, and LTAS_skew are considered spectral moments and are measures of the LTAS of the voice signal. The LTAS displays the power of frequencies within a voice signal and is calculated from a fast Fourier transform (mean of all spectra during a voice sample). These spectral moments have been demonstrated to capture compensatory voice production to some degree (e.g., Hammarberg et al., 1980; Harwardt, 2011; Mendoza, Muñoz, & Naranjo, 1996) and deviant perceptual voice qualities including nasality, breathiness, and atypical loudness variation (Mendoza, Valencia, et al., 1996).

VLT and Conditions

Prior to each AAF condition of the VLT, the participants completed two preloading speech tasks, namely, (a) reading aloud the first six sentences of *The Rainbow Passage*, a standardized text in English (Fairbanks, 1960), and (b) sustaining an /a/ vowel for at least 5 s. These tasks were completed with the same AAF device (or lack thereof) that was used in the AAF condition and was repeated after each AAF condition as well to gather postloading data. For example, prior to and after the AAF condition that used the standard Forbrain headset, the participants read aloud *The Rainbow Passage* and sustained an /a/ vowel while wearing the same standard Forbrain headset used during the main VLT, and the same occurred for the other two AAF conditions. These pre- and postloading measures were used to provide baseline data for each AAF condition, as well as postloading data, which was intended to reveal the effects of vocal loading associated with each AAF condition. One component of the rationale for implementing these pre- and postloading tasks was to gather voicing data that were unobscured by the fixed voicing level required during the VLT (see below). For this reason, it was necessary to retain the forthcoming (preloading) or preceding (postloading) AAF condition (i.e., the participant kept wearing the AAF device during these pre- and postloading tasks, if applicable), in order to assess the effects of the given AAF device (or lack thereof) on the voice signal.

For the VLT, the participants were instructed to read aloud five short stories by Baum: *The Glass Dog* (Baum & Ilie, 2011), *The Queen of Quok* (Baum et al., 2005b), *The Magic Bon Bons* (Baum et al., 2005a), *The Capture of Father Time* (Baum, n.d.-a), and *The Wonderful Pump* (Baum, n.d.-b). A reading task (as opposed to a nonspeech VLT) was selected to elicit running speech in order to assess the influence of the AAF devices on a realistic voice signal (i.e., running speech, which reflects the type of speech used during daily communication scenarios). These short stories were presented in a random order, to stratify their linguistic content randomly across the AAF conditions. During the VLT, participants' voice level (intensity) was fixed at 73 dBA (i.e., a loud vocal effort level; International Organization for Standardization [ISO], 2003), which was achieved through real-time visual feedback from a sound-level meter application on a tablet computer (described below). This visual feedback was incorporated to ensure that the participants were objectively achieving a loud vocal effort level, according to the international standard (ISO, 2003). To this end, the participants were instructed to maintain a level of 73 dBA on the sound-level meter for the duration of the reading task, consistent with previous studies (e.g., Kelchner et al., 2006). During the VLT, the participants were prompted to rate their vocal fatigue on a VAS every 2 min of reading, in a similar manner as a previously validated VLT paradigm (Nudelman et al., 2021). The VAS was 100 mm in length and included the instructions, “Please rate level of vocal fatigue from 0–100.” The VAS limits were labeled 0 = *not at all* (left) and 100 = *extremely* (right). Prior to the start of the VLT, *vocal fatigue* was defined for the participants as “your perception of a decline in your voice during the voice production task” (Hunter et al., 2020).

The duration of each AAF condition during the VLT was 20 min. The three different AAF conditions were (a) a control condition, (b) AAF sidetone amplification via a modified Forbrain device, and (c) filtered AAF via a standard Forbrain headset. The control condition involved performing the VLT without any AAF headset; that is, the participants were speaking with unaltered sidetone during the control condition. One reason the control condition was included was to gauge the magnitude of the results associated with the AAF conditions. In other words, the control condition allowed for the comparison of the AAF devices to each other and to a non-AAF speaking scenario. An additional justification for this control condition was providing a more ecologically valid speaking scenario familiar to the participants, that is, speaking without AAF. All conditions were presented without external noise added. Following each AAF condition (i.e., every 20 min), the participants were offered an optional 5-min water break prior to starting the next condition. This process was repeated 3 times until the participant had completed the entire VLT (all three AAF conditions). The entire VLT was completed within a single session lasting approximately 1 hr. The order of administration of the AAF conditions was randomized to control for any unknown confounding variables relating to the task order.

Equipment

All speech materials were recorded by an M2211 microphone (NTi Audio), which was placed at 0° azimuth from the speaker at a fixed distance of 30 cm from the mouth (Švec & Granqvist, 2010). The direct digital recording sampled at 44100 Hz was recorded using an external soundboard (UH-7000 TASCAM, TEAC Corporation) connected to a personal computer running Audacity 3.1.3 (SourceForge). While the participants read the short stories for the VLT on a Dell monitor, an iPad running Too Noisy software (iOS), a sound-level meter application, was used to display the visual feedback to maintain a loud voice level (73 dBA). The iPad was 1 m from the participants and was calibrated on running speech in a process that involved an author (C.N.) reading *The Rainbow Passage* at a loud vocal effort level continuously, while the loud vocal effort level of 73 dBA was confirmed via a lingWAVES II SPL meter (WEVOSYS 234 hardware [IEC 651 Type 2, ANSI S1.4 Type 2]) by another author (D.U.). During this calibration process, the specifications of the Too Noisy app were manipulated until the sound-level meter accurately responded to a 73-dBA voice signal. The specifications within the app for the “sensitivity” setting was 95%, and the “dampening” setting within the app was 47%. The iPad was always visible during the VLT, thus providing uninterrupted real-time visual feedback, which maintained a loud vocal effort level throughout the experiment. If the participants’ voice signal was below the 73-dBA threshold, the iPad would display a red screen, which prompted the participants to increase their vocal effort level.

External Auditory Feedback Equipment

Two AAF devices were compared, as well as a control condition. The first AAF device was a modified Forbrain device, provided at no cost by the manufacturer. In this case, the manufacturer removed their patented filter from the device, and thus, the Forbrain provided only sidetone amplification. That is, the direct microphone output was played back to the participant at a level of +2.7 dB, as determined through the calibration procedure (see below).

The second device was a standard Forbrain headset, developed by Sound for Life LTD (Soundev) in Luxembourg (Model UN38.3; http://www.forbrain.com). This device uses a pair of bone conductors and a microphone to provide a speaker with external auditory feedback and was provided at no cost by the manufacturer. According to its patent registration and information outlined in previous research (Escera et al., 2018; Guajarengues & Lohmann, 2015), Forbrain implements a two-band dynamic filter similar to a Baxandall equalizer (Baxandall, 1952). The two bands of the filter are triggered based on the voice energy at 1 kHz (mic input). One of the settings (Setting 1) raises low frequencies (100–800 Hz, +12 dB) while dampening high frequencies (800–15000 Hz, −12 dB) when the input signal energy at 1 kHz exceeds −56 dBV for a trigger time $t1 = 10–50$ ms. The other setting (Setting 2) performs the opposite (i.e., dampening low frequencies ranging from 100 to 800 Hz and raises high frequencies ranging from 800 to 15000 Hz) when the input signal at 1 kHz drops below −66 to −70 dBV for a holding time t2 = 20–200 ms. For the Forbrain device, the direct microphone output was played back to the participant at a level of approximately 7 dB, as determined through the calibration procedure (see below).

Both AAF devices (sidetone amplification and filtered) were calibrated (post hoc) through a procedure in which their vibration was captured while a head and torso simulator (HATS; GRAS 45BB KEMAR) was producing white noise at a level of 70.6 dB SPL at 1 m in a sound booth (corresponding to the experimental protocol). This white noise was recorded using an identical experimental setup, with each AAF device placed on the HATS, using the same settings, as well as a control condition with no AAF devices used. The white noise produced by the mouth of the HATS and recorded by the ears of the HATS was amplified through both the modified (sidetone amplification) and standard Forbrain devices by a magnitude of 2.7 and 7 dB, respectively. Of note, the Forbrain implements an adaptive filter, which changes based on the energetic content within specified frequencies. In selecting white noise in the present calibration, the Forbrain was characterized as if it were linear and time invariant, which is not reflective of its overall response to speech. Figure 2 displays the amplitude responses of the Forbrain, sidetone amplification, and no AAF conditions as recorded during the calibration process.

Analysis

All participant recordings (pre- and postloading tasks as well as reading tasks associated with the VLT) were processed to calculate the (a) amount of self-reported

Figure 2. Differences in spectra recorded by a head and torso simulator during the calibration procedure for the Forbrain device, sidetone amplification device, and no altered auditory feedback (AAF) conditions. AAF = altered auditory feedback.

vocal fatigue on a VAS, (b) SPL values, (c) LTAS_mean, (d) LTAS_SD, and (e) LTAS_skew. Specifically, three separate analyses were completed: (a) analysis of the effects of the AAF devices on self-reported vocal fatigue (VAS), (b) analysis of the effects of the VLT (i.e., analyzing the voice signal from the pre- and postloading tasks, which occurred immediately prior to and immediately following each of the three AAF conditions), and (c) analysis of the reading tasks associated with the VLT (i.e., analyzing the voice signal during the VLT itself).

The recordings were processed with MATLAB R2022b (MathWorks) and Praat 5.4/5.4.17. Specifically, a custom MATLAB script was applied to calculate the SPL values on the voiced speech signal. This script included the MATLAB function detectVoiced (Giannakopoulos, 2009), which extracts (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 are applied in order to detect voiced segments and remove unvoiced segments. To analyze all LTAS measures, the voiced segments were inputted into Praat 5.4/5.4.17, and a script was applied with the following settings: 512-point fast Fourier transform, 0.0025 s of spectrogram window length, Gaussian window shape, and 50 dB of dynamic range. From the LTAS, the spectral moments were calculated with the standard queries of Praat.

Statistical analyses were conducted using R Version 4.2.0 (R Development Core Team). Linear mixed-effects (LME) models were fitted by restricted maximum likelihood (REML). Random effects terms were chosen based on variance explained. Tukey's post hoc pairwise comparisons (multiple comparisons of means: Tukey contrasts) were performed to examine the differences between all levels of the fixed factors of interest. These are pairwise z tests, where the z statistic represents the difference between an observed statistic and its hypothesized population parameter in units of the standard deviation. The LME output includes the estimates of the fixed effects 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 values. The details regarding each model's response variable, predictor variables, and random factors are included in the Results section.

Results

Vocal Fatigue

To assess the effects of the AAF devices on vocal fatigue, an LME model was fitted with "vocal fatigue" as the response variable. The predictors used in the model were time (a numerical variable including the time in minutes from 2 to 20 within each AAF condition) and AAF condition (a factor with three levels: Forbrain, sidetone amplification, and control condition). The interaction between time and AAF condition was not statistically significant. We included the participant ID and the randomized order of AAF condition as random factors to remove their variance from the model.

Across all participants, the use of the Forbrain and sidetone amplification AAF devices had a statistically significant effect on self-reported vocal fatigue ratings (elicited through a VAS). Specifically, across participants in the Forbrain conditions, the vocal fatigue VAS ratings were approximately 9 points (i.e., 9 mm) lower (p = .002) when compared to the condition with no AAF. Across participants in the sidetone amplification condition, the vocal fatigue VAS ratings were approximately 15 points lower (p < .001) when compared to the condition with no AAF. Post hoc comparisons confirmed that the increases in vocal fatigue ratings during the Forbrain conditions compared to the non-AAF conditions (estimate = −8.63, SE = 2.83, z = −3.05, p = .006) and comparing the sidetone amplification conditions to the non-AAF conditions (estimate = −14.83, SE = 2.83, z = −5.23, p < .001) are statistically significant.

Additionally, over the course of the VLT, self-reported vocal fatigue increased by approximately 4 points on the vocal fatigue VAS each time a rating was made (i.e., every 2 min). Figure 3 and Table 1 display the results.

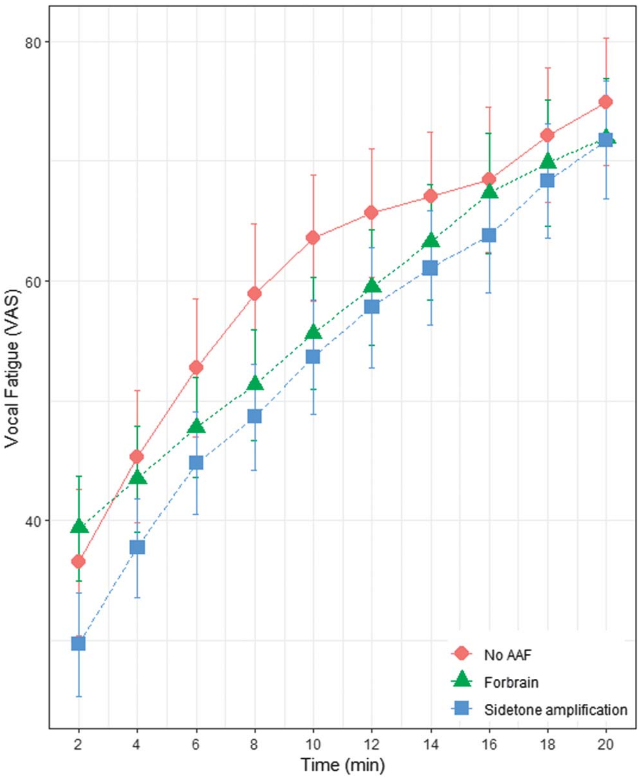
Pre- and Postloading

The following results represent the data analyzed from the pre- and postloading tasks, which occurred immediately prior to and immediately following each of the three AAF conditions. Table 2 summarizes multiple LME models fit by REML for each of the response variables (SPL, LTAS_mean, LTAS_SD, and LTAS_skew). The predictors used in all the four models were the two factors: pre-/postloading (two-level factor) and AAF condition (three levels: Forbrain, sidetone amplification, and control condition). The interaction between pre-/postloading and AAF condition was not significant. We included the participant ID and gender as well as task (reading and spontaneous speech) as random factors to remove their variance from the model. Figures 4–7 represent mean and standard error for each response variable measured pre- and postloading for vowel and connected speech tasks.

SPL

The use of the Forbrain and sidetone amplification AAF devices during the pre- and postloading tasks had a

Figure 3. Mean and standard error of vocal status ratings for the AAF conditions and their change over time during the vocal loading task. AAF = altered auditory feedback; VAS = visual analog scale.



statistically significant effect on SPL, with SPL decreasing by approximately 1.2 dB (p = .048) during the Forbrain conditions and 1.5 dB (p = .015) during the sidetone amplification conditions compared to the non-AAF conditions. Comparing the pre- and postloading tasks themselves, there was a significant increase in SPL by approximately 2.5 dB (p < .001) when speaking in the postloading tasks. Post hoc comparisons confirmed that the changes in SPL during the sidetone amplification conditions compared to the non-AAF conditions (estimate = −1.53, SE = 0.63, z = −2.44, p = .039) and comparing the preloading to the postloading conditions (estimate = 2.46, SE = 0.51, z = 4.83, p < .001) are statistically significant.

LTAS_mean

The use of an AAF device had a statistically significant effect on LTAS_mean during pre- and postloading tasks, with LTAS_mean decreasing by approximately 92.52 Hz (p < .001) during the Forbrain conditions compared to the non-AAF conditions and by approximately 86.58 Hz (p < .001) during the sidetone amplification conditions compared to the non-AAF conditions. Comparing the pre- and postloading tasks, there was no detectable relationship between LTAS_mean and order. Post hoc comparisons confirmed that the decreases in LTAS_mean comparing the Forbrain conditions to the non-AAF conditions (estimate = −92.52, SE = 23.25, z = −3.98, p < .001) and the sidetone amplification conditions to the non-AAF conditions (estimate = −86.58, SE = 23.25, z = −3.72, p < .001) are statistically significant.

LTAS-SD

The use of an AAF device had a statistically significant effect on LTAS_SD during pre- and postloading tasks, with LTAS_SD decreasing by approximately 66.66 Hz (p = .030) during the Forbrain conditions compared to the non-AAF conditions and by approximately 70.98 Hz (p = .021) during the sidetone amplification conditions compared to the non-AAF conditions. Comparing the pre- and postloading tasks, there was no detectable relationship with LTAS_SD. Post hoc comparisons did not confirm any LTAS_SD results with significance.

LTAS_skew

The use of an AAF device had a statistically significant effect on LTAS_skew during pre- and postloading tasks, with LTAS_skew increasing by approximately 0.83 Hz (p < .013) during the Forbrain conditions compared to the non-AAF conditions and by approximately 0.66 Hz (p < .049) during the sidetone amplification conditions compared to the non-AAF conditions. Comparing the pre- and postloading tasks, there was no detectable relationship between LTAS_skew and order. Post hoc comparisons confirmed that the increases in LTAS_skew comparing the Forbrain conditions to the non-AAF conditions (estimate = 0.83, SE = 0.33, z = 2.50, p = .034) are statistically significant.

Table 1. Linear mixed-effects models' output run with vocal fatigue as the response variable and altered auditory feedback (AAF) condition and time as the fixed factors.

Fixed factors	Estimate (–)	*SE* (–)	*df*	*t*	*p*
			Vocal fatigue (VAS)		
(Intercept: no AAF)	42.84	8.36	3	5.12	.012*
Forbrain	–8.63	2.83	573	–3.05	.002**
Sidetone amplification	–14.83	2.83	573	–5.24	< .001***
Time	3.87	0.32	573	12.08	< .001***

Note. VAS = visual analog.

*p < .05. **p < .01. ***p < .001.

Table 2. Summary of the pre- and postloading data including linear mixed-effects models with all response variables, the altered auditory feedback (AAF) conditions, and order (posttasks) as fixed factors.

Fixed factors	**Estimate (–)**	***SE* (–)**	***df***	***t***	***p***
SPL (dB)					
(Intercept: preloading, no AAF)	63.72	3.46	1	18.41	.019*
Forbrain	–1.23	0.63	216	4.81	.048*
Sidetone amplification	–1.53	0.63	216	–1.99	.015*
Postloading conditions	2.46	0.51	217	4.83	< .001**
LTAS_mean (Hz)					
(Intercept: preloading, no AAF)	789.62	73.16	1	10.79	.047*
Forbrain	–92.52	23.25	217	–3.98	< .001**
Sidetone amplification	–86.58	23.25	217	–3.72	< .001**
Postloading conditions	35.73	17.23	217	2	.061†
LTAS_SD (Hz)					
(Intercept: preloading, no AAF)	792.75	285.23	1	2.78	.165
Forbrain	–66.66	30.48	216	–2.18	.030*
Sidetone amplification	–70.98	30.48	216	–2.33	.021*
Postloading conditions	–4.09	24.83	217	–0.17	.869
LTAS_skew (Hz)					
(Intercept: preloading, no AAF)	5.9	1.03	2	5.75	.050*
Forbrain	0.83	0.33	216	2.5	.013*
Sidetone amplification	0.66	0.33	216	1.98	.049*
Postloading conditions	–0.14	0.27	217	–0.5	.615

Note. Participant ID and participant gender were the random effects terms, and the reference levels were no AAF for the condition and preloading for the task. SPL = sound pressure level; LTAS_mean = spectral mean of the long-term average spectrum; LTAS_SD = standard deviation of the long-term average spectrum; LTAS_skew = skewness of the long-term average spectrum.

*p < .05. **p < .001. †p < .1.

Figure 4. Mean and standard error of sound pressure level for the AAF conditions and pre- versus postloading values. AAF = altered auditory feedback; SPL = sound pressure level.

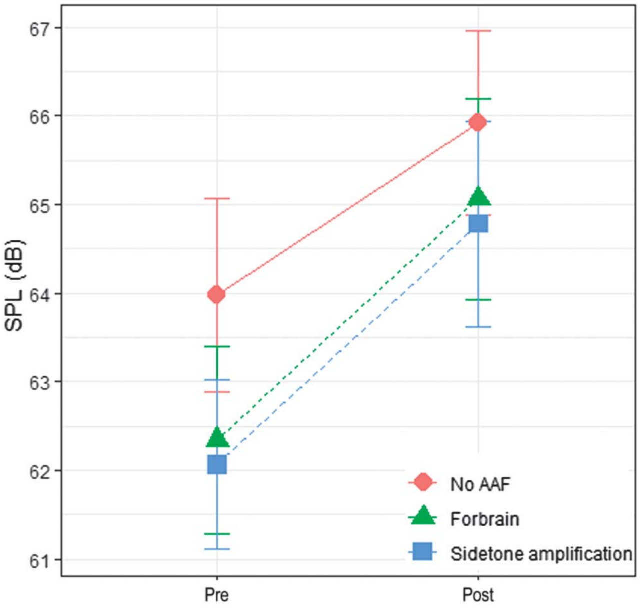


Figure 5. Mean and standard error of the spectral mean of the long-term average spectrum for the altered auditory feedback (AAF) conditions and pre- versus postloading values.

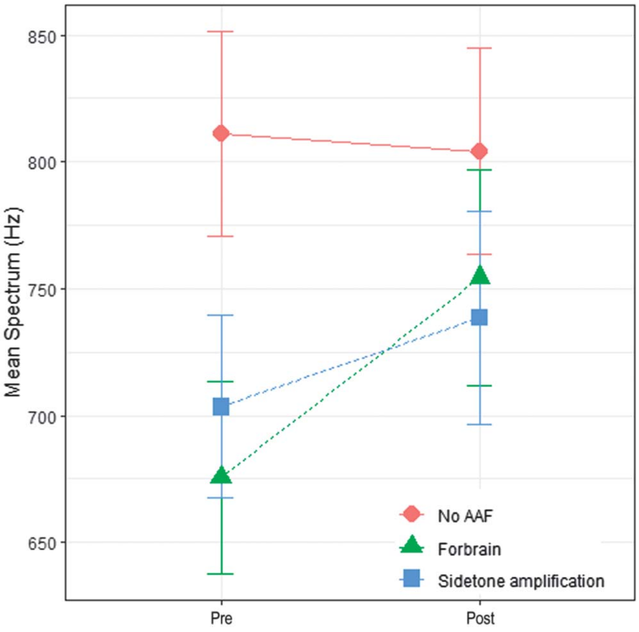
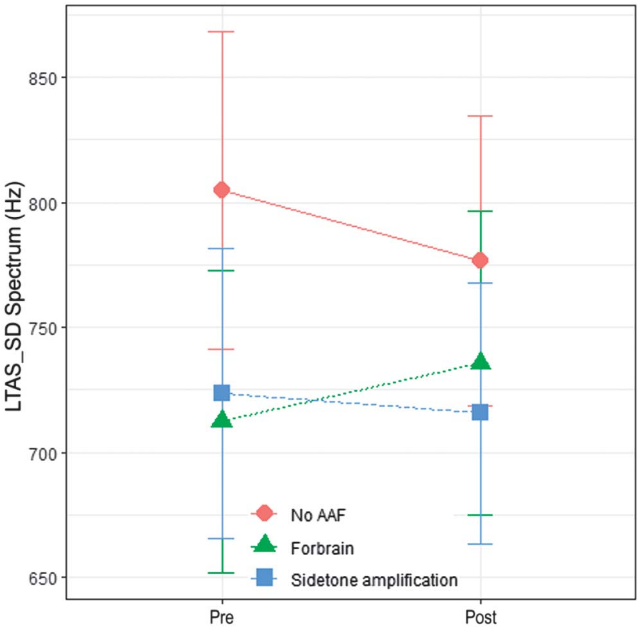


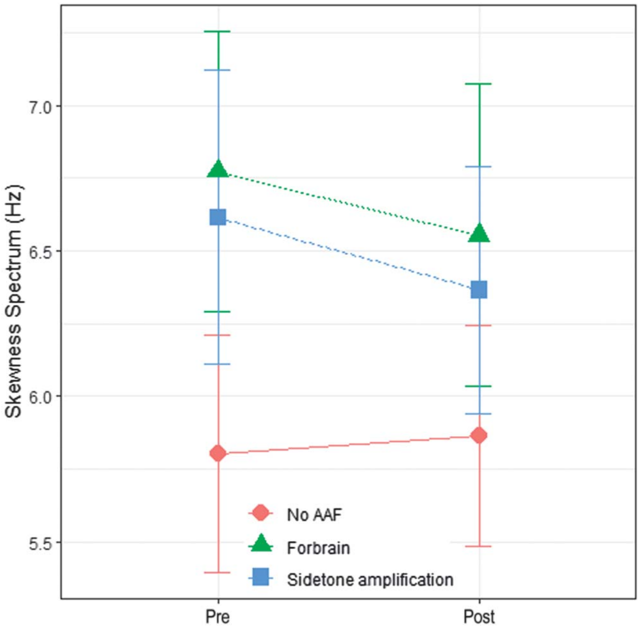
Figure 6. Mean and standard error of the standard deviation of the long-term average spectrum (LTAS_SD) for the altered auditory feedback (AAF) conditions and pre- versus postloading values.



During VLT

The following results represent the data analyzed from the reading tasks associated with the VLT. Table 3 summarizes multiple LME models fit by REML for each of the response variables (LTAS_mean, LTAS_SD, and LTAS_skew) recorded during each condition of the VLT. The predictors used in all the four models are time (a numerical variable including the time in minutes from 2 to 20 within each AAF condition) and AAF condition (three levels: Forbrain, sidetone amplification, and control condition). The interaction between time and AAF condition was not significant. We included the participant ID and gender as well as the randomization order of the three AAF condition as random factors to remove their variance from the model.

Figure 7. Mean and standard error of the skewness of the long-term average spectrum for the altered auditory feedback (AAF) conditions and pre- versus postloading values.



LTAS_mean

During each condition of the VLT, as time progressed, LTAS_mean decreased significantly by approximately 1.85 Hz (p = .001). During the VLT, LTAS_mean was significantly lower by approximately 53 Hz (p < .001) in the Forbrain conditions compared to the non-AAF conditions and by approximately 15 Hz in the sidetone amplification conditions compared to the non-AAF conditions (p = .031). Post hoc comparisons confirmed that the decreases in LTAS_mean comparing the Forbrain conditions to the non-AAF conditions (estimate = −53.00, SE = 6.73, z = −7.74, p < .001) and the Forbrain conditions to the sidetone amplification conditions (estimate = 37.57, SE = 6.64, z = 5.66, p < .001) are statistically significant. Post hoc comparisons did not confirm that the decreases in LTAS_mean comparing the sidetone amplification conditions to the non-AAF conditions are significant (estimate = −14.53, SE = 6.73, z = −2.16, p = .079).

LTAS_SD

During the VLT, as time progressed, LTAS_SD decreased significantly by approximately 1.5 Hz (p = .025). During the VLT in the Forbrain conditions, LTAS_SD was significantly lower by approximately −32 Hz (p < .001) compared to the non-AAF conditions. Post hoc comparisons confirmed that the decreases in LTAS_SD comparing the Forbrain conditions to the non-AAF conditions (estimate = −32.43, SE = 9.66, z = −3.36, p = .002) are statistically significant. There were no detectable relationships between the other LTAS_SD and the other conditions during the VLT.

LTAS_skew

During the VLT, there was no detectable relationship with the progression of time and LTAS_skew. During the VLT, LTAS_skew was significantly higher by approximately 0.43 Hz (p < .001) in the Forbrain conditions compared to the non-AAF conditions and by approximately 0.17 Hz in the sidetone amplification conditions compared to the non-AAF conditions (p = .015). Post hoc comparisons confirmed that the decreases in LTAS_skew

Table 3. Summary of voice data during the vocal loading task, including linear mixed-effects models with all response variables and the altered auditory feedback (AAF) conditions and time as the fixed factors.

Fixed factors	**Estimate (–)**	***SE* (–)**	***df***	***t***	***p***
LTAS_mean (Hz)					
(Intercept: no AAF)	911.09	153.26	1	5.94	.105
Forbrain	–53.00	6.73	576	–7.74	< .001***
Sidetone amplification	–14.53	6.74	576	–2.16	.031**
Time	–1.85	0.47	575	–3.96	< .001***
LTAS_SD (Hz)					
(Intercept)	979.40	160.90	1	6.09	.100
Forbrain	–32.43	9.66	576	–3.36	< .001***
Sidetone amplification	–10.71	9.66	576	–1.11	.268
Time	–1.50	0.67	575	–2.24	.025*
LTAS_skew (Hz)					
(Intercept: no AAF)	6.31	0.61	1	10.32	.057†
Forbrain	0.43	0.07	561	6.21	< .001***
Sidetone amplification	0.17	0.07	561	2.43	.015*
Time	0.01	> 0.00	575	1.89	.058†

Note. Participant ID, participant gender, and the order of randomization were the random effects terms, and the reference level was no AAF for the condition. LTAS_mean = spectral mean of the long-term average spectrum; LTAS_SD = standard deviation of the long-term average spectrum; LTAS_skew = skewness of the long-term average spectrum.

$^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$. $^{\dagger}p < .1$.

comparing the Forbrain conditions to the non-AAF conditions (estimate = 0.43, *SE* = 0.07, *z* = 6.21, *p* < .001), the sidetone amplification conditions to the non-AAF conditions (estimate = 0.17, *SE* = 0.06, *z* = 2.43, *p* = .040), and the Forbrain conditions to the sidetone amplification conditions (estimate = 0.25, *SE* = 0.07, *z* = −3.82, *p* = .001) are statistically significant.

Discussion

The primary aim of this study was to compare the effects of AAF on voice production and self-reported vocal fatigue when the AAF was provided by two bone conduction devices: (a) sidetone amplification via a modified Forbrain device and (b) Forbrain's filtered auditory feedback through a VLT. The results demonstrated that both the sidetone amplification and Forbrain's filtered AAF resulted in significantly decreased self-reported vocal fatigue during the VLT.

Comparing Pre- and Postloading During VLT

In this study, both the effects of the VLT (pre- and postloading) and the vocal accommodations to the AAF conditions during the VLT itself (during VLT) were analyzed. When comparing these two analyses, the results across the variables were similar in direction and relatively similar in magnitude. However, each analysis provides distinct information. That is, the pre- and postloading data revealed that, after loading, the AAF devices resulted in improved voice quality (improved measures of LTAS) compared to the control condition. Moreover, the sidetone amplification device resulted in significantly lower SPL values compared to the control condition. The during-VLT data represent a similar trend regarding measures of voice quality, but to a lesser extent. This could be attributed to the vocal demands associated with the VLT (i.e., sustained loud vocal effort level).

For the pre- and postloading tasks, the use of both devices resulted in significantly decreased spectral mean compared to the no-AAF condition, the Forbrain device resulted in significantly increased LTAS_skew, and the sidetone amplification device resulted in significantly decreased SPL. Of note, the increases in SPL with the Forbrain and the decreases in LTAS_SD with both types of AAF during the pre- and postloading tasks were not confirmed as statistically significant.

For the voice recordings captured during the VLTs, both the sidetone amplification and Forbrain's filtered AAF resulted in significantly decreased LTAS_mean and significantly increased LTAS_skew. Additionally, during the VLT, LTAS_SD was significantly reduced in the Forbrain conditions compared to the non-AAF conditions.

A secondary finding of the study was that the VLT paradigm that was employed resulted in significant increases in vocal fatigue over time and significant increases in SPL in the postloading tasks compared to the preloading tasks, which has been verified as an objective marker of vocal fatigue in prior VLT paradigms (e.g., Anand et al., 2021; Bottalico, 2017). Thus, the VLT can be considered valid in eliciting subjective and objective measures of vocal fatigue.

Vocal Fatigue

Compared to the no-AAF condition, the use of AAF devices significantly reduced the amount of self-reported vocal fatigue during the VLT. Vocal fatigue ratings were 9 points lower on the VAS comparing the Forbrain condition to the no-AAF condition and were 15 points lower on the VAS during the sidetone amplification condition compared to the no-AAF condition. These results have clinical significance and support the possibility that AAF devices that target sensorimotor integration could reduce voice symptoms and possibly serve as a preventative tool. In contrast, the current preventative recommendation mainly provided by voice clinicians is to use personal voice amplification systems (Bovo et al., 2013; Jónsdottir et al., 2001, 2002, 2003; McCormick & Roy, 2002; Roy et al., 2003). However, it has been empirically demonstrated that personal voice amplification devices actually worsen voice-related outcomes, ostensibly due to the relationship between amplification devices and increased room noise (a risk factor for voice disorders; Banks et al., 2022; Nudelman et al., 2023). In addition to voice amplification, other devices exist to help speakers, such as sound field amplification (SFA), which aims to help speakers' voices reach listeners. In classrooms, SFA has been empirically demonstrated to aid in students' speech perception of their teacher (Trinite & Astolfi, 2021). Some advantages that AAF has over SFA are (a) the ability for teachers to move around their classroom without the restraint of electrical cables, which are commonly included within SFA devices, and (b) the absence of a temporal delay between the voice signal leaving the mouth and the signal leaving the loudspeaker used for SFA.

Although the results of this study demonstrate statistically significant differences in the VAS ratings of vocal fatigue, previous research indicates that individuals' self-rated vocal status is prone to inaccuracy and error (e.g., Mehta et al., 2016). Thus, it is possible that other factors influenced the vocal fatigue ratings in our participants. For example, the participants' mood, motivation, pain, and expectations may have played a role in their vocal fatigue ratings. Emotional stress could be another explanation (Dietrich et al., 2008). More likely is the fact that performance feedback affects self-reported vocal fatigue (Hunter et al., 2020), and this study involved both visual and auditory performance feedback (i.e., visual feedback from the sound-level meter and the AAF).

SPL

Previous literature has demonstrated that AAF targeting increased bone conduction reduces vocal SPL in healthy speakers and those with voice disorders (Bauer et al., 2006; Heinks-Maldonado et al., 2006; Nudelman, Codino, et al., 2022; Tomassi et al., 2023). Regarding SPL, the present results demonstrate that the sidetone amplification AAF resulted in significant decreases in voice intensity compared to the no-AAF condition. These results reinforce bone conduction AAF as a tool that can 2successfully reduce the vocal SPL in running speech for users, ostensibly reducing their risk for sustaining a voice disorder (e.g., S. H. Chen et al., 2010). The magnitude of change in vocal SPL during the sidetone amplification condition was 1.53 dB SPL. While this magnitude may seem trivial, previous research has correlated changes in vocal SPL ranging from 0.8 to 2.0 dB SPL to the accumulation of vocal loading during a workday in occupational voice users (Jónsdottir et al., 2002; Laukkanen et al., 2008).

Spectral Measures: Mean, Standard Deviation, and Skewness

In this study, measures of the LTAS had significant relationships with AAF devices, to varying degrees. That is, LTAS_mean was significantly lower during the Forbrain conditions, LTAS_SD was significantly lower during the Forbrain conditions compared to the sidetone amplification conditions during the VLT, and LTAS_skew was significantly higher during the use of AAF, with the Forbrain conditions having significantly higher LTAS_skew compared to the sidetone amplification conditions. Overall, LTAS_mean has been demonstrated to be the primary spectral voice measure that consistently accounts for the majority of variance in changes in compensatory voice production (Tanner et al., 2005). In this study, the Forbrain conditions resulted in significant decreases in LTAS_mean, indicating more energy near the fundamental frequency, as opposed to more energy in the higher frequency ranges. According to prior research, this shift in the spectral energy during the Forbrain conditions implies that the participants were using less vocal effort compared to the non-AAF control condition (Harwardt, 2011). In the context of this evidence, vocal effort was strongly linked with increasing one's vocal intensity in response to a communication demand. This is interesting, as the present experiment employed a task that required a loud vocal effort as well. In light of these results from the study of Harwardt (2011), which associates decreased vocal effort with decreased LTAS_mean, we can gain insight into the effects of bone conduction AAF. The present results affirm that, in vocally demanding scenarios, the use of bone conduction AAF contributes significantly to decreases in the acoustic correlates of vocal effort, even at a loud vocal intensity. Additionally, previous studies have found significant decreases in spectral mean in patients' voices after they had completed successful voice therapy (Tanner et al., 2005). Of note, spectral measures also tend to have a positive relationship with SPL and fundamental frequency. That is, increases in SPL have been demonstrated to lead to increases in fundamental frequency (Gramming et al., 1988) and ostensibly contribute increased energy in the higher frequencies in the voice signal (i.e., increased LTAS_mean). In this study, the opposite occurred during AAF conditions, as participants demonstrated reduced SPL and reduced LTAS_mean, particularly during the pre- and postloading tasks. These results imply that AAF provided via bone conduction may also benefit a listener, as the improved voice quality is associated with increased signal-to-noise ratio (i.e., there is less high-frequency noise in the voice signal based on the reduced LTAS_mean; Evitts et al., 2016; Lallh & Rochet, 2000; Lyberg-Åhlander et al., 2015).

Bone Conduction AAF in Practice

The AAF devices used in this study are publicly available and comparable in price to typical air-conduction headphones used in voice science. Based on the present results, as well as previous studies that examined the effects of bone conduction AAF on voice production (e.g., Lee et al., 2019; Nudelman, Codino, et al., 2022), these devices seem to be promising tools in the prevention and treatment of voice disorders, as they appear to augment auditory–motor integration during speech in a positive way for both healthy speakers and those with voice disorders. An important consideration for future research and clinical applications with these devices has to do with the microphone. At present, the direct voice signal cannot be recorded from the Forbrain device's attached microphone. With this in mind, the use of a contact microphone (Bottalico & Nudelman, 2023) or an accelerometer (Mehta et al., 2012) placed on the neck may be necessary to capture voice recordings in daily life. With such data, researchers and clinicians could ostensibly assess the effectiveness of the use of bone conduction AAF in daily communication scenarios.

Limitations

There are a few limitations of the study that should be acknowledged. The first limitation involves generalizability. Only vocally healthy participants were included, and thus, it is unclear how the results may differ in individuals with voice disorders, including categories of voice disorders that have been linked to impaired sensorimotor integration (e.g., hyperfunctional voice disorders; Castro et al., 2022; Hillman et al., 2020; Stepp et al., 2017; Ziethe et al., 2019). Previous research has found that bone conduction sidetone amplification results in consistent adaptation in the SPL values and mean pitch strength in patients with vocal hyperfunction, glottal insufficiency, and organic/neurological laryngeal pathologies compared to conditions with no feedback (Nudelman, Codino, et al., 2022). However, these results from a clinical population remain to be verified during a VLT and during daily communication scenarios.

Another limitation has to do with the ecological validity of the VLT used in this study. Given that reading at a fixed intensity level likely does not simulate everyday vocal loading, the present results should be interpreted with caution and should not be generalized to imply that AAF will result in reduced vocal fatigue or reduced compensatory voice production during daily communication scenarios. Recent studies have examined vocal loading with the goal of utilizing more ecologically valid approaches (Nusseck et al., 2022; Sandage et al., 2022; Trinite et al., 2022). These studies each implemented ecologically valid vocal loading in different ways, such as reading tasks (Nusseck et al., 2022), providing fixed background noise levels in real-life rooms (Trinite et al., 2022), and pre-/post-measures after unstandardized daily VLTs in daily life (Sandage et al., 2022). It would be useful to examine the efficacy of AAF devices in ecologically valid VLTs such as these and potentially incorporate multivariate objective measures (e.g., Daily Phonotrauma Index; Nudelman, Ortiz, et al., 2022; Van Stan et al., 2021, 2023) in association with self-reported vocal status ratings.

Along similar lines, a final limitation is associated with the possibility that the VLT employed in this study did not effectively fatigue the voice mechanism. Previous research has verified that individuals' self-rated vocal status is prone to inaccuracy and error (e.g., Mehta et al., 2016). Additionally, there is inconsistency in outcome data from VLTs employing loud reading tasks for an hour or less in duration. Prior VLTs with short, loud reading tasks failed to elicit objective measures of vocal fatigue (e.g., Buekers, 1998; Whitling et al., 2015), while more recent studies (which elicited loud reading ranging from 10 to 60 min) successfully achieved objective measures of vocal fatigue (Echternach et al., 2020; Free et al., 2021; Lei et al., 2020; Xue et al., 2019). These inconsistent results have prompted recommendations that a short (less than 1 hr) VLT using a loud reading task should involve at least one additional factor to produce measurable change in voice (Fujiki & Sivasankar, 2017). Such additional factors could involve altering vocal quality, eliciting nonhabitual speech, or implementing environmental perturbations. Additionally, it has been recommended that VLTs are assessed in a multisystem manner. That is, the suggested outcome measures from VLTs should capture the physiologic fatigue response of the respiratory, laryngeal, and supralaryngeal subsystems (e.g., Sundarrajan et al., 2017). The present VLT failed to follow these two guidelines. Thus, to better extend the present results, future VLT experiments utilizing AAF would benefit from employing a similar reading task that is longer in duration and also involves additional factors in the elicitation of multisystem vocal fatigue.

Conclusions

This study provides evidence that both AAF sidetone amplification via a modified Forbrain device and filtered AAF via a standard Forbrain headset device contribute to significantly reduced self-reported vocal fatigue, significantly decreased LTAS_mean and LTAS_SD, increased LTAS_skew, and decreased SPL during a VLT. During the VLT, the Forbrain device resulted in improved voice quality in regard to LTAS_SD and LTAS_skew compared to the sidetone amplification condition. These results promote bone conduction AAF as a possible preventative tool that may reduce self-reported vocal fatigue and compensatory voice production for healthy individuals without voice disorders.

Data Availability Statement

All data obtained and/or analyzed are available from the authors upon reasonable request.

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