# The Effect on Vocal Fatigue of Altered Auditory Feedback via Bone Conduction

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Pro gradu-avhandling i logopedi

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Abstract for master´s thesis



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Voice disorders are common communicational disorders, especially for people who use their voice occupationally. Various factors can have an effect on vocal health. Previous research suggests that individuals with different voice related issues often report experiencing vocal fatigue when asked to describe their vocal symptoms. Research has found that participants reported feeling more comfortable when speaking with an auditory feedback device. This comfort may be linked to a reduction in vocal loading. In speech therapy altered auditory feedback (AAF) has been used to improve speech fluency, reduce stuttering as well as to help individuals with voice disorders to modify their vocal patterns.

The main purpose of this study is to assess the influence of bone conduction devices, specifically Forbrain®, on vocal fatigue during a vocal loading task (VLT). Two types of AAF devices were compared: a standard Forbrain® with filtered auditory feedback and a modified Forbrain® with sidetone amplification. A control condition without any AAF devices was also included. Twenty participants were included in the study. During the VLTs the participants speech was recorded while they read a short story in a loud voice. The VLTs included three conditions: AAF using a standard Forbrain® device, AAF sidetone amplification using a modified Forbrain® device, and a control condition without any device. Linear Mixed-Effects (LME) models fitted through restricted maximum likelihood (REML), random effects were used to analyze the data.

The outcomes of this study suggest improved control over vocal output by participants during VLTs when using a Forbrain® device compared to the control condition. The study also observed a decrease in self-perceived vocal fatigue when using any of the Forbrain® devices compared to control conditions. These results suggest a potential use of the Forbrain® devices in relieving voice symptoms and as a potential preventative measure against the development of voice issues such as vocal fatigue.




| Keywords: altered auditory feedback, bone conduction, Forbrain, vocal fatigue, vocal loading, vocal loading tasks. | |
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Röststörningar är vanliga kommunikativa störningar, särskilt för personer som använder rösten i sitt yrke. Olika faktorer kan påverka rösthälsa. Tidigare forskning visar att personer med olika röstrelaterade problem ofta rapporterar att de upplever rösttrötthet när de ombeds beskriva sina röstsymtom. Forskning har visat att deltagarna kände sig mer bekväma då de talade med en auditiv återkopplingsenhet. Denna bekvämlighet kan vara kopplad till en minskning av röstbelastningen. Inom logopedin har modifierad auditiv återkoppling (eng. *altered auditory feedback*, AAF) använts för att förbättra talflyt, minska stamning samt för att hjälpa personer med röststörningar att modifiera röstmönster.

Syftet med denna avhandling är att bedöma hur benledningsenheterna, Forbrain®, påverkar rösttrötthet under en röstbelastningsuppgift (eng. vocal loading task, VLT). Två typer at AAF-enheter jämfördes: en standardmodells Forbrain-enhet med filtrerad auditiv återkopplind och en modifierad Forbrain-enhet med sidotonsförstärkning. Ett kontrollförhållande utan några AAF-enheter ingick också. Tjugo deltagare ingick i studien. Under VLT-uppgifterna läste deltagarna en kort berättelse med hög röst. Deltagarnas tal spelades in medan de utförde röstansträngnings uppgifter under tre olika förhållanden: AAF med en standardmodells Forbrain-enhet, AAF med en modifierad Forbrain-enhet och ett kontrollförhållande. För analysen användes Linjär Mixed-Effects-modeller (LME) anpassade genom restricted maximum likelihood (REML). För att skilja mellan olika nivåer på de relevanta faktorerna utfördes parvis jämförelse med Tuckeys post-hoc-metod (Multiple Comparison of Means: Tuckey Contast).

Resultaten från denna avhandling tyder på att deltagarna har bättre kontroll över sin röstproduktion under VLT-uppgifter när de använder någon av Forbrain-enheterna jämfört med kontrollförhållandet. Studien observerade även en minskning av den upplevda rösttröttheten vid användning av Forbrain-enheterna jämfört med kontrollförhållandet. Dessa resultat tyder på en potentiell användning av Forbrain-enheterna för att lindra röstsymtom och som en potentiell förebyggande åtgärd mot utvecklingen av röstproblem, exempelvis rörsttrötthet.



Nyckelord: altered auditory feedback, bone conduction, benledning, Forbrain, rösttrötthet.

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In many countries voice production is important to citizens' livelihood, as nearly half of the population are occupational voice users. An occupational voice user is someone whose voice is essential in their work tasks (Titze et al., 1997; Vilkman, 2004). These include teachers, singers and telemarketers (Roy et al., 2004; Titze et al., 1997). Several factors can affect voice production, and some of the factors can potentially cause voice-related issues or voice disorders. These factors include: vocal usage, stress, (vocal) health, room acoustics, and background noise (Bottalico et al., 2016; Roy et al., 2005).

**Voice disorders**

Vocal health can be influenced by different factors, some of which include: usage, such as intensive voice use and prolonged voice usage, physical factors, such as poor sleep, environmental factors, such as dust and air quality, and emotional factors, such as stress (Anand et al., 2021; Gilman & Johns, 2017; Vilkman, 2004). A voice disorder refers to a condition when the speaker's pitch, volume, or quality of voice interferes with the speaker's communication (i.e., leading to reduced speech intelligibility) or causing discomfort to the speaker (Sala & Rantala, 2019). Voice disorders are relatively common communicational disorders among the adult population, especially for occupational voice users. According to previous research, the prevalence of voice disorders varies from 4.8% to 29.9% of the general population (Bhattacharyya, 2014; Lyberg-Åhlander et al., 2019; Roy et al., 2004, 2005). Studies indicate that teachers are at a higher risk of developing voice disorders than other occupational voice users (Lyberg-Åhlander et al., 2012; Lyberg-Åhlander et al., 2014; Roy et al., 2004). According to a study by Roy et al. (2004), the lifetime prevalence of voice disorders is higher for teachers (57.7%) compared with non-teachers (28.8%). It is, however, somewhat unclear what factors contribute to the development of voice disorders. In fact, some speakers are more prone to developing voice disorders than others, even with similar vocal loading history (Lee et al., 2019). In a study conducted by Whitling et al. (2017), it was observed that women with high everyday vocal demands who reported voice issues exhibited strain-related problems during vocal loading tasks (VLTs) and at work. On the other hand, women with functional dysphonia who experienced voice problems during VLTs and during work, also experience voice problems during leisure activities. This finding might shed light on why individuals with voice issues associated with occupational voice usage might not actively seek voice therapy (Whitling et al., 2017).

In the literature the terms: “vocal load”, “vocal loading”, “vocal effort” and “vocal fatigue”, are all used to describe similar voice related problems, and their definition and use are often overlapping (Hunter et al., 2020). Earlier research also indicates that clients with various voice disorders often mention a feeling of vocal fatigue when describing the vocal symptoms or when complaining about their voice after vocally demanding activities (Gilman & Johns, 2017; Hunter et al., 2020). However, because of the complex nature of the terms “vocal fatigue” and “vocal loading” there is not a universal definition of the term (Anand et al., 2021; Hunter et al., 2021).

***Vocal fatigue and vocal loading***

The term vocal fatigue can be considered subjective, and is often described in the literature as a feeling of discomfort and/or weakness in the voice following extended use (Anand et al., 2021; Vilkman, 2004). The term refers, according to Hunter et al. (2020), to the fatigue of laryngeal muscles and tissues, which can cause discomfort and a decrease in the range and control of voice. Several factors can contribute to the feeling of vocal fatigue. These include internal and external factors such as: vocal health, occupation, stress levels and history of vocal use. Symptoms of vocal fatigue include, according to Anand et al. (2021), increased vocal effort, reduced pitch range and reduced control of the quality of voice.

The literature that discusses vocal loading often defines it as the result of prolonged voice use combined with additional factors that increase the load on the vocal system, such as speaking loudly at high sound pressure levels (SPL). Vocal loading is not only about prolonged intense phonation; it also involves extended phonation at high fundamental frequencies (Whitling et al., 2017). The factors that can impact various aspects of vocal function include: fundamental frequency, loudness, phonation, and laryngeal characteristics such as the vibratory behavior of the vocal folds or the structure of the larynx itself (Vilkman, 2004; Whitling et al., 2015). According to Jónsdottir et al. (2003) the use of an amplification or/and a dampening device could decrease vocal loading.

**Vocal loading tasks**

For identifying and developing a clinical tool for individuals that have a higher risk for developing voice disorders, VLTs studies have been used by researchers in the field (Fujiki & Sivasankar, 2017). VLTs have been used in speech and language pathology to investigate the effects of prolonged voice use on the voice and the vocal system (Fujiki & Sivasankar, 2017). In research, VLTs are frequently used as a technique that requires the participant to complete a particular vocal task, such as reading aloud or producing a sustained vowel sound, for an extended duration. VLTs aim to challenge the participant's vocal mechanism and induce vocal fatigue (Anand et al., 2021). Throughout a given VLT, various tasks may require different degrees of vocal exertion, such as speaking at a comfortable volume versus speaking loudly or even shouting. In a review by Fujiki and Sivasankar (2017), they suggest that the VLTs should last for over an hour if the task relies on speaking in a loud voice to affect the vocal apparatus. According to Fujiki and Sivasankar (2017), tasks that are shorter than this have not resulted in any significant changes in objective measures. Researchers have used various measures to assess the effect of VLTs. These include the subject's own ratings of vocal fatigue or comfort, changes in voice quality or pitch, and physiological measures such as changes in vocal fold vibration patterns (Whitling et al., 2015).

**Auditory feedback**

Auditory feedback plays a crucial role in voice production by incorporating auditory sensory information with ongoing vocalization to facilitate effective communication (Lane & Tranel, 1971). Contemporary understanding has expanded upon this concept, particularly through the use of the Direction into Velocities of Articulators (DIVA) model, which offers a comprehensive framework for understanding auditory feedback in speech production (Tourville & Guenther, 2011). DIVA is a computational model that employs neural networks to simulate various aspects of speech production, including the influence of feedback and feedforward control, the significance of auditory feedback in speech motor control, and the neural mechanisms involved in speech motor learning (Lane & Tranel, 1971; Tourville & Guenther, 2011). Within the DIVA model, auditory feedback assumes a critical role as it is compared to the auditory target for the intended sound, represented by a cluster of neurons known as the auditory state map. If any auditory-based errors occur, a separate cluster of neurons in the higher-order auditory cortical areas, known as the auditory error map, generates corrective motor commands (Berhman, 2021).

Research has shown that our ability to hear ourselves speak (i.e., auditory feedback) plays an important role in the development and in the maintenance of intelligible speech (Coughler et al., 2022). Auditory feedback is also important for speech production and learning (Cai et al., 2012; Purcell & Munhall, 2006). Limitations in the auditory feedback might result in distortions of the speech production (Berhman, 2021). Through speech perception we control and adapt our voice when we speak in different environments (Lane & Tranel, 1971). The participants in a study by Jónsdottir et al. (2001) reported feeling more comfortable when speaking with an auditory feedback device. According to Jónsdottir et al. (2001) this comfort may be linked to a reduction in vocal loading.

***Altered auditory feedback (AAF)***

Altered auditory feedback (AAF) refers to the process of changing or manipulating the sound that a person hears while they speak (Lincoln et al., 2006). The manipulation can be done by introducing various types of auditory distortions such as delayed auditory feedback (DAF), masked auditory feedback (MAF) and frequency altered feedback (FAF). AAF is often used as a collective term for electronically distorting speech signals, and this distortion will make the speaker perceive their voice differently (Lincoln et al., 2006).

DAF involves introducing a short delay between the speaker's voice and the sound they hear when the voice signal is fed back to the speaker. The delay time is typically between 50 – 250 milliseconds (Lincoln et al., 2006). FAF involves shifting the pitch of the speaker's voice higher or lower (Lincoln et al., 2006). FAF has been shown to have varying effects on speech fluency, which depend on the individual and how the pitch alteration is used (Ingham & Moglia, 1997). MAF is a technique that involves covering the speaker's perception of their voice by presenting, for example, white noise in the speaker's ears while they speak. MAF has been used in research and has been shown to increase fluency in a group of individuals with aphasia and/or apraxia of speech (Jacks & Haley, 2015).

In speech therapy, different AAF methods have been used. For example, DAF has been used to improve speech fluency, reduce stuttering as well as to help individuals with voice disorders to modify their vocal patterns (Lincoln et al., 2006). Research has also used AAF for several disorders, for example, to improve speech fluency, reduce stuttering (Ingham & Moglia, 1997; Lincoln et al., 2006), reduce vocal load (Jónsdottir, Laukkanen, et al., 2001) and voice disorders (Nudelman et al., 2022). According to a systematic literature review by Maryn et al. (2006), 83.3% of the reviewed studies found that the voice quality improved after using an AAF device.

One method of AAF is through bone conduction. Bone conduction transmits sound vibrations to the inner ear through the bones in the skull, skipping the outer and middle ear. By altering the sounds that the talker hears through the bone conduction, AAF can disrupt the natural feedback loop that is involved in speech production and might prompt changes in speech behavior (Stenfelt & Goode, 2005). According to Stenfelt & Goode (2005) the bone conduction sound is considered a more accurate representation of cochlear function.

**Sidetone amplification.**

Sidetone amplification focuses on enhancing the perception of the speaker's own voice by increasing the volume of the voice, while AAF encompasses broader manipulations of the auditory feedback, including changes in pitch, timing, or intensity, to investigate or influence speech production (Chang-Yit et al., 1975). That is, sidetone amplification involves the process of increasing the volume or amplifying the sound of the speaker's own voice that is fed back to the user's ears during speaking. It is often used in communication devices like headphones to provide a clearer perception of the user's own voice and to improve the user's vocal control (Chang-Yit et al., 1975). The purpose of sidetone amplification is to enhance self-monitoring and maintain proper vocalization during conversation (Chang-Yit et al., 1975).

***Bone conduction feedback***

A limited amount of research has been done regarding the use of bone conduction devices as AAF devices. There are studies that examined the possible use of bone conduction devices in speech therapy for people who stutter (Escera, Gorina-Careta, et al., 2018; Stidham et al., 2006) and studies that examine the usage of a bone conduction device as an AAF tool (Escera, López-Caballero, et al., 2018; Lee et al., 2019; Nudelman et al., 2022, 2023).

A goal in voice therapy is often to create a vibrational sensation in the facial bones, especially in resonance therapy for vocal nodules (Saltürk et al., 2019; Simberg & Laine, 2007). Therefore, Lee et al. (2019) suggests that the vibration from the bone conduction device could create a similar feeling and thus could be a usable device during voice therapy.

**Forbrain®.**

Forbrain® is a device that has recently become available in the market, developed by Sound for Life Limited (Soundev). The Forbrain® headset comes with a microphone and two bone conductors. The bone conductor provides the user with auditory feedback of their voice (Escera, López-Caballero, et al., 2018). The Forbrain® device also uses a patented dynamic filter that blocks out environmental noises and so amplifies the voice of the user (Escera, Gorina-Careta, et al., 2018). See Figure 1 for an illustration of the device.

**Figure 1**

*An illustration of the Forbrain® headset.*


*Notes.* The picture illustrates features of the Forbrain® device and is from the Forbrain® home webpage (https://www.forbrain.com/).

## Aims

In general, the objective of AAF research is to discover and validate techniques that enhance speakers' awareness of their vocal patterns, reduce their perception of vocal fatigue, as well as enhance their acoustic voice parameter (Nudelman et al., 2023). Therefore, the aim of this study is to compare the effects of a bone conduction device, Forbrain®, on the participant's vocal fatigue after performing VLTs. This study compares two AAF devices: a standard Forbrain® device with filtered auditory feedback and a modified Forbrain® device that employs sidetone amplification, as well as a control condition. During the control condition the participants did not use a bone conduction device or any other devices. The acoustic voice parameters and subjective self-assessment of vocal fatigue of the participants will be evaluated by subjecting them to VLTs.

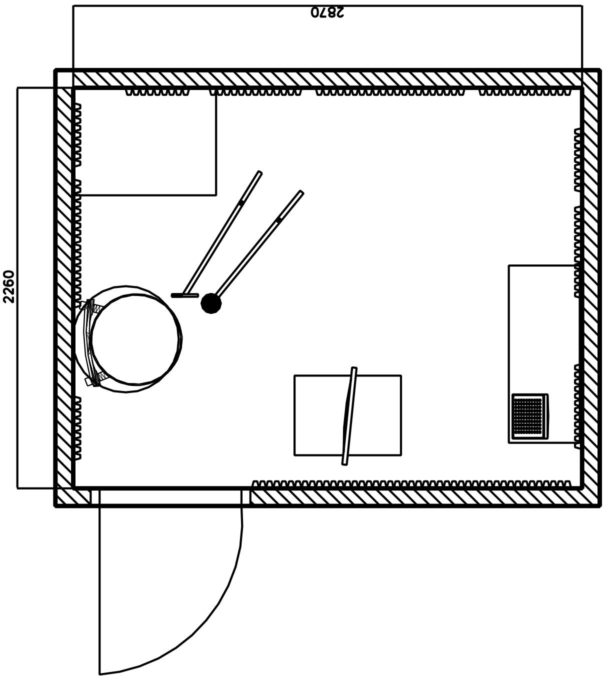
The hypothesis of this study is that using the standard Forbrain® device will result in improved vocal performance during situations of vocal strain, loud speech, or suboptimal voice production. Additionally, it anticipates a reduced occurrence of vocal fatigue during the VLTs, when compared to a control condition and to the modified Forbrain® device.

## Material and method

The current paper is a part of a larger research project performed at the University of Illinois at Urbana-Champaign (Nudelman et al., 2023). The research project was approved by the University of Illinois at Urbana-Champaign Institutional Review Board (IRB # 18179). The purpose of the research project is to compare two AAF devices and a control condition, in this part of the project the purpose is to see if the Forbrain® devices could be used to minimize the restraint on the talkers' voice, compared to not using an AAF device. The speech samples of each participant were recorded during the VLTs in the three different conditions. The VLTs took place in a soundproof double-walled sound booth, called the Whisper room (interior dimensions: 226 × 287 cm and 203 cm high, see Figure 2 and 3).

**Figure 2**

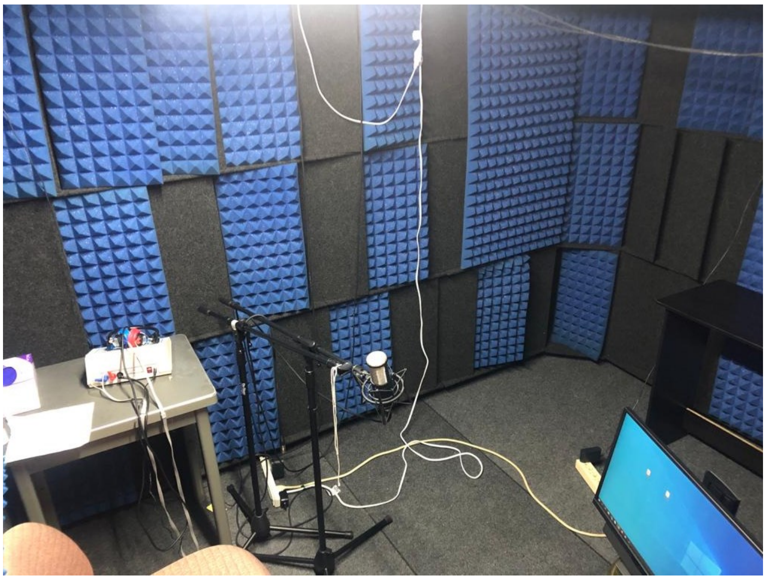
*The illustration of the layout of the sound proofed room, called the Whisper room.*




*Notes.* The illustration of the soundproofed (whisper) room is not to scale.

**Figure 3**

*The sound proofed room, called the Whisper room.*



The first AAF device used in the research was a standard Forbrain® headset, model UN38.3 and developed by Sound for Life Limited (Soundev) in Luxemburg. This device uses a microphone and a pair of bone conductors to provide a speaker with AAF, as well as a patented filter that blocks out noises from the environment and amplifies the voice of the user (Guajarengues & Lohmann, 2015). The second device was the modified Forbrain® device that had the patented filter removed by the manufacturer, resulting in the Forbrain® device providing only sidetone amplification. By removing the patented filter, the modified Forbrain® device does not block the noises from the environment as the standard Forbrain® headset does. That is, the modified device increases the volume or amplifies the sound of the user's own voice that is fed back to the user's ear during, for example, speaking. Both devices were provided without cost by the manufacturer. During the control condition the participant performed the VLT in the same manner as during the other conditions, however, without any devices.

**Participants**

A total of twenty participants, ranging in age from 19 to 33, with a mean age of 25.5 years, were included in the study using a sequential convenience sampling approach. Ten of the participants were female and ten were male. The participants were over the age of 18 and signed a consent form before participating in the study. They were informed that they have the right to withdraw, say no, and/or discontinue participating at any time.

The inclusion criteria for this study were individuals aged 18 or older who are proficient in the English language (speaking and understanding) and could provide a signed consent form. Exclusion criteria included individuals who did not pass a hearing screening test. The hearing screening test was performed on each participant before the experiment. The presence of hearing loss was defined as bilateral thresholds exceeding 20 dB hearing level at octave frequencies ranging from 500 to 4000 Hz (Nudelman et al., 2023).

For more information about the participants´ vocal health, they were asked to fill out the Voice Handicap Index – 10 (VHI-10) (Rosen et al., 2004), Voice – Related Quality of Life (V-RQOL) (Hogikyan & Sethuraman, 1999), and Vocal Fatigue Index (VFI) (Nanjundeswaran et al., 2015). Specifications about the self-assessment tools are listed under the equipment section.

**Instructions and conditions**

Three different AAF conditions were used during the VLTs, and the length of each condition was approximately 20 minutes. Aside from the AAF itself, no external noise was added during the VLTs (i.e., no external background noise was presented). The conditions during the VLTs were the following: AAF using a standard Forbrain® device, AAF sidetone amplification using a modified Forbrain® device, and a control condition without a device. Participants performed the VLTs in every condition. The conditions as well as the stories were introduced in a randomized order to ensure that any unidentified variables that potentially could affect the performance of the task are considered.

***VLT***

For the VLT, the participants read five short stories from the collection American Fairy Tales written by L. Frank Baum (1901) in a loud voice. The stories included: *The Glass Dog*, *The Queen of Quak*, *The Magic Bon Bons*, *Capture of Father Time*, and *The Wonderful Pump* (Baum, 1901) and were presented on a Dell monitor that was in front of the participants. The order of the stories was randomized between the participants to minimize the possibility of bias.

During the VLT, an iPad running the app “Too Noisy” was used to help the participants keep their vocal level at a fixed rate of 73dB (A) (ISO 9921). Specifications about the app are listed under the equipment section.

Before and after each VLT, the participants read the first six sentences from *The Rainbow Passage* (Fairbanks, 1960), a standardized text in English, and held an /a/ vowel for a minimum of 5 seconds. These tasks were performed using the same AAF device, or no device, employed in the VLT. For example, before and after the condition using the standard Forbrain® device the participants read aloud *The Rainbow Passage* and sustained /a/ vowel while wearing the same device used during the VLT. The same procedure was repeated for all conditions. The conditions were introduced in a randomized order between the participants to minimize bias.

During the VLTs the participants were asked to rate their vocal fatigue with the help of a visual analog scale (VAS), from 0, no fatigue, to 100, extremely fatigued. The question concerning the participant's vocal fatigue appeared in-between the text on the screen approximately every 2 minutes. Vocal fatigue was described to the participants as "your perception of a decline in your voice associated with the voice production task" (Hunter et al., 2020). The participants were also offered a short break in-between the conditions.

***Equipment***

The standard and the modified Forbrain® where both later calibrated by recording their vibration while a Head and Torso Simulator (HATS, GRAS 45BB KEMAR) produced 70.6 dB white noise at one meter in a sound booth, following the experimental setup. This was also repeated with a control condition without an AAF device. The white noise was created by the HATS mouth and the noise was picked up by its ears. It is important to note that Forbrain® usually adjusts its filter according to specific frequency energy, but in this calibration, it was assumed to be consistent and linear, unlike its response to speech (Nudelman et al., 2023).

For the VLTs, speech samples were recorded using an M2211 microphone (NT1 Audio, Tigard, OR, United States) placed to the left of the participants and positioned 30 cm away from their mouth (Švec & Granqvist, 2018). The direct digital recording was captured via an external soundboard (UH-7000 TASCAM, Teac Corporation, Montebello, CA, United States) connected to a PC- computer running Audacity 174 3.1.3 (SourseForge, La Jolla, CA). During the VLT, participants read short stories presented on a Dell monitor while an iPad running the app "Too Noisy" (a sound level meter software) provided visual feedback, at one meter from the participants, to maintain a consistent raised voice level of 73dB (A).

The specifications of the Too Noisy app were adjusted during the calibration process using Lingwaves II SPL-meter (WEVOSYS234 hardware (IEC 651 Type 2, ANSI S1.4 Type 2)), until the sound level meter accurately responded to a 73 dB (A) voice signal, with sensitivity setting of 95% and a dampening setting of 45%. The iPad remained visible during the VLTs, providing uninterrupted feedback of the participant's vocal effort level throughout the experiment.

***Self-assessment questionnaires***

Self-assessment questionnaires are used in this study to gather subjective information directly from the individuals about various aspects, such as vocal health. The questionnaires are considered to be suitable tools for international multicentric research, as they are not influenced by the clinician's education, experience, or native language, unlike perceptual analysis (Behlau et al., 2016). In the current study a voice disorder was considered present if a participant had: a score above 11 on VHI-10; a score above 91.25 on V-RQOL (Behlau et al., 2016); or a score greater or equal to 24.47 on section 1, 6.90 in section 2, 7.71 in section 3 of the VFI (Nanjundeswaran et al., 2015).

The self-assessment tool VHI was proposed by Jacobson et al. (1997) to measure individuals' perceptions of vocal functional handicap. The VHI consists of 30 items, including functional, physical and emotional aspects of voice disorder. Rosen et al. (2004) developed the VHI-10 to be used as a shorter, but equally valid version, of the VHI. The VHI-10 consists of 10 items that provides information about the aspects of voice disorders. The greater the score, the more challenges the individual experiences with their voice. The highest score on the questionnaire is 40.

The self-assessment tool V-RQOL is suggested by Hogikyan and Sethuraman (1999) as a clinical tool for evaluating dysphonic patients and assessing treatment outcomes. An individual living with a voice disorder will be impacted through a change in their quality of life associated with their voice, that is, vocal quality of life (Hogikyan & Sethuraman, 1999). Similar to the VHI-10 scoring system, a greater score indicates a higher impact of the voice disorder on the individual's perception of their quality of life.

The self-assessment questionnaire VFI is, according to Nanjundeswaran et al. (2015) a standardized tool that is capable of identifying individuals likely to have voice disorders, such as vocal fatigue. The VFI consists of 19 items, divided in three parts, that provides information about the individuals' subjective perceptions and experiences regarding their voice in everyday life. As in the VHI-10 scoring, the higher the score on the VFI the more likely the individual experiences vocal fatigue. The highest possible score from VFI part 1 is 44, part 2 is 20, and for part 3 is 12, total highest score is 76. See Table 1 for the participants' mean answer from the questionnaires included in the study (i.e*.,* VHI-10, V-RQOL, VFI and VAS).

**Table 1**

*The mean and standard deviation of the answers by the participants, prior to the VLT, from the self-assessment tools used in the study.*

| Self-assessment tool | Mean | SD |
|---|---|---|
| VHI-10 | 6.4 | 4.79 |
| V-RQOL | 83.8 | 7.56 |
| VFI Part 1 | 9.4 | 6.87 |
| VFI Part 2 | 2.85 | 2.21 |
| VFI Part 3 | 5.95 | 3.82 |
| Standard Forbrain® VAS | 56.93 | 19.87 |
| Modified Forbrain® VAS | 53.84 | 19.35 |
| Control condition VAS | 60.85 | 23.94 |

*Notes.* VHI-10= Vocal handicap index-10, V-QROL = Voce-related quality of life, VFI = Vocal fatigue index, VAS = Visual analogue scale, SD = standard deviation.

**Analysis**

To analyze the participants' recordings (including before and after VLTs) the data was processed to calculate the self-perceived vocal fatigue on a VAS, SPL values, harmonics-to-noise ratio (HNR), the spectral mean, standard deviation (SD) and skewness of the long-term average spectrum (LTAS mean, LTAS SD, LTAS skew). According to Roy et al. (2013) certain vocal measures can offer valuable information about the voice. In addition, Roy et al. (2013) recommend using both objective and subjective measures to improve the assessment of vocal function. The recordings were processed using MATLAB R2022b (Mathworks, Natick, 284 MA, USA) and Praat 5.4/5.4.17 (Netherlands).

VAS can be used as a subjective self-rating scale and is commonly used in research (Castillo-Allendes et al., 2022). In voice research it can measure various aspects related to vocal health in different ways. When VAS is used as a self-assessment tool to assess vocal issues it can, according to Castillo-Allendes et al. (2022), be used to examine changes in the quality of voice in healthy individuals who use their voice in their occupations and thus aid in the early detection of voice issues related to work.

SPL is often used as a substitute term for vocal strength (Švec & Granqvist, 2018). SPL is considered a fundamental characteristic in voice and speech as it influences the perceived loudness of voice and speech perceptually (Švec & Granqvist, 2018). Vocal loading correlates with SPL values and with vocal cord adduction (Jónsdottir, Laukkanen, et al., 2001). For example, when speaking to a larger audience, the speaker increases their SPL and uses a more stressed quality of voice, indicating a stronger adduction of the vocal cords, which can be stressful for the voice (Jónsdottir, Laukkanen, et al., 2001).

HNR is a measure used to assess the presence of additive noise in the voice signal (Ferrand, 2002). It serves as an acoustic indicator that can provide valuable insights into vocal function (de Krom, 1993). When we produce speech, turbulent airflow is generated at the glottis due to incomplete closure of the vocal folds. This incomplete closure allows excessive airflow, which results in turbulence. The resulting friction noise manifests as increased noise in the spectrum of voice signal (de Krom, 1993). According to de Krom (1993) lower HNR scores are associated with higher ratings on semantic scales related to dysphonia, including hoarseness and breathiness. That is, a higher HNR could indicate a clearer voice. In short, HNR captures the relative proportion of additive noise in relation to the overall voice signal (Ferrand, 2002; Teixeira & Fernandes, 2014).

LTAS is a measure used in audio signal processing to help describe the frequency content of a sound signal over a period of time (e.g., several seconds or minutes). According to Löfqvist (1986) LTAS may not be ideal for screening, however, it can help track changes in an individual's voice over time. The advantage of using LTAS in tracking changes in an individual's voice over time is the ability to perform the voice analysis on continuous speech. The spectral changes, such as the decrease in spectral slope, observed during speech can be measured using LTAS, aiding in the comprehension of the individual's voice (Guzman et al., 2013). LTAS mean, LTAS SD and LTAS skew are moments that capture characteristics of the LTAS of the voice signal (Tanner et al., 2005). LTAS is acknowledged as a reliable and efficient method to evaluate the vocal characteristics (Tarai et al., 2021). LTAS mean represents the average value of the LTAS distribution and a lower value indicates better voice quality (Hartmann & von Cramon, 1984). LTAS SD measures the variance of the spectral distribution, where lower variance indicates better voice quality (Tanner et al., 2005). LTAS skew refers to whether the LTAS of the voice signal has a positive or a negative tilt. Positive skewness means that there is a so-called tail of values extending to the right of the bell curve, which shifts the overall shape of the spectrum towards lower frequencies. Negative skewness, on the other hand, results in the opposite, that is a tail extending to the left of the bell curve, indicating more energy at the higher frequencies, thus, indicating aspects of voice quality. (Tanner et al., 2005).

For the purpose of statistical analysis, R version 4.2.0 was used. To carry out this analysis, Linear Mixed-Effects (LME) models were fitted via restricted maximum likelihood (REML). This statistical approach is valuable for dealing with the complexity of the data, particularly when considering both fixed and random effects. The choice of random effects (which capture variations not explained by the fixed factors) was determined by explained variance. Additionally, for the purpose of discerning distinctions between different levels of the pertinent fixed factors, Tuckey's post-hoc pairwise comparisons (Multiple Comparison of Means: Tuckey Contrast) were executed. This method helps to discern differences between various levels of fixed factors. In these comparison tests, pairwise z-tests were applied, with the z statistic representing the difference between an observed value and its hypothesized population parameter, measured in standard deviation units. The LME output provides assessments of fixed effects coefficients, associated standard errors (SE), degrees of freedom (df), test statistics (t), and p-value (p). To estimate df and to calculate p-values the Satterthwaite method was used.

## Results

In this section of the thesis the results are presented for vocal fatigue, SPL, HNR and LTAS. Specific results are described under the various subheadings.

### Vocal fatigue on VAS

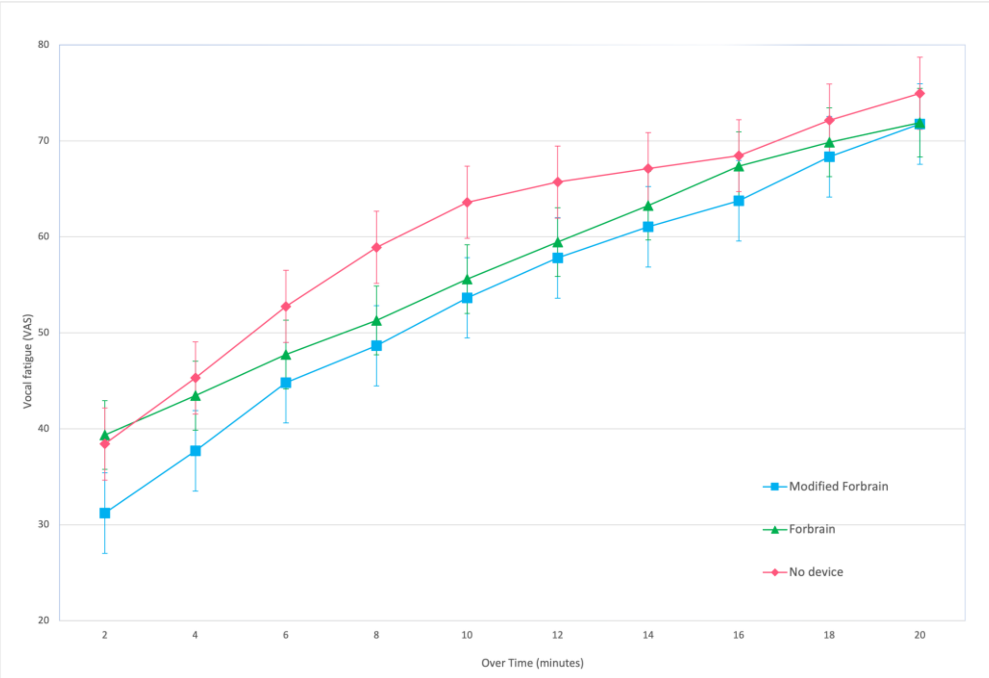
To evaluate the effect of the Forbrain® devices on the participant's self-reported vocal fatigue, an LME model was constructed with "vocal fatigue" as the response variable. The model incorporated time (a numerical variable ranging from 2 to 20 minutes within each condition) and condition (a factor with three levels: standard Forbrain®, modified Forbrain®, and control condition) as predictors. The VAS scale that was used during the VLTs to analyze the self-perceived vocal fatigue of all the participants had a scale from 0 (no fatigue) to a 100 (extremely fatigued).

When using the standard Forbrain® as well as the modified Forbrain® devices, there was a statistically significant effect on self-reported vocal fatigue ratings as assessed through a VAS, among all participants (see Table 2). More specifically, when using the standard

Forbrain® device, the participants reported vocal fatigue ratings approximately 9 points lower on the VAS (p = 0.002) when compared to the control condition. Similarly, in the modified Forbrain® sidetone amplification condition, the participant's reported vocal fatigue ratings on the VAS approximately 15 points lower (p < 0.001) when compared to the control condition. Post-hoc analyses verified the statistical significance of the differences in vocal fatigue ratings between the Forbrain® conditions and the control conditions (Estimate = -14.83, SE = 2.83, z = -5.23, p < 0.001). Additionally, during the VLT, participants reported an increase of approximately 4 points on the VAS with each rating that the participant made (i.e., every two minutes). See Figure 4 for an examination of the participants' self-assessed vocal fatigue over time during the VLTs. See Figure 5 for an examination of the participants' mean answer for the different conditions during the VLTs.

**Figure 4**

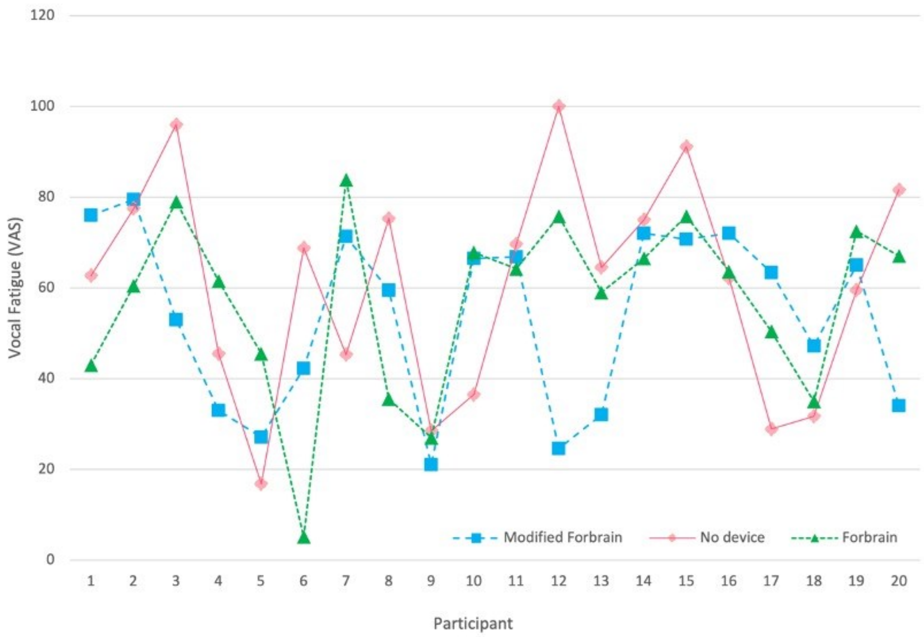
*Mean and standard error of vocal status ratings were assessed for the different conditions for the participants (N=20), examining their evolution over time during the vocal loading task.*




*Notes:* VAS = Visual analog scale. Average answer on self-perceived vocal fatigue. The question was asked about every 2 minutes during the 20-minute-long vocal loading tasks.

**Figure 5**

*Median answer on visual analog scale per participant (N=20) during the different conditions of the vocal loading task (VLT).*




*Notes:* VAS = Visual Analog Scale. Average answer on self-perceived vocal fatigue, during the different conditions. The question was asked about every 2 minutes during the 20-minute-long vocal loading tasks.

**Table 2**

*Linear mixed-effects models were employed using the 20 participants' perception on vocal fatigue as the response variable and incorporating altered auditory feedback condition and time as the fixed factors.*

| Fixed Factors | Estimate (-) | Std. Error (-) | df | t | p |
|---|---|---|---|---|---|
| (Intercept: No AAF) | 42.84 | 8.36 | 3 | 5.12 | 0.012* |
| AAF Conditions | -12.16 | 2.45 | 573 | -5.00 | 0.001*** |
| Standard Forbrain® | -8.63 | 2.83 | 573 | -3.05 | 0.002** |
| Modified Forbrain® | -14.83 | 2.83 | 573 | -5.24 | 0.001*** |
| Over time | 3.87 | 0.32 | 573 | 12.08 | 0.001*** |

*Notes.* AAF = Altered Auditory Feedback, df = degrees of freedom, t = test statistics, p =p-value. Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05'.'

**SPL**

Using the Forbrain® devices during the VLTs had a notable impact on SPL measured in the before and after speech tasks. Specifically, there was a significant decrease of approximately 1.2 dB (p = 0.048) in SPL values when using the standard Forbrain® device when compared to the control conditions. When using the modified Forbrain® device there was a decrease of approximately 1.5dB (p = 0.015) when compared to the control conditions. Moreover, when comparing the before and after VLTs themselves, there was a significant increase in SPL of approximately 2.5dB (p < 0.001) during the after VLTs. Post-hoc comparison confirmed the statistical significance of the SPL reduction that can be observed during the modified Forbrain® conditions compared to control conditions (Estimate = -1.53, SE = 0.63, z = -2.44, p = 0.039). The post-hoc comparison also confirmed that the increase in SPL when comparing the before and after VLTs conditions are statistically significant (estimate = 2.46, SE = 0.51, z = 4.83, p < 0.001). See Table 3 for the details.

**Table 3**

*Linear mixed-effect models were used to assess the effect of the conditions (AAF conditions and control condition) on Sound Pressure Level before and after vocal loading task. The conditions and order (before and after) as fixed factors.*

| Fixed Factors | Estimate (-) | Std. Error (-) | df | t | p |
|---|---|---|---|---|---|
| (Intercept: Before VLT, No AAF Conditions) | 63.72 | 3.46 | 1 | 18.41 | 0.019* |
| AAF Conditions | -1.39 | 0.54 | 217 | -2.56 | 0.011* |
| Standard Forbrain® | -1.23 | 0.63 | 216 | 4.81 | 0.048* |
| Modified Forbrain® | -1.53 | 0.63 | 216 | -1.99 | 0.015* |
| After VLT Condition | 2.46 | 0.51 | 217 | 4.83 | 0.001*** |

*Notes.* Random effects in the model include participant ID. VLT = Vocal Loading Task, AAF = Altered Auditory Feedback, df = degrees of freedom, t = test statistics, p =p-value. Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05'.'

**HNR**

During the Forbrain® conditions there was a notable increase of approximately 0.34 dB (p = 0.033) in HNR when compared to the control conditions. Furthermore, there was a significant increase in HNR of approximately 0.60 dB (p < 0.001) observed during the after VLT tasks. No significant associations were found between HNR and the modified Forbrain® conditions (p = 0.109). However, post-hoc comparisons confirmed the statistical significance of the HNR increases when comparing the before and after VLT conditions (Estimate = 0.60, SE = 0.15, z = 4.12, p < 0.001). See Table 4 for the details.

**Table 4**

*Linear mixed-effect models were used to assess the effect of the conditions (AAF conditions and control condition) on Harmonic-to-Noise Ratio before and after vocal loading task. The conditions, gender, and order (before and after) as fixed factors.*

| Fixed Factors | Estimate (-) | Std. Error (-) | df | t | p |
|---|---|---|---|---|---|
| (Intercept: Before VLT, No AAF Conditions) | 15.52 | 0.50 | 21 | 30.78 | 0.001*** |
| AAF Conditions | 0.34 | 0.16 | 98 | 2.16 | 0.033* |
| After VLT Condition | 0.60 | 0.15 | 98 | 4.10 | 0.001*** |

*Notes.* Participant ID was used as a random effect. VLT = Vocal Loading Task, AAF = Altered Auditory Feedback, df = degrees of freedom, t = test statistics, p =p-value. Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05'.'

**LTAS mean, SD, and skew**

Using Forbrain® devices significantly impacted LTAS measurements. Notably, during standard Forbrain® conditions, the LTAS mean decreased by approximately 92.52 Hz (p < 0.001) compared to control conditions. Furthermore, during the modified Forbrain® conditions there was a decrease of about 86.58 Hz (p < 0.001) in comparison to control conditions. However, no correlation was found between LTAS mean and the task order of before and after VLT. Post-hoc analysis confirmed the significance of the LTAS mean reduction in both standard Forbrain® and modified Forbrain® conditions when compared to control conditions. See Table 5 for more details about LTAS mean outcome.

For LTAS SD, standard Forbrain® conditions resulted in a decrease of around 66 Hz (p = 0.030) compared to control conditions, while modified Forbrain® conditions saw a decrease of approximately 70.98 Hz (p = 0.021) compared to control conditions. However, no correlation was observed between LTAS SD and task order before and after VLT. Additionally, the post-hoc analysis did not confirm statistically significant results when looking at LTAS SD. See Table 6 for more details regarding LTAS SD.

LTAS skew was affected by the use of Forbrain® devices. Standard Forbrain® conditions resulted in an increase of about 0.83 Hz (p = 0.013) in LTAS skew compared to control conditions, and modified Forbrain® conditions led to an increase of around 0.66 Hz (p = 0.049) compared to the control conditions. No correlation was observed between LTAS skew and task order before and after VLT. However, post-hoc analysis confirmed the significance of increased LTAS skew in Forbrain® conditions compared to control conditions (Estimate = 0.83, SE = 0.33, z = 2.50, p = 0.034). See Table 7 for the details regarding LTAS skew.

**Table 5**

*Linear mixed-effect models were used to assess the effect of the conditions (AAF conditions and control condition) on Spectral Mean of the Long-Term Average Spectrum before and after vocal loading task. The conditions and order (before and after) as fixed factors.*

| Fixed Factors | Estimate (-) | Std. Error (-) | df | t | p |
|---|---|---|---|---|---|
| (Intercept: Before VLT, No AAF Conditions) | 750.70 | 73.57 | 1 | 10.20 | 0.050* |
| AAF Conditions | -89.55 | 19.34 | 217 | -4.63 | 0.001*** |
| Standard Forbrain® | -92.52 | 23.25 | 217 | -3.98 | 0.001*** |
| Modified Forbrain® | -86.58 | 23.25 | 217 | -3.72 | 0.001*** |
| After VLT Condition | 35.73 | 18.23 | 217 | 2.00 | 0.051 |

*Notes.* Participant ID was used as a random effect. AAF = Altered Auditory Feedback, VLT = Vocal loading task, df = degrees of freedom, t = test statistics, p =p-value. Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05'.'

**Table 6**

*Linear mixed-effect models were used to assess the effect of the conditions (altered auditory feedback conditions and control condition) on Standard Deviation of the Long-Term Average Spectrum (LTAS SD) before and after vocal loading task. The conditions and order (before and after) as fixed factors.*

| Fixed Factors | Estimate (-) | Std. Error (-) | df | t | p |
|---|---|---|---|---|---|
| (Intercept: Pre-VLT, No AAF Conditions) | 792.75 | 285.23 | 1 | 2.78 | 0.165 |
| AAF Conditions | -68.82 | 26.34 | 217 | -2.61 | 0.010** |
| Standard Forbrain® | -66.66 | 30.48 | 216 | -2.18 | 0.030* |
| Modified Forbrain® | -70.98 | 30.48 | 216 | -2.33 | 0.021* |
| After VLT Condition | -4.09 | 24.83 | 217 | -0.17 | 0.869 |

*Notes.* Participant ID was used as a random effect. AAF = Altered Auditory Feedback, VLT = Vocal Loading Task, df = degrees of freedom, t = test statistics, p =p-value. Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05'.'

**Table 7**

*Linear mixed-effect models were used to assess the effect of the conditions (AAF conditions and control condition) on Skewness of the Long-Term Average Spectrum (LTAS skew) before and after vocal loading task. The conditions and order (before and after) as fixed factors.*

| Fixed Factors | Estimate (-) | Std. Error (-) | df | t | p |
|---|---|---|---|---|---|
| (Intercept: Pre-VLT, No AAF Conditions) | 5.90 | 1.03 | 2 | 5.75 | 0.050* |
| AAF Conditions | 0.75 | 0.29 | 217 | 2.59 | 0.010* |
| Standard Forbrain® | 0.83 | 0.33 | 216 | 2.5 | 0.013* |
| Modified Forbrain® | 0.66 | 0.33 | 216 | 1.98 | 0.049* |
| After VLT Condition | -0.14 | 0.27 | 217 | -0.50 | 0.615 |

*Notes.* Participant ID was used as a random effect. AAF = Altered Auditory Feedback, VLT = Vocal Loading Task, df = degrees of freedom, t = test statistics, p =p-value.
Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05'.'

## Discussion

The main purpose of this study was to examine the impact of the Forbrain® bone conduction devices on vocal fatigue in participants who performed VLTs. We compared the effects of two bone conduction AAF devices: a modified Forbrain® device that provides sidetone amplification, and a standard Forbrain® device with filtered auditory feedback, as well as a control condition without any AAF device being used. This section discusses the findings of the present part of the study in relation to some earlier research and discusses how our analysis sheds light on issues related to vocal fatigue on VAS, SPL, HNR, and LTAS. Special attention is paid to some limitations of the study and important clinical implications and directions for future research.

The findings of the present part of the study indicate a favorable outcome associated with the use of the Forbrain® devices, aligning with prior research on the impact of bone conduction as a provider of AAF on voice production (Escera, Gorina-Careta, et al., 2018; Escera, López-Caballero, et al., 2018; Lee et al., 2019; Nudelman et al., 2022; Stidham et al., 2006;). The study observed a reduction in the self-reported vocal fatigue when using Forbrain® devices, compared to the control conditions not using any device. Additionally, the results suggest enhanced control over vocal output when using a Forbrain® device. According to Hunter et al. (2020) vocal fatigue can cause a decrease in the range and control of voice. Therefore, using Forbrain devices might assist the speaker in having a more controlled vocal output.

VLTs, similar to the ones performed in this study, are often used in research to study the effect of prolonged voice usage and the vocal system (Fujiki & Sivasankar, 2017). To assess the effect of VLTs on the voice, studies often use different measures, that is, subjects' own rating or/and objective ratings of the voice (Whitling et al., 2015). The length of the VLTs used in this study were about an hour, not counting the breaks between tasks, as suggested by Fujiki and Sivasankar (2017). They suggest that the VLTs should last over an hour, as tasks shorter than this have not shown any significant changes regarding the objective measures of voice (Fujiki & Sivasankar, 2017). As mentioned, the current study used both subjective and objective measures to help gather comprehensive data by considering both the individual`s perspective and measurable, quantifiable data. That is, the subjective measures are the participant's self-reported assessment of their vocal fatigue, while objective measures are quantifiable and involve acoustic analysis of speech parameters.

**Vocal fatigue on VAS**

The results of this study show that both the standard and the modified Forbrain® devices had a significant impact on the self-reported vocal fatigue ratings, as measured by the VAS. Participants using either device reported statistically significantly lower vocal fatigue ratings when compared to the control condition. According to these findings there is a potential benefit in using either one of the Forbrain® devices to reduce self-perceived vocal fatigue during vocally loading tasks. In addition, these findings suggest the devices could potentially serve as a preventive tool against vocal fatigue. However, this result relies heavily on the subjective measures of the participants' self-reported assessment of their vocal fatigue. VAS is often used as a subjective rating scale in research. In voice research it can assess aspects related to vocal health in different ways (Castillo-Allendes et al., 2022). While self-assessment measures can offer valuable insights into the participants' experience, feelings, and/or symptoms, the results should be examined with caution. According to Mehta et al. (2016) participants often overestimate their vocal usage time. Similarly, during the VLTs in this study the participants were asked to rate their vocal fatigue on the VAS, and this might have had an effect on the participants' self-reporting. Additionally, the participants were provided with visual feedback of their vocal usage (the iPad running the "Too Noisy" app) during the VLTs, which could have affected their self-perceived vocal fatigue.

**SPL**

The results of the study found that using the Forbrain® devices during the VLTs had a significant effect on SPL when comparing the before and after speech tasks. The Forbrain® devices showed reduced SPL values when comparing the before and after VLTs. These results are in line with previous research that suggests that using an AAF device can reduce SPL in individuals (Jónsdottir, Laukkanen, et al., 2001; Nudelman et al., 2022; Tomassi et al., 2021).

An increase in SPL values indicates that the individual is exerting more effort to produce a louder voice, indicating a stronger adduction of the vocal cords, which can be stressful for the voice (Jónsdottir, Laukkanen, et al., 2001). According to the findings in this study, Forbrain® devices can have a positive effect on SPL and may potentially contribute to a more controlled vocal output as well as enhance vocal quality. By reducing the SPL, bone conduction devices such as Forbrain® may help the user to use their voice more effectively. In line with previous research (Nudelman et al., 2022), these findings suggest that the

Forbrain® devices could potentially help the user reduce strain and increase vocal control. It is, however, crucial to interpret these findings together with other measures that assess vocal quality.

**HNR**

This study found an increase in HNR values during the Forbrain® conditions compared to the control conditions. The results also indicate that there was a significant increase in HNR during the after-VLTs. However, there was no significant association found between HNR and the modified Forbrain® condition.

Previous research has indicated that higher HNR values are associated with a clearer voice (de Krom, 1993; Teixeira & Fernandes, 2014). In view of previous research, these findings suggest that using the standard Forbrain® as an AAF could possibly improve vocal fold function as well as the quality of voice of the user. However, it is important to note that HNR is only one of many measures used in voice analysis, and it is important to use different tools in addition to HNR to receive a more comprehensive assessment of the vocal output.

**LTAS**

The results show that during conditions using either the standard or the modified Forbrain® devices there was a notable decrease in LTAS mean and LTAS SD when compared to the control condition. There was, however, no significant results found for LTAS SD in the post-hoc comparison. The findings from this study suggest that the use of Forbrain® devices has a positive effect on LTAS. According to previous research, lower LTAS mean values and lower variance in LTAS SD indicate a better quality of voice (Hartmann & von Cramon, 1984; Tanner et al., 2005). In this study the Forbrain® devices lowered the LTAS SD variance and LTAS mean values. The results could suggest an improvement in the quality of voice of the participants when using a Forbrain® device.

There was also a positive effect on LTAS skew during the conditions using Forbrain® devices. The results suggest a beneficial change associated with the vocal output and could be interpreted as an improvement of voice quality. However, there are studies that disagree on whether or not to interpret LTAS skew as a voice quality indicator (Nudelman et al., 2023). In fact, some studies suggest no significant impact on voice quality (Tanner et al., 2005), while other studies point to a link between LTAS skew and dysphonic voice quality (Hillenbrand & Houde, 1996). Therefore, the interpretation of this result is difficult. Additionally, it is important to interpret LTAS results by taking into account other objective measures as well as subjective measures of the voice.

**Limitations**

There are several limitations that need to be taken into account. First, there were only a few participants (N = 20), making it difficult to generalize the outcome to the broader population. Moreover, the sample was fairly homogeneous and primarily consisted of university students, which further restricts the generalizability of the outcome. Nevertheless, the findings of this study could serve as a guiding reference for future research in this area of study.

Second, although the same directions were given to all participants, the participants might have interpreted the directions in different ways. A related limitation is that people may use their voice differently and may also have a different perspective of what constitutes a loud voice. Therefore, despite receiving the prompting from the iPad, participants had the ability to exceed or undercut the fixed threshold for the vocal intensity if they chose to. This suggests that there was variation among participants in terms of vocal loading experienced, with some participants potentially experiencing more vocal loading than others.

Third, the result of self-assessment relies on the participants' own ratings of their vocal fatigue. The self-assessment measures come with both advantages as well as limitations. While it allows individuals to provide subjective insight into their own experiences or symptoms, this insight might be biased and can lead to inaccurate or incomplete information. The self-assessment tools are usually quick and convenient. However, the participant may respond, consciously or unconsciously, in a way they think is desirable, leading to response bias. Moreover, self-assessment tools capture the individual's state at a particular moment but do not provide a comprehensive view of long-term trends.

Fourth, the distribution of the different conditions and reading material used during the VLT were randomized, but the distribution was not equal across all the experiments. That is, some order condition combinations were introduced more frequently than others. For example, 9 out of 20 participants experienced the standard Forbrain® device as the last condition, while 10 out of 20 experienced the control condition (i.e., no AAF device) first. This occurred due to the randomization process but can nonetheless have an effect on the results.

Fifth, participants were recruited from the class overseen by one of the researchers, and these participants were offered extra credits on that class. The remaining individuals were friends or acquaintances of members of the research team and were offered compensation for participating in the study. This recruitment method may limit the generalizability of the findings beyond the specific class or social circles represented in the study.

All the participants in this study also self-identified as being vocally healthy, and while some reported a higher number of voice-related difficulties, none categorized themselves as having a voice disorder. Consequently, observing a substantial change in vocal load and self-perceived vocal fatigue may be challenging. The outcomes might have varied if the participant pool encompassed a broader spectrum, including both vocally healthy individuals and those with diagnosed voice disorders.

**Clinical implications**

As mentioned, research as well as clinicians, such as speech and language pathologists, can use different feedback tools and technology to provide visual or auditory feedback to individuals regarding their vocal patterns. This feedback can help individuals make adjustments to reduce strain on their voice. Previous research has explored various forms of AAF for different purposes, such as reducing stuttering (Ingham & Moglia, 1997; Lincoln et al., 2006), reducing vocal loading (Jónsdottir, Laukkanen, et al., 2001), and voice disorder (Nudelman et al., 2022). According to the findings of this study, bone conductor AAF could offer similar benefits. This method holds particular promise for teachers, as they are the population that has a high probability of developing voice disorders (Lyberg-Åhlander et al., 2012; Lyberg-Åhlander et al., 2014; Roy et al., 2004). Some of the previous research suggests that using an amplification system reduces vocal load (Jónsdottir, Rantala, et al., 2001). Many teachers currently use sound amplification devices to mitigate voice symptoms and to prevent the development of voice disorders. In a study by Trinite & Astolfi (2021), it was found that first graders benefited most from using a sound amplification system, irrespective of classroom acoustic or language development levels. On the contrary, this effect was not observed in older students. Some sound amplification devices on the market uses headphones or other sound amplification forms (e.g., stereos) that might have negative effects due to generated noise. According to Banks et al. (2017), using amplification devices might have a negative effect on the user's voice, which is caused by the noise the amplification device makes. In contrast, the Forbrain® bone conductor uses skull vibration to provide auditory feedback (Stenfelt & Goode, 2005), which leaves the ear canal open to the surroundings, allowing teachers to hear students' questions. The Forbrain® bone conductor device is a tool meant exclusively for the user (i.e., the speaker). For this reason, the Forbrain® device has little impact on the listener, unlike the sound amplification system.

Additionally, bone conduction devices eliminate distractions for others, as the auditory feedback is exclusively provided to the speaker. Furthermore, the volume of the auditory feedback provided to the speaker can be adjusted on the bone conductors, similar to headphones, which makes it easy to change the volume of the auditory feedback according to the needs of the user. The results also suggest that the Forbrain® devices may enhance the voice quality which could benefit the listeners. Accordingly, a study by Lyberg-Åhlander et al. (2015) suggests that children might academically underachieve in situations involving noisy classrooms and teachers hoarse voice. Therefore, the device might be a useful tool for teachers to enhance their quality of voice and possibly vocal health.

According to this study, there are positive effects on the voice when using bone conduction as an AAF method. Both the standard and the modified Forbrain® devices appear to contribute to the reduction in the self-perceived vocal fatigue. This indicates their potential use in alleviating voice symptoms and possibly as a preventive measure against developing voice symptoms such as vocal fatigue. The results suggest the possible use of bone conduction devices in voice therapy for individuals who are occupational voice users as well as for individuals with voice disorders, such as vocal fatigue.

**Future research**

Given the limited amount of existing research on this subject, further explorational research using bone conductor devices is needed. Future studies could investigate the efficacy of the bone conductor devices in various settings, both clinical and non-clinical settings. Comparative studies with other forms of AAF devices should be performed, specifically focusing on occupational voice users, for example teachers (as they are a population that has a high probability of developing voice disorders). Furthermore, other occupational voice users should be investigated comparing different AAF devices with bone conductor devices. Studies of this nature could enhance our understanding of the unique possible benefits these devices offer to reduce vocal loading and/or to reduce the perceived feeling of vocal fatigue for the users. Additionally, different forms of AAF devices have been used in previous research (Ingham & Moglia, 1997; Jónsdottir, Laukkanen, et al., 2001; Lincoln et al., 2006; Nudelman et al., 2022). However, Maryn et al. (2006) found that only a small percentage (29.4%) of the studies in their literature review who reported a positive effect on voice quality when using AAF mentioned a long-term carryover to real-life situations. Therefore, future research should also include longitudinal studies that measure the long-term carryover of the effects on vocal fatigue and vocal output into real-life situations.

## Conclusion

The results of the study suggest potential benefits of using Forbrain® devices to reduce and prevent self-reported vocal fatigue during vocally demanding tasks. However, these results rely on subjective measures. Even though VAS is commonly used in voice related research as an assessment tool, the results should be approached with caution. According to the findings, the use of the Forbrain® devices may contribute to a more controlled vocal output. There also seem to be potential benefits, including aiding in reducing strain, enhancing vocal control, and improving vocal fold function and quality of voice when using Forbrain® devices. In addition, using the Forbrain® devices may decrease vocal effort, prompting a more sustainable use of the voice. The results of this study are in line with prior research on the impact of bone conduction as a provider of AAF on voice production.

Bone conduction devices could hold a particular promise for teachers, as many teachers currently use sound amplification devices to mitigate voice symptoms. However, the sound amplification devices might produce side noise that may distract others or even result in a suboptimal vocal usage. In contrast, the bone conduction devices eliminate distractions for others, as the auditory feedback is exclusively provided to the speaker. Additionally, the bone conduction devices leave the ear canal open to the surroundings, allowing teachers to hear students' questions. Future research is needed to investigate the effectiveness of bone conductor devices in various contexts, both clinical and non-clinical. This is crucial for establishing comprehensive insight into the broader applicability of bone conduction devices for individuals who are occupational voice users.

## Summary in Swedish – svensk sammanfattning

### Hur benledningsenheten, Forbrain®, påverkar upplevelsen av rösttrötthet

Flera faktorer påverkar en persons röstproduktion. Till dessa hör bland annat rösthälsa, röstanvändning, stress samt rummets akustik. Röststörningar är relativt vanliga kommunikativa störningar. Enligt tidigare forskning är röststörningsprevalensen mellan 4,8 % till 29,9 % bland den allmänna befolkningen (Bhattacharyya, 2014; Lyberg-Åhlander et al., 2019; Roy et al., 2004, 2005). Flera studier tyder på att prevalensen bland lärare är större (57,6 %) jämfört med andra yrkesmässiga röstanvändare (28 %) (Lyberg-Åhlander et al., 2012; Lyberg-Åhlander et al., 2014; Roy et al., 2004). Tidigare forskning lyfter fram att ett vanligt klagomål som klienter med röststörningar ofta nämner är en känsla av ökad rösttrötthet då de intervjuas om hurdana röstsymptom de har. Detta gäller speciellt efter aktiviteter som anstränger rösten (Gilman & Johns, 2017; Hunter et al., 2020).

Forskning tyder på att vår förmåga att höra oss själv tala, det vill säga auditiv återkoppling, spelar en viktig roll i bland annat talproduktion och inlärning (Cai et al., 2012; Coughler et al., 2022; Purcell & Munhall, 2006). Deltagarna i en studie av Jónsdottir, Laukkanen, et al. (2001) rapporterade att de kände sig mera bekväma då de talade med en auditiv återkopplingsenhet. Inom logopedisk forskning kan s.k. förändrad auditivåterkoppling (eng. *altered auditory feedback*, AAF) användas. AAF är en metod som ändrar talets återkoppling till hjärnan genom att manipulera talet på ett bestämt sätt (Lincoln et al., 2006). Det finns en begränsad mängd forskning om benledningsenheters användning för att manipulera tal genom AAF. Studier har undersökt användning av benledningsenheters inom talterapi för personer som stammar (Escera, Gorina-Careta, et al., 2018; Stidham et al., 2006) samt som ett AAF-verktyg för personer med röststörningar (Escera, López-Caballero, et al., 2018; Lee et al., 2019; Nudelman et al., 2022). Lee m.fl. (2019) föreslår att vibrationen från benstrukturen i öronen, som uppstår under benledning, kan inducera vibrationer i ansiktsbenen. Det är vanligt att känslan av ansiktsvibrationer är något man försöker uppnå under röstterapi med exempelvis resonansrör för stämbandsknottror (Saltürk et al., 2019; Simberg & Laine, 2007).

Benledningsenheten Forbrain® har en mikrofon, två benledare samt ett filter som blockerar omgivningens ljud och förstärker användarens röst. Benledarna ger auditiv återkoppling åt användaren av hens röst (Escera, López-Caballero, et al., 2018).

Syftet med denna avhandling är att utreda om benledningsenheterna, Forbrain®, kan användas för att minska ansträngningen på talarens röst. Syftet är även att utreda om användningen av benledningsenheterna kunde minska upplevelsen av rösttrötthet och bidra till att förebygga röststörningar genom AAF. Hypotesen är att användningen av standardmodells Forbrain®-enheter kommer att resultera i förbättrad röstanvändning. Därtill förutses den minska förekomsten av rötttrötthet under röstansträngnings uppgifter (vocal loading tasks, VLT) jämfört med kontrollförhållande.

**Metod och material**

Denna avhandling är en del av ett större forskningsprojekt som utförts vid University of Illinois i Urbana-Champaign (Nudelman et al., 2023) där syftet är att jämföra två benledande AAF-enheter, en standardmodells Forbrain®-enhet och en modifierad Forbrain®-enhet, samt ett kontrollförhållande (där ingen enhet användes). Syftet med denna del av projektet är att utreda om Forbrain®-enheterna kan användas för att minska hur talaren anstränger sin röst, jämfört med då AAF-enheterna inte används. Deltagarnas tal spelades in medan de utförde VLT-uppgifterna under tre olika förhållanden. VLT-uppgifterna genomfördes i ett ljudisolera rum med dubbelväggar. I studien användes två olika AAF-enheter. Den första enheten var standardmodells Forbrain®-enhet med ett filter. Den andra enheten var en modifierad Forbrain®-enhet, där tillverkaren tagit bort filtret. Det borttagna filtret gjorde att enheten endast gav sidotonsförstärkning, det vill säga den endast förstärkte ljudet av användarens egen röst, som återkopplas till användaren exempelvis under tal. Enheten blockerade inte ljudet från omgivningen, i motsats till standardmodells Forbrain®-enhet (Guajarengues & Lohmann, 2015). Båda enheterna försågs kostnadsfritt av tillverkaren. Under kontrollförhållandena utförde deltagarna VLT-uppgifterna på samma sätt som under de andra förhållandena, men utan några AAF-enheter eller andra anordningar.

Ljudtrycksnivån (eng. Sound Pressure Level, SPL) är ett mått på röstsignalen och påverkas av det subglottala trycket. SPL anses vara en grundläggande egenskap i röst och tal eftersom det påverkar den upplevda ljudstyrkan (Švec & Granqvist, 2018). Harmonic-to-noise ratio (HNR) är ett mått för att utreda mängden ökat brus i röstsignalen(Ferrand, 2002; Teixeira & Fernandes, 2014). Enligt Krom (1993) är lägre värden på HNR knutet till högre mängd heshet och läckage i rösten. Långtidsmedelvärdesspektrum (eng. long-time average spectrum, LTAS) är ett mått som används för att hjälpa beskriva frekvensinnehållet i en ljudsignal, då denna signal produceras under en längre tid (exempelvis flera sekunder eller minuter). LTAS mean representerar medelvärdet: lägre värden indikerar bättre röstkvalitet (Hartmann & von Cramon, 1984). LTAS SD mäter variansen i den spektrala fördelningen: lägre varians indikerar enligt Tanner m.fl. (2005) bättre röstkvalitet. LTAS skew visar ifall röstsignalen har en positiv eller negativ lutning: en negativ lutning indikerar mer energi vid de högre frekvenserna.

I studien deltog 20 engelsktalande personer i åldern 19 till 33, som inkluderades genom ett sekventiellt bekvämlighetsprovtagningssätt. Tio av deltagarna var kvinnor och tio var män. Deltagarna gav sitt informerade och skriftliga samtycke. De informerades också om sin rättighet att avsluta sitt deltagande när som helst under studiens gång. För information om deltagarnas rösthälsa ombads de fylla i Voice Handicap Index-10 (VHI-10), Voice – Related Quality of Life (V-RQOL) och Vocal Fatigue Index (VFI). Deltagarna läste upp en text i 20 minuter med hög röstvolym, under de tre förhållandena. Under experimentets gång frågades deltagarna med cirka två minuters mellanrum om hur stark känsla av rösttrötthet de upplevde. Rösttröttheten under VLT-uppgifterna rapporterades med hjälp av självskattningsskalan (engelska visual analog scale, VAS), på en skala mellan 0, ingen rösttrötthet, och 100, extrem rösttrötthet

För att utföra den statistiska analysen av data användes R version 4.2.0. I analysen monterades Linear-Mixed Effects (LME)-modeller via Restricted Maximum Likelihood (REML). För att skilja mellan olika nivåer på de relevanta faktorerna utfördes parvis jämförelse med Tuckeys post-hoc-metod (Multiple Comparison of Means: Tuckey Contast). För att utvärdera effekten av användning av benledningsenheterna på deltagarnas självupplevda rösttrötthet användes en LME-modell med ”rösttrötthet” som responsvariabel, samt tid (2 till 20 minuter) och tre olika förhållanden som prediktorer.

**Resultat**

Resultaten visade att då deltagarna använde en standardmodells Forbrain®-enhet rapporterade deltagarna cirka 9 poäng lägre ($p = 0{,}002$) värden för rösttrötthet på VAS jämfört med kontrollförhållandena. Under användningen av modifierad Forbrain®-enheten rapporterade deltagarna cirka 15 poäng lägre ($p < 0{,}001$) värden för rösttrötthets på VAS-skalan jämfört med kontrollförhållanden. Resultaten visade även att såväl standardmodells Forbrain®-enheten ($p = 0{,}048$) som modifierade Forbrain®-enheten ($p = 0{,}015$) reducerade deltagarnas SPL-nivåer då man jämförde inspelningarna gjorda före och efter VLT-uppgifterna. Resultaten tyder även på att det fanns en signifikant ökning av HNR-värdena under efter VLT-inspelningarna ($p = 0{,}033$). Däremot fanns det inget signifikant samband mellan HNR-värdena och modifierade Forbrain®-enheten. Resultaten tyder även på att Forbrain®-enheterna hade en positiv effekt då det kom till LTAS (LTAS mean standardmodellens Forbrain®-enheten $p < 0{,}001$, modifierade Forbrain®-enheten $p < 0{,}001$, SD standardmodellens Forbrain®-enheten $p = 0{,}030$, modifierade Forbrain®-enheten p =

0,021 och skew standardmodellens Forbrain®-enheten p = 0,013modifierade Forbrain®-enheten p = 0,049), vilket tyder på en förbättrad röstkvalitet då deltagarna använde Forbrain®-enheterna jämfört med under kontrollförhållandena.

**Diskussion**

I denna del av forskningsprojektet tyder resultaten på att Forbrain®-enheterna har en positiv effekt på rösten, vilket är i linje med tidigare forskning om användning av olika AAF-enheter när det kommer till röstproduktion. Studien observerade att deltagarna rapporterade en minskning av rösttrötthet vid användning av Forbrain®-enheterna, jämfört med under kontrollförhållandena. Det framkom även att Forbrain®-enheterna hade en positiv effekt på de olika röstmåtten och kunde bidra till en mera kontrollerad röstproduktion samt förbättra röstkvaliteten.

Det är viktigt att minnas att även om dessa resultat är i linje med tidigare forskning fanns det begränsningar i studien. Mängden deltagare i studien var liten (N=20) och deltagarna var röstfriska unga vuxna. Detta kan ha påverkat resultatet och resultatet kunde varit annorlunda ifall deltagarna lidit av exempelvis röststörningar. Ordningen i vilken deltagarna gick igenom försöksförhållandena och vilken text de läste var slentrianmässig, men eftersom randomiseringen inte gav lika mängder av alla förhållanden (10 av 20 deltagarna gjorde VLT-uppgifterna under kontrollförhållandet först, samtidigt som 9 av 20 deltagare gjorde uppgifterna med en standardmodells Forbrain®-enhet sist) kan även detta ha påverkat resultatet.

Dessa resultat kan tolkas som riktgivande och framtida forskning kring effektiviteten av användning av beneldningsenheter som AAF-metod i olika miljöer är viktig. Dessa typer av studier kan förbättra vår förståelse av de möjligheter benledningsenheter erbjuder för att minska röstbelastningen och den upplevda känslan av rösttrötthet.

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**Pressmeddelande**

**Hur benledningsenheten Forbrain® påverkar rösten under röstansträngning.**

Pro gradu-avhandling i logopedi

Fakulteten för humaniora, psykologi och teologi, Åbo Akademi

Resultaten från en pro-gradu avhandling vid Åbo Akademi tyder på en positiv effekt på rösten då man använder en s.k. *altered auditory feedback* (AAF) benledningsenhet. Altered auditory feedback är en metod som ändrar talets återkoppling till hjärnan, genom att förvränga talet på ett bestämt sätt. Daniela Udd har undersökt hur benledningsenheterna, standard Forbrain® och modifierad Forbrain®, påverkar rösten under röstansträngningsuppgifter (vocal loading tasks, VLTs). På självskattningsskalan visual analog scale (VAS) rapporterade deltagarna en mindre känsla av rösttrötthet då de använde någon av Forbrain®-enheterna.

I studien deltog 20 personer i åldern 19 – 33. Deltagarna läste upp en text i 20 minuter med hög röstvolym, under tre olika förhållanden. Förhållandena inkluderade: standard Forbrain ® (Forbrain® med ett filter som filtrerar sidoljud och förstärker talarens röst), modifierad Forbrain® (som enbart återkopplar ljudet) samt ett kontrollförhållande (där ingen enhet användes). Under experimentets gång ställdes deltagarna, med två minuters mellanrum, frågan om huruvida de upplevde en känsla av rösttrötthet.

Enligt Udd tyder resultaten på att Forbrain®-enheternas användning kunden lindra redan förekommande röstsymptom samt förhindra utvecklingen av röstsymptom, som exempelvis rösttrötthet. Det framkom även att Forbrain®-enheterna hade en positiv effekt på röstkvaliteten och kunde även bidra till en mer kontrollerad röstproduktion. Resultaten från denna studie är i linje med resultaten från tidigare studier med olika typer av AAF. Resultaten tyder på att användning av benledning AAF minskade deltagarnas känsla av rösttrötthet. Det behövs mera studier om hur benledning enheter kunde användas för att minska röstsymptom, som rösttrötthet, hos individer som använder sin röst för arbete (exempelvis lärare).

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