



# ALTERED AUDITORY FEEDBACK VIA BONE CONDUCTION: EVALUATING THE FORBRAIN DEVICE AND SIDETONE AMPLIFICATION

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## ABSTRACT

**Purpose** This study assesses changes in speech production caused by altered auditory feedback provided through two bone conduction devices. The first device uses sidetone amplification through bone conduction headphones and the second device, called Forbrain®, applies a two-band equalizer filter to the voice signal and provides this altered auditory signal through bone conduction headphones. Together with objective voice acoustics, self-reported vocal fatigue ratings were also assessed.

**Methods** Speech samples were recorded during a vocal loading task in which speakers received different types of altered auditory feedback delivered from the two devices, and a condition with no feedback. At consistent intervals during each condition, the participants provided vocal fatigue ratings. The voice recordings were processed to calculate acoustic parameters. The effects of the feedback conditions on the vocal fatigue ratings and acoustic voice parameters were analyzed.

**Results** The altered auditory feedback conditions resulted in reduced magnitudes of vocal fatigue and significant variations in acoustic voice parameters compared to the condition with no feedback.

**Conclusions** This study provides evidence that altered auditory feedback delivered by bone conduction devices can reduce vocal fatigue in users.

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**Keywords:** voice production, altered auditory feedback, biofeedback

## 1. INTRODUCTION

Across the lifespan, approximately 30% of the population will experience impairments in voice production, resulting in a voice disorder [1]. One of the most commonly treated voice disorders is vocal hyperfunction (e.g., [2]). Within this group of highly prevalent voice disorders, a possible underlying factor is impaired sensorimotor integration. Sensorimotor integration can be defined as the integration of auditory, visual, and somatosensory information with motor actions—in this case, voice production. Given the prevalence of vocal hyperfunction, it would be informative to explore possible preventative measures that target vocal responses to impaired sensorimotor integration.

### 1.1 Altered Auditory Feedback

Real-time altered auditory feedback (AAF) is one tool that could address impaired sensorimotor information present in those with vocal hyperfunction. Typically, AAF is presented in the daily lives of individuals through headphones, including traditional air conduction headphones [3], and more recently, via bone conduction headphones [4, 5].

### 1.2 The Forbrain® Device

There is one commercially available AAF device that uses bone conduction to improve speech. Forbrain®, developed by Sound For Life Limited (Soundev) in Luxemburg

uses a pair of bone conductors and a microphone to provide a speaker with real-time AAF. 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 ranging 10–200 ms [6]. 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 [4].

Previously, a simplified version of bone conduction AAF (without the two-band filtering), which provided sidetone amplification, was demonstrated to significantly improve the voice quality of speakers with voice disorders [5].

### 1.3 Purpose

The present study aims to examine the effects of AAF provided by two bone conduction devices: 1) AAF sidetone amplification via a modified Forbrain® device and 2) filtered AAF via a standard Forbrain® headset. These devices will be assessed through a vocal loading task (VLT) in terms of acoustic voice parameters produced by healthy participants and their subjective self-ratings of vocal fatigue. We hypothesize that AAF provided via the modified and unmodified Forbrain® devices will result in improvements in compensatory voice production and decreased vocal fatigue during the VLT, as compared to a control condition with no AAF.

## 2. METHODS

Twenty participants (19 - 33 years; mean (SD) 25.5 (3.85) years) were enrolled in the study. Ten of the participants were male and ten were female. Inclusion criteria for the present study was being over the age of 18 years old, passing a hearing screen and reporting no history of voice, speech, language, or hearing disorders. Speech samples of each participant were recorded during a VLT in three different AAF conditions. The recordings were performed in a sound attenuating double-walled Whisper Room. The effects of the type of AAF on 1) the amount of self-reported vocal fatigue on a visual analog scale (VAS) during the VLT, 2) voice intensity (SPL) values, 3) harmonics-to-noise ratio (HNR), 4) the spectral mean of the long term average spectrum (LTAS\_mean), 5) the standard deviation of the long term average spectrum (LTAS\_SD), and 6) the skewness of the long term average spectrum (LTAS\_skew) during pre- and post- VLT voice tasks were evaluated.

### 2.1 Vocal Loading Task and Conditions

For the VLT, the participants were instructed to read aloud five short stories by L. Frank Baum [7–11], which were presented in a randomized order to stratify their linguistic content randomly across three randomized AAF conditions (each lasting 20 minutes). The three different randomized AAF conditions were:

- 1) A control condition
- 2) AAF sidetone amplification via a modified Forbrain® device
- 3) Filtered AAF via a standard Forbrain® headset

During the VLT, participants' voice level (intensity) was fixed at 73 dB(A) (i.e., a raised vocal effort level [12]), which was achieved through real-time visual feedback from a sound level meter application displayed on an iPad. During the VLT, the participants were prompted to rate their vocal fatigue on a visual analog scale (VAS) every two minute of reading, in a similar manner as a previous VLT paradigm [13]. Vocal fatigue was defined for the participants as “your perception of a decline in your voice during the voice production task” [14].

Prior to and following each AAF condition of the VLT, the participants completed two speech tasks, 1) reading aloud the first six sentence of *The Rainbow Passage*, a standardized text in English [15] and 2) sustaining an /a/ vowel for at least 5 seconds. These tasks were completed with the same AAF device (or lack thereof) that was used in the AAF condition, were performed at a comfortable voice level, and served as measures of objective voice parameters (i.e., pre- and post- VLT data).

### 2.2 Equipment

All speech material was recorded by an M2211 microphone (NTi Audio, Tigard, OR, United States). During the VLT, an iPad running *Too Noisy* software (ios), a sound level meter application, was used to display the visual feedback to maintain a raised voice level (73 dB(A)).

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 modified Forbrain® provided only sidetone amplification. The second device was a standard Forbrain® headset, which implements a two-band dynamic filter similar to a Baxandall equalizer [16]. 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  $t_1=10-50$  ms. The other setting (Setting 2) performs the opposite (i.e., dampening low frequencies ranging 100–800 Hz and raises high frequencies ranging 800-15000 Hz) when the input signal at 1 kHz drops below -66 to -70 dBV for a holding time  $t_2=20-200$  ms [6].

### 2.3 Analysis

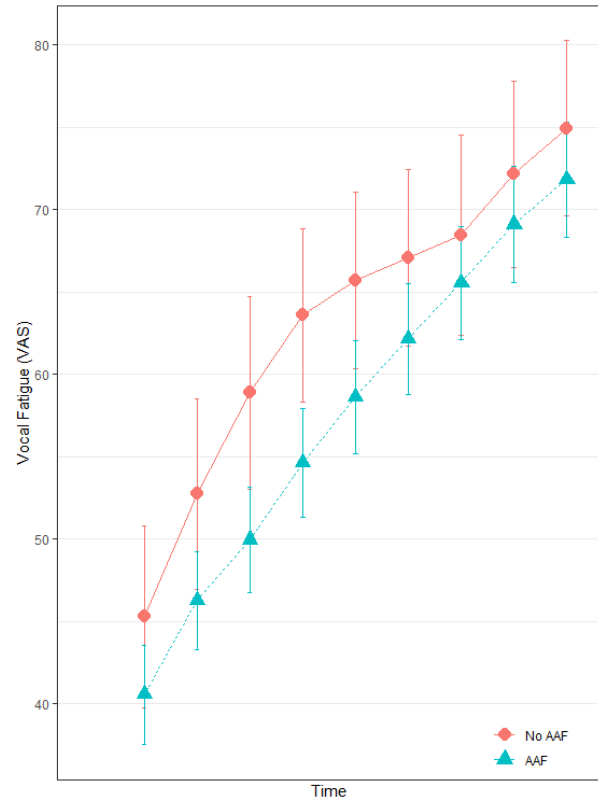
In addition to analyzing the amount of self-reported vocal fatigue on the visual analog scale (VAS) during the VLT, all participant pre- and post- VLT voice recordings were processed to calculate 1) voice intensity (SPL) values, 2) harmonics-to-noise ratio (HNR), 3) the spectral mean of the long term average spectrum (LTAS\_mean), 4) the standard deviation of the long term average spectrum (LTAS\_SD), and 5) the skewness of the long term average spectrum (LTAS\_skew). The recordings were processed with MATLAB R2022b (Mathworks, Natick, 284 MA, USA) and Praat 5.4/5.4.17 (Netherlands). Statistical analyses were conducted using R version 4.2.0 (R Development Core Team, 2022). Linear Mixed-Effects (LME) models were fitted by restricted maximum likelihood (REML). Tukey's post-hoc pairwise comparisons 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 included 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.

## 3. RESULTS

### 3.1 Results: Vocal Fatigue

Across all participants, the use of an AAF device had a statistically significant effect on self-reported vocal fatigue ratings (elicited through a VAS). Specifically, across patients in the conditions that included AAF, the vocal fatigue VAS ratings were approximately 12 points lower ( $p < 0.001$ ) when compared to the condition with no AAF. 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

two minutes). Figure 1 and Table 1 display the results.



**Figure 1:** Mean and standard error (SE) of vocal status ratings for the AAF conditions and their change over time during the VLT.

**Table 1:** LME models output run with vocal fatigue as the response variable and the AAF condition and time as fixed factors.

Fixed factors	Estimate (-)	Std. Error(-)	df	t	p
Vocal Fatigue (VAS)					
(Intercept: No AAF)	43.60	8.29	3	5.26	0.011**
AAF Conditions	-12.16	2.45	573	-5.00	<0.001***
Time	3.76	0.32	573	11.75	<0.001***
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1					

### 3.2 Results: Sound Pressure Level

The use of an AAF device during the pre- and post- VLT tasks had a statistically significant effect on SPL, with SPL decreasing by approximately 1.4 dB ( $p = 0.011$ ) during

AAF conditions compared to non-AAF conditions. Comparing the pre- and post- VLT tasks themselves, there was a significant increase in SPL by approximately 2.5 dB ( $p < 0.001$ ) when speaking in the post-VLT tasks. Post-hoc comparisons confirmed that the decreases in SPL during the AAF compared to non-AAF conditions (Estimate = -1.39, SE = 0.54,  $z = -2.56$ ,  $p = 0.010$ ) and comparing the pre- to the post- VLT conditions (Estimate = 2.46, SE = 0.51,  $z = 4.83$ ,  $p < 0.001$ ) are statistically significant. Table 2 displays the results.

**Table 2:** LME models output run with sound pressure level as the response variable and the AAF conditions and order (post-VLT tasks) as fixed factors.

Fixed factors	Estimate (-)	Std. Error(-)	df	t	p
SPL					
(Intercept: Pre-VLT, No AAF)	63.72	3.46	1	18.41	0.019*
AAF Conditions	-1.39	0.54	217	-2.56	0.011*
Post-VLT Condition	2.46	0.51	217	4.83	<0.001***

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1

### 3.3 Results: Harmonics-To-Noise Ratio

HNR increased by approximately 0.34 dB ( $p = 0.033$ ) during AAF conditions compared to non-AAF conditions. There was also a significant increase in HNR by approximately 0.60 dB ( $p < 0.001$ ) when speaking in the post-VLT tasks. Finally, HNR was approximately 1.96 dB higher in the female participants compared to the male participants ( $p = 0.011$ ). Post-hoc comparisons confirmed that the increases in HNR comparing the AAF conditions to the non-AAF conditions (Estimate = 0.34, SE = 0.16,  $z = 2.16$ ,  $p = 0.031$ ), comparing the pre- to the post- VLT conditions (Estimate = 0.60, SE = 0.15,  $z = 4.12$ ,  $p < 0.001$ ), and comparing the female to the male participants (Estimate = 1.96, SE = 0.69,  $z = 2.84$ ,  $p = 0.005$ ) are statistically significant. Table 3 displays the results.

**Table 3:** LME models output run with harmonics-to-noise ratio as the response variable and the AAF conditions, order (post-VLT tasks), and participant sex as fixed factors.

Fixed factors	Estimate (-)	Std. Error(-)	df	t	p
HNR					
(Intercept: Pre-VLT, No AAF)	15.52	0.50	21	30.78	<0.001***
AAF Conditions	0.34	0.16	98	2.16	0.033*
Post-VLT Condition	0.60	0.15	98	4.10	<0.001***
Female Participants	1.96	0.69	18	2.84	0.011*

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1

### 3.4 Results: Spectral Mean of the Long Term Average Spectrum

The use of an AAF device had a statistically significant effect on LTAS\_mean, with LTAS\_mean decreasing by approximately 89.55 Hz ( $p = 0.047$ ) during AAF conditions compared to non-AAF conditions. Comparing the pre- and post- VLT tasks, there was no detectable relationship between LTAS\_mean and order. Post-hoc comparisons confirmed that the decreases in LTAS\_mean comparing the AAF conditions to the non-AAF conditions (Estimate = -89.55, SE = 19.34,  $z = -4.63$ ,  $p < 0.001$ ) are statistically significant. Table 4 displays the results.

**Table 4:** LME models output run with Spectral Mean of the Long Term Average Spectrum as the response variable and the AAF conditions and order (post-VLT tasks) as fixed factors.

Fixed factors	Estimate (-)	Std. Error(-)	df	t	p
LTAS_mean					
(Intercept: Pre-VLT, No AAF)	750.70	73.57	1	10.20	0.050*
AAF Conditions	-89.55	19.34	217	-4.63	<0.001***
Post-VLT Condition	35.73	18.23	217	2.00	0.051.

Signif. codes: 0 '\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1

### 3.5 Results: Standard Deviation of the Long Term Average Spectrum

The use of an AAF device had a statistically significant effect on LTAS\_SD, with LTAS\_SD decreasing by approximately 68.82 Hz ( $p = 0.010$ ) during AAF conditions compared to non-AAF conditions. Comparing the pre- and post- VLT tasks, there was no detectable relationship between LTAS\_SD and order (post-VLT task 4.1 Hz lower than pre-VLT task ( $p = 0.869$ )). Post-hoc comparisons confirmed that the decreases in LTAS\_SD comparing the AAF conditions to the non-AAF conditions (Estimate = -68.82, SE = 26.34,  $z = -2.61$ ,  $p = 0.009$ ) are statistically significant. Table 5 displays the results.

### 3.6 Results: Skewness of the Long Term Average Spectrum

The use of an AAF device had a statistically significant effect on LTAS\_skew, with LTAS\_skew increasing by approximately 0.74 Hz ( $p = 0.010$ ) during AAF conditions compared to non-AAF conditions. Comparing the pre- and post- VLT tasks, there was no detectable relationship between LTAS\_skew and order (post-VLT task 0.14 Hz

**Table 5:** LME models output run with Standard Deviation of the Long Term Average Spectrum as the response variable and the AAF conditions and order (post-VLT tasks) as fixed factors.

Fixed factors	Estimate (-)	Std. Error(-)	df	t	p
LTAS_SD					
(Intercept: Pre-VLT, No AAF)	792.75	285.23	1	2.78	0.165
AAF Conditions	-68.82	26.34	217	-2.61	0.010**
Post-VLT Condition	-4.09	24.83	217	-0.17	0.869

Signif. codes: 0 '\*\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1

lower than pre-VLT task ( $p = 0.615$ ). Post-hoc comparisons confirmed that the increases in LTAS\_skew comparing the AAF conditions to the non-AAF conditions (Estimate = 0.74, SE = 0.29,  $z = 2.59$ ,  $p = 0.010$ ) are statistically significant. Table 6 displays the results.

**Table 6:** LME models output run with Skewness of the Long Term Average Spectrum as the response variable and the AAF conditions and order (post-VLT tasks) as fixed factors.

Fixed factors	Estimate (-)	Std. Error(-)	df	t	p
LTAS_skew					
(Intercept: Pre-VLT, No AAF)	5.90	1.03	2	5.75	0.050*
AAF Conditions	0.74	0.29	217	2.59	0.010*
Post-VLT Condition	-0.14	0.27	217	-0.50	0.615

Signif. codes: 0 '\*\*\*\*' 0.001 '\*\*' 0.01 '\*' 0.05 '.' 0.1

#### 4. DISCUSSION

The primary aim of the present study was to evaluate the effects of AAF provided by two bone conduction devices: 1) sidetone amplification via a modified Forbrain® device and 2) Forbrain®'s filtered auditory feedback through a VLT. The results demonstrated that together, both the sidetone amplification and Forbrain®'s filtered AAF resulted in significantly decreased self-reported vocal fatigue during the VLT, significantly decreased SPL, significantly increased HNR, significantly decreased LTAS\_mean, significantly decreased LTAS\_SD, and significantly decreased LATS\_skew. Additionally, the VLT implemented was sufficient to induce vocal fatigue in all participants, as evidenced by the significant increases in self-reported vocal fatigue as the VLT progressed and the significantly increased SPL and HNR, in the post-VLT voice tasks, which have been verified as objective markers of vocal fatigue in prior VLT paradigms [17, 18].

#### 5. CONCLUSION

The present study found that AAF provided by two bone conduction devices results in significantly less vocal fatigue during a VLT. We propose that these AAF devices may hold utility as preventative tools for patients with vocal hyperfunction.

#### 6. ACKNOWLEDGMENTS

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