JSLHR

Research Article

The Potential Effect of Forbrain as an Altered Auditory Feedback Device

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Purpose: The purpose of this study was to run a proof of concept on a new commercially available device, Forbrain® (Sound For Life Ltd/Soundev, Luxemburg, model UN38.3), to test whether it can modulate the speech of its users.
Method: Participants were instructed to read aloud a text of their choice during 3 experimental phases: baseline, test, and posttest, while wearing a Forbrain® headset. Critically, for half of the participants (Forbrain group), the device was turned on during the test phase, whereas for the other half (control group), the device was kept off. Voice recordings were analyzed to derive 6 quantitative measures of voice quality over each of the phases of the experiment.
Results: A significant Group × Phase interaction was obtained for the smoothed cepstral peak prominence, a measure of voice harmony, and for the trendline of the long-term average spectrum, a measure of voice robustness, this latter surviving Bonferroni correction for multiple comparisons.
Conclusions: The results of this study indicate the effectiveness of Forbrain® in modifying the speech of its users. It is suggested that Forbrain® works as an altered auditory feedback device. It may hence be used as a clinical device in speech therapy clinics, yet further studies are warranted to test its usefulness in clinical groups.

There is increasing evidence that a range of speech, language, and communication disorders may involve central auditory processing deficits. These conditions include dyslexia (Ahissar, Lubin, Putter-Katz, & Banai, 2006; Hämäläinen, Salminen, & Leppänen, 2013), specific language impairment (Miller, 2011), speech sound disorder (SSD; Iliadou, Chermak, & Bamiou, 2015; Murphy, Pagan-Neves, Wertzner, & Schochat, 2015), and developmental stuttering (Cai et al., 2012; Hampton & Weber-Fox, 2008), among others. Children suffering from these conditions typically show difficulties for sound localization and discrimination, auditory performance with degraded acoustic stimuli, dealing with the temporal aspects of the sound sequence, and generally with auditory discrimination (Miller, 2011). For example, several studies measuring event-related brain potentials associated with acoustic sound discrimination have revealed abnormal mismatch negativity (Näätänen, Paavilainen, Rinne, & Alho, 2007) in dyslexia (Corbera, Escera, & Artigas, 2006; Halliday, Barry, Hardiman, & Bishop, 2014) and specific language impairment (Bishop, Hardiman, & Barry, 2010; Rota-Donahue, Schwartz, Shafer, & Sussman, 2016), and adults who stutter have been shown to have abnormal speech sound representation, as revealed also with the mismatch negativity brain potential (Corbera, Corral, Escera, & Idiazábal, 2005) in speech-related cerebral regions with atypical gyrification in these adults (Foundas et al., 2004). For all these disorders, finding appropriate treatments is urgent as their consequences span literacy (Hayiou-Thomas, Carroll, Leavett, Hulme, & Snowling, 2017; Peterson, Pennington, Shriberg, & Boada, 2009), educational attainment (Olofsson, Taube, & Ahl, 2015), emotional adjustment (Alexander-Passe, 2008; Iverach & Rapee, 2014), and social outcomes (Riddick, 2001; Roberts, Solis, Ciullo, McKenna, & Vaughn, 2015).

It has been suggested that altered auditory feedback (AAF) in several of its different forms, such as masked auditory feedback, delayed auditory feedback, and frequency-altered feedback (Lincoln, Packman, & Onslow, 2006), may play an important role in ameliorating the symptoms of some of these disorders, for example, in stuttering (Cai et al., 2012; Packman, 2012) and SSD

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Editor-in-Chief: Julie Liss
Editor: Jack Jiang
Received February 22, 2017
Revision received July 10, 2017
Accepted November 10, 2017
https://doi.org/10.1044/2017_JSLHR-S-17-0072

Disclosure: The present research was sponsored by Sound for Life Ltd (Soundev). Sound for Life Ltd (Soundev) had, however, no role in the study design; in the collection, analysis, and interpretation of the data; in the writing of the report; and in the decision to submit the paper for publication. Solely, the authors had full access to all data in this study, and the corresponding author takes complete responsibility for the integrity of the data and the accuracy of the data analysis. None of the authors has any private, including financial, interest in Soundev for Life Ltd (Soundev).

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(Cummings & Barlow, 2011). Also, other less clinically used forms of AAF, such as the Lombard effect (Arciuli, Simpson, Vogel, & Ballard, 2013; Garnier, Henrich, & Dubois, 2010; Stathopoulos et al., 2014), sidetone amplification (Bauer, Mittal, Larson, & Hain, 2006; Garber, Siegel, & Pick, 1976; Heinks-Maldonado & Houde, 2005), and the so-called *feedback filtering* (Burzynski & Starr, 1985; Garber et al., 1976; Garber, Siegel, & Pick, 1980, 1981), which alter the speech input in the amplitude domain or in specific frequency bands, have been shown to affect speech in fluent-speaking adults and those who stutter (Martin, Siegel, Johnson, & Haroldson, 1984) and in children with SSD (Siegel & Kennard, 1984). *AAF* refers to a range of procedures that, through electronic or digital manipulation, alter the speaker's voice so that it is perceived differently from normal (Fairbanks, 1954; Yates, 1963). Recently, it has been suggested that these AAF effects may reflect a compensatory motor command on the perceived shift in the acoustic input on the basis of a predictive internal model of the expected output (Hahnloser & Narula, 2017; Ostry & Gribble, 2016), and a candidate brain region to support these interactions has been proposed, namely, *Spt area in the planum temporale of the left temporal lobe* (Hickok, Houde, & Rong, 2011). Such a compensatory motor command may result in the retuning of the phono-articulatory loop (Eliades & Wang, 2008; Keller & Hahnloser, 2009) and might have consequences on the speaker's voice (Houde & Jordan, 1998; Jones & Munhall, 2000). Several commercial AAF devices are currently available, such as SpeechEasy® by Janus Development Group (Greenville, NC, USA; Foundas, Mock, Corey, Golob, & Conture, 2013), SmallTalk® and Basic Fluency System® from Casa Futura Technologies (Boulder, CO, USA; Unger, Glück, & Cholewa, 2012) and VA601i Fluency Enhancer by VoiceAmp Ltd. (Capetown, South Africa; Unger et al., 2012). Evidence supporting the effects in treating stuttering or SSD with AAF devices, however, is equivocal (Foundas et al., 2013; Pollard, Ellis, Finan, & Ramig, 2009; Ritto, Juste, Stuart, Kalinowksi, & de Andrade, 2016; Stuart, Kalinowski, Rastatter, Saltuklaroglu, & Dayalu, 2004; Stuart, Kalinowski, Saltuklaroglu, & Guntupalli, 2006).

A newly marketed device has become available recently, which is Forbrain®, developed by Sound For Life Limited (Soundev) in Luxemburg (model UN38.3; Europe; http://www.forbrain.com). Forbrain® is a headset equipped with a microphone and a pair of bone conductors, which feeds the user back with his or her own voice during natural speech through bone conduction. According to its patent registration (Guajarengues & Lohmann, 2015), Forbrain® implements a dynamic, two-band equalizer filter (close to a Baxandall equalizer; Baxandall, 1952) that applies to the voice input either of two different settings. These two settings are switched to by the user's voice energy at 1 kHz over a time window of integration ranging 10–200 ms (see technical description in Method section). The resulting sound flow, which is altered in its frequency spectrum by the dynamic equalizer, is then delivered through bone conduction to the temporal bones, thus providing AAF, presumably in the amplitude domain, as with, for example, semitone amplification (Bauer et al., 2006: Garber et al., 1976; Heinks-Maldonado & Houde, 2005) or feedback filtering (Burzynski & Starr, 1985; Garber et al., 1976, 1980, 1981).

One advantage of Forbrain® over other commercially available devices is its low cost, as it is offered by a fraction of the cost of its competitors.[1] However, no study has so far tested whether Forbrain® provides any of the above-mentioned effects (AAF) on the user's voice quality and speech. Before attempting an effortful and costly study on a clinical population, the present experiment was, hence, run as a proof of concept to test whether the speaker's voice of a sample of fluent speakers would be altered during the use of this device. Voice quality over other fluency parameters (e.g., speech rate and so forth) was preferred as it offers quantitative and objective measures of the fine-grained articulatory loop. It is hypothesized that, by providing AAF, the use of Forbrain® will affect the user's voice during natural speech. Should our results confirm the departing hypothesis, this study should set the grounds to test the potential utility of Forbrain® in all clinical conditions in which central auditory processing deficits may be involved.

Materials and Method

Participants

A sample of $N = 32$ adult healthy Catalan–Spanish bilingual participants (18 men, 14 women; mean age = 23.3 ± 2.5 years; three left-handed) were recruited for the experiment and randomly assigned to one of the two groups of the study (16 participants each). Inclusion criteria included no self-report of psychiatric, neurological, and voice/speech/language disorders, no family antecedents of these disorders, no excessive alcohol consumption, no formal musical training for more than 3 years, normal sleep habits, and normal hearing levels. A pure-tone audiometry (frequency range: 250–4000 Hz), using audiometric Beyerdinamic DT48-A headphones (Beyerdynamic GmbH & Co, Heilbronn, Germany), was performed for each participant before the experiment started to confirm mean hearing thresholds below 20 dB HL at each ear. The study was conducted according to the WMA Declaration of Helsinki Ethical Principles for Medical Research Involving Human Subjects and with the approval of the Bioethics Committee of the University of Barcelona. Before the experimental sessions, written informed consent was obtained from each participant, after providing a detailed description of the methods involved in the study, without, however, revealing the nature of the

[1]Forbrain® cost is $299 per unit according to its official webpage (https://www.forbrain.com/order-now/order-form). SpeechEasy® ranges from $2,500 to $4,500 depending on the model (http://www.speecheasy.com/models.php). SmallTalk® cost is $2,495, whereas Basic Fluency System® is worth $1,495 (http://www.casafuturatech.com/). Data was retrieved from the Internet on February 7, 2017.

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working hypothesis. At the end of the experiment, participants were compensated by monetary payment (8 €/hr).

Device

A standard headset of Forbrain® (Sound For Life Ltd/Soundev, Luxemburg; http://www.forbrain.com) was used in this study. The headset was provided at no cost by the manufacturer. As described above, Forbrain® is equipped with a microphone and a pair of bone conductors, which, during its use, feeds the user back with his or her own voice speech through bone conduction, after digital processing, to amplify high frequencies and manipulate its intensity, so it is filtered with alternating contrast. At the beginning of the experimental session, a Forbrain® headset was placed on the participants' heads in a way that they felt comfortable, with the microphone located at 3 cm from the participant's mouth. Forbrain® is a completely safe device, and its use does not convey any risk for the participant's health.

According to its patent registration (Guajarengues & Lohmann, 2015), Forbrain® implements a dynamic, two-band equalizer filter (close to a Baxandall equalizer; Baxandall, 1952) that applies to the voice input either of two different settings. These two settings are switched to by the user's voice energy at 1 kHz (mic input). One of the settings (Setting 1) raises low frequencies (100–800 Hz, +12 dB) while dampers 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., dampers 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. By applying these functionalities, it is conceivable that Forbrain® conveys some kind of AAF on the speaker's voice, which is in turn fed back via a bone conductor. Yet, to objectively characterize the actual nature of these effects, we performed a comparison of a speech signal at the input (microphone) and the output (bone conductor), following the approach suggested by Stuart et al. (2003). The speech signal was the classical opening statement, in Spanish, of *Don Quixote* by Miguel de Cervantes (1605): "*En un lugar de la Mancha de cuyo nombre no quiero acordarme*" ("*In a village of La Mancha, the name of which I have no desire to call to mind"*). It lasted 4.14 s and was uttered by a female voice and recorded in WAV format with a sampling rate of 44.1 kHz using a DR-40 TASCAM Microphone (TEAC America, Inc.) located at 30 cm from the speaker's mouth. This signal was then sent as input to Forbrain®'s microphone and recorded in WAV format with a 44.1-kHz sampling rate, at the system's output from leads connected at the input of the bone transducer through the microphone external input of the DR-40 TASCAM Microphone. Notice that with this approach, we could only measure the effect of Forbrain® on its electrical output, and hence, the bone conduction transducer is not considered. Both the input and output signals were compared in the time domain, cross-correlated, and analyzed with the Fast Fourier Transform (0.17-Hz resolution) and, subsequently, with Praat 6.0.10 software (Boersma, 2001; Boersma & Weenink, 2016) to retrieve their spectrograms. Because we did not have access to the internal device hardware, we let it operate in its normal mode so that Settings 1 and 2 as described above could alternate on the basis of the input characteristics.

Figure 1 shows the comparison of these recordings and their cross-correlation and spectral analysis; Figure 2 shows the corresponding spectrograms retrieved with Praat (Boersma, 2001; Boersma & Weenink, 2016). While it is evident in the time domain that Forbrain® modified the input signal (Figure 1A), cross-correlogram yielded a lag zero, indicating that the output was not delayed compared to the input (Figure 1B). However, the Fast Fourier Transform of the signals revealed clear differences (Figure 1C), in the sense that all frequencies present in the input speech were enlarged in spectral power (Figure 1D), particularly over high-frequency ranges (above 800 Hz). Moreover, the analysis of the spectrograms revealed that these spectral changes had particular effects on the formant structure of the speech, which resulted in larger amplitude and less-defined or blurred in the output compared with the input, and the impossibility to track the first formant (Figure 2).

Procedure and Experimental Design

The experiments were conducted on a single session for each participant, at the premises of the Brainlab-Cognitive Neuroscience Research Group (http://www.ub.edu/brainlab), located in the Department of Clinical Psychology and Psychobiology, University of Barcelona. Participants were asked to refrain from alcohol intake and from taking any drugs during the 24 hr before the experiment. Additionally, they were asked to let us know in case they were taking any medication, which might affect speech and attentive and other cognitive abilities (e.g., antihistamines), but none of the participants reported the intake of such medication.

Participants were assigned randomly to either the experimental (Forbrain on) or the control (Forbrain off) group in a blind manner, so that the participant was not told to which of the groups he or she pertained. The only restriction in the assignment of participants was that about the same number of men and women were assigned to each of the groups. Moreover, the experimenter carrying out the experiment and the subsequent analyses was also blind to the participant's group, as a third independent experimenter kept track of the subjects' assignment. Besides, this latter experimenter was in charge to set the Forbrain® device to the participant and to turn it on or keep it off according to the assigned group and was not involved in data analysis. This is, therefore, a randomized double-blind design providing the strongest falsative power for clinical studies. Only when conclusions of the study were drawn based on the final set of statistical results were the group

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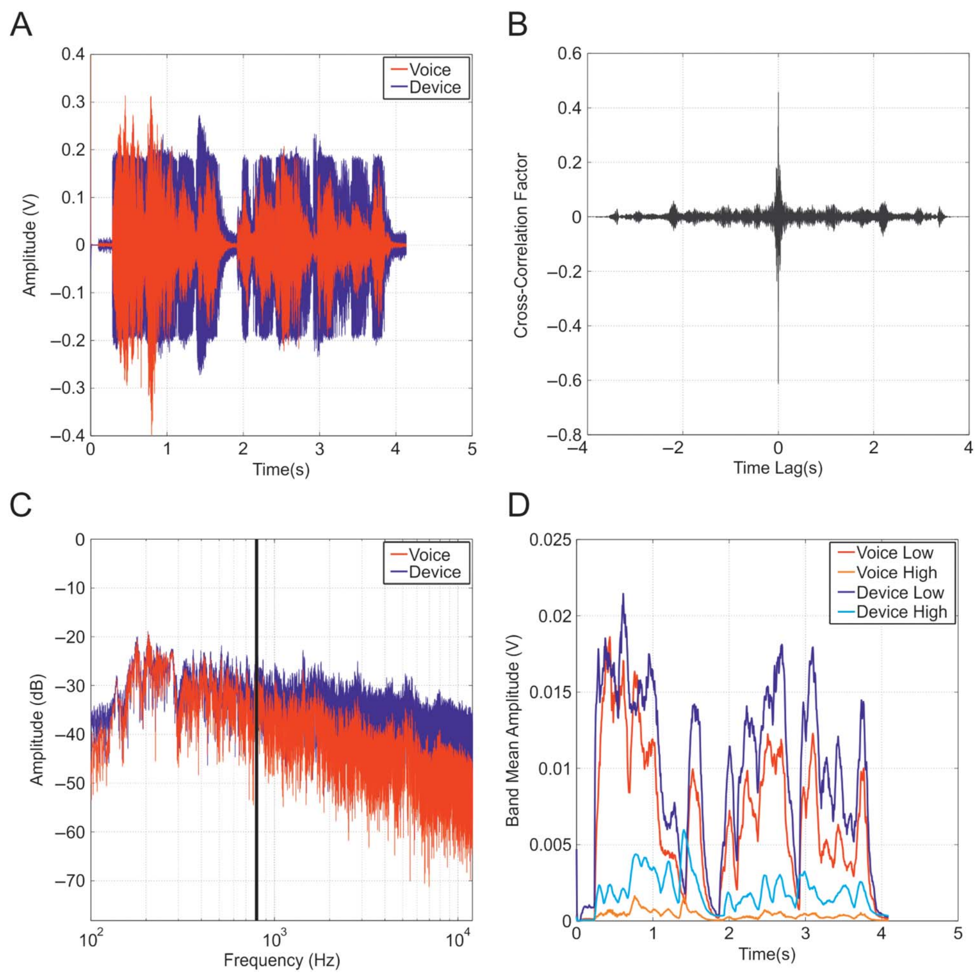
Figure 1. Effects of Forbrain® on the input signal. The Spanish statement "*En un lugar de la Mancha de cuyo nombre no quiero acordarme*" uttered by a female voice (4.14 s long) was fed as input at the microphone (red) and recorded as output (blue) right before the bone transducer. A) Input and output signals, clearly differing in amplitude. B) The cross-correlogram between the input and the output, revealing a time lag zero. C) The spectra of the input and the output. The vertical black line separates low (100–800 Hz) from high (800–12000 Hz) frequencies. D) Changes over time of the spectral amplitude retrieved in two frequency bands: low (100–800 Hz) and high (800–12000 Hz). A sliding window of 50 ms shifting 5 ms across the entire signal served to compute the average amplitude spectrum in the two frequency bands (red hues: voice; blue hues: device).



identities disclosed and any potential differences attributed to either Forbrain® or placebo.

During the experimental sessions, participants were seated comfortably in a sound-attenuated chamber and were instructed to read aloud, in their preferred language (either Catalan or Spanish, yet they all chose to read in Spanish), on a self-administered but regular pace, a self-selected text during three separate runs of 7, 14, and 7 min, while wearing the Forbrain® headset. During these runs, participant's voice was recorded. For participants belonging to the experimental group, Forbrain® device was in off, on, and off modes, respectively, for each of the three reading phases. For participants belonging to the control group, Forbrain® device was in off mode in the three phases. Between reading phases, an experimenter entered into the chamber to turn on or off the Forbrain® device when needed (by pressing a button built into the device), as well as to stop and restart the audio recordings.

Voice Recording and Analysis

The participant's voice was recorded during reading aloud with a sampling rate of 44.1 kHz using a DR-40 TASCAM Microphone (TEAC America, Inc.) placed in a fixed position on the table in front of the participant, with a mouth-to-microphone distance of approximately 30 cm. The voice samples were saved in WAV format.

To analyze the quality of the participant's voice during reading, the voice samples of the three reading phases (7, 14, and 7 min) were trimmed into 1-min time windows without overlap. The first and last 2 min of each voice sample were then removed from analysis, thus obtaining three

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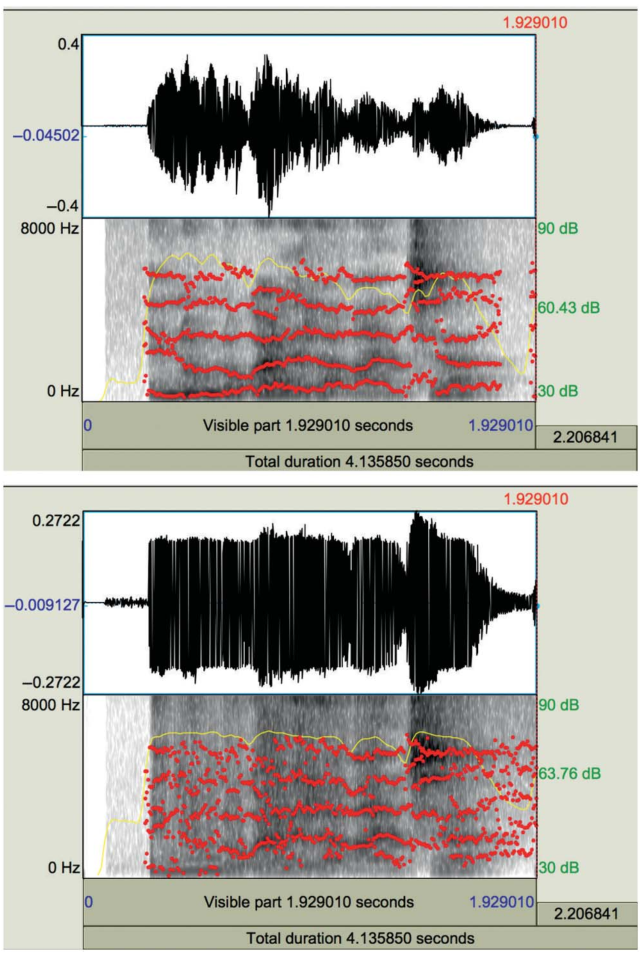
Figure 2. Waveforms and spectrograms at Forbrain® input and output. Analysis is for the early part (1.92 s: "*En un lugar de la Mancha*") of the sentence at the input (top) and recorded at the output of Forbrain® (bottom). A visual comparison between the two waveforms clearly shows a larger overall amplitude at the device output. Moreover, the spectrograms corroborate this overall larger amplitude at the device output (yellow lines) and further indicate that formants were less defined (red lines), particularly the first one (bottom red line), which could not be tracked.



recordings of 1 min for the baseline measurements (with Forbrain® off), ten 1-min recordings during Forbrain® use (with Forbrain® on or off, depending on the experimental group), and three 1-min recordings for the posttreatment measurement (with Forbrain® off). Six different acoustic parameters were derived from every single of the mentioned 1-min recordings, using Praat 6.0.10 software (Boersma, 2001; Boersma & Weenink, 2016) according to the method proposed by Maryn and Weenink (2015).

First, because the acoustic measures used to analyze voice quality are only valid for voiced segments of the running speech, automated detection, segmentation, and concatenation of these voice segments were applied employing a modified version of the Praat script created by Maryn et al. (2010). The algorithm for the detection and extraction of voiced segments was based on the three criteria proposed by Parsa and Jamieson (2001), where frames of 30 ms are designated as voiced if sound energy exceeded 30% of the overall signal energy, zero crossing rate was below 1500 Hz, and the normalized autocorrelation peak was above 0.3.

Then, the six acoustic parameters mentioned above were determined for the obtained voiced segments. The smoothed cepstral peak prominence (CPPS) measures the degree of harmony in a voice sample, which increases as the voice signal is more periodic, and it is considered a reliable and valid measure of voice quality, especially breathiness (Maryn, Corthals, Van Cauwenberge, Roy, & De Bodt, 2010). It was determined as the distance between the first harmonic's peak and the point with equal frequency on the regression line through the smoothed cepstrum (Heman-Ackah, Michael, & Goding, 2002; Hillenbrand & Houde, 1996). Harmonics-to-noise ratio (HNR) is a glottal noise measure that refers to the relative contributions of aperiodic and periodic components of the voice signal, with periodic voice signals having larger HNR. This feature is closely related to the efficacy of the vocal fold closure (Zhang, Mongeau, Frankel, Thomson, & Park, 2004), and it was calculated as the base 10 logarithm of the ratio between the periodic energy and the noise energy multiplied by 10.

Shimmer local (ShimLoc) and shimmer local Db (ShimDB) are measures of the irregularities in the amplitude of cycles of the waveform signal, that is, the perturbation in amplitude along the voice sample. Physiologically, such perturbation could be produced by some asymmetry in the vocal folds, which would make them to meet the same way only every two or three cycles, causing the periodicity to be achieved every second or third cycle of the vibration, respectively. This results in random variations in timing and amplitude of the voice signal. ShimLoc value was calculated as the absolute difference between the amplitudes of consecutive periods in the voice sample, divided by the average amplitude, whereas the ShimdB is the average absolute base-10 logarithm of the difference between the amplitudes of consecutive periods, multiplied by 20 (Maryn & Weenink, 2015).

The trendline of the long-term average spectrum (LTAS) is a spectral measure and shows the average frequency distribution of the sound energy in a continuous (at least 30 s) speech sample. By averaging over a long portion of speech, spectral differences due to individual segments are evened out, and the method thus yields information pertaining to the general voice quality (Vaňková & Skarnitzl, 2014). In the LTAS, the general spectral slope (slope of the long-term average spectrum [sLTAS]) was measured as the difference between the energy in the 0–1 kHz range and the energy in the 1–10 kHz range of the LTAS. The spectral trendline inclination (tilt of long-term average spectrum [tLTAS]) was computed as the difference between the energy in the 0–1 kHz range and the energy in the 1–10 kHz range of the trendline through the LTAS.

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Statistical Analysis

Voice data during reading aloud were analyzed by means of analysis of variance for repeated measures with phase (baseline, test, and posttest) and group (Forbrain and control) as factors for each of the six acoustic parameters to assess voice quality. Whenever the interaction resulted significant, post-hoc pairwise comparisons were carried out, and the Greenhouse–Geisser correction was applied whenever the assumption of sphericity was violated, the corrected degrees of freedom being reported. The alpha level was set to 0.05. For all the statistical analyses, Bonferroni corrections for multiple comparisons were performed to adjust the *p* values of the post-hoc tests.

Results

Results for each of the six voice parameters are illustrated in Figure 3 and described below. Out of the six parameters analyzed, two of them yielded strong significant results regarding the use of Forbrain®.

The CPPS was significantly affected by the use of Forbrain®. The results obtained on this parameter revealed a main effect of phase, $F(2, 60) = 7.145$, $p = .002$, $\eta_p^2 = .192$, indicating an effect with time speaking, and a Phase × Group interaction, $F(2, 60) = 4.044$, $p = .023$, $\eta_p^2 = .119$ (Figure 3A). This latter effect, however, did not survive Bonferroni correction for the multiple voice variables measured ($p = .138$). Post-hoc pairwise comparison revealed that, whereas in the control group, there were no statistical differences between measurements (baseline, test, and posttest phases), the Forbrain group's voice was perturbed by the use of Forbrain®, as measurements dropped from baseline to Forbrain® use (test phase; $t(15) = 4.085$, $p = .001$, $d = 0.28$) to restore its normal values after the Forbrain® device was turned off (i.e., a significant difference between test and posttest phases, $t(15) = 3.921$, $p = .001$, $d = 0.26$, while no difference remained in the posttest compared with the baseline phase, $t(15) = 0.270$, $p = .791$, $d = 0.01$.

Analyses of the HNR (Figure 3B) revealed a significant effect of phase, $F(1.57, 47.32) = 4.332$, $p = .026$, $\eta_p^2 = .126$, suggesting variations on this measure occurring along the reading session. However, the effect did not survive as significant after the Bonferroni correction ($p = .156$). Furthermore, there were no overall effect of group factor, $F(1, 30) = 3.163$, $p = .085$, $\eta_p^2 = .095$, and no Phase × Group interaction, $F(1.57, 47.32) = 1.432$, $p = .247$, $\eta_p^2 = .046$.

As for the perturbation measures, ShimDB (Figure 3C) and ShimLoc (Figure 3D) were not significantly affected by the use of Forbrain®, as there were no significant variations as a function of the time reading (phase) neither for the ShimDB, $F(1.46, 43.95) = 1.287$, $p = .278$, $\eta_p^2 = .041$, nor for the ShimLoc, $F(1.37, 41.25) = 1.292$, $p = .275$, $\eta_p^2 = .041$. Moreover, these voice parameters did not differ between Forbrain® and control groups (ShimDB); $F(1, 30) = 0.134$, $p = .716$, $\eta_p^2 = .004$. ShimLoc; $F(1, 30) = 0.343$, $p = .563$, $\eta_p^2 = .011$, overall across the experimental sessions, and there was no Phase × Group interaction (ShimDB); $F(1.46, 43.95) = 2.745$, $p = .090$, $\eta_p^2 = .084$. ShimLoc; $F(1.37, 41.25) = 2.057$, $p = .154$, $\eta_p^2 = .064$, suggesting variations along the session in the irregularities of the voice sample, as measured with ShimDB and ShimLoc, were not dependent on the use of the device.

Finally, measures of the LTAS yielded different results for the slope (sLTAS; Figure 3E) and the tilt (tLTAS; Figure 3F). sLTAS values were not significantly affected neither by phase, $F(2, 60) = 0.228$, $p = .797$, $\eta_p^2 = .008$, nor by group, $F(1, 30) = 1.406$, $p = .245$, $\eta_p^2 = .045$, and no Phase × Group interaction was present, $F(2, 60) = 1.400$, $p = .255$, $\eta_p^2 = .045$. However, in the tLTAS, there was a strong significant interaction between Phase × Group, $F(2, 60) = 9.885$, $p = .001$, $\eta_p^2 = .248$. After applying the Bonferroni correction, this interaction remained significant ($p = .006$). The results obtained here, illustrated in Figure 3F, revealed a tonic decrease of tLTAS across the reading sessions (main effect of phase: $F(2, 60) = 11.763$, $p = .001$, $\eta_p^2 = .282$), whereas the use of Forbrain® prevented this effect to occur during its use; that is, for the Forbrain group, the measurements obtained in the baseline and test phases did not differ, $t(15) = 1.876$, $p = .08$, $d = 0.14$, whereas they did for the control group, $t(15) = 4.206$, $p = .001$, $d = 0.31$. This contrasted with the lack of differences for the control group between the test and posttest phases, $t(15) = 0.439$, $p = .667$, $d = 0.03$, whereas there was a clear decrease for the Forbrain group, $t(15) = 5.099$, $p = .001$, $d = 0.45$. This suggests that the use of Forbrain® softened the tLTAS of voice and, thus, enhanced the voice quality, at least during the short period of 14 min that lasted its use.

Discussion

This study was set as a proof of concept to investigate the potential effects of Forbrain® on voice production and to establish whether it could be considered as of clinical relevance in the areas of speech and language therapy as an AAF device. Forbrain® is a headset equipped with a microphone, which feeds the user back with his or her own voice during natural speech through a pair of bone conductors. According to its patent description (Guajarengues & Lohmann, 2015), Forbrain® applies to the voice input a dynamic, two-band equalizer filter, which is triggered by the user's voice energy at 1 kHz over a time window of integration ranging 10–200 ms. Moreover, the results reported here when comparing a test speech signal at the input (microphone) and the output (bone transducer) of Forbrain® have shown that the device indeed alters the input by changing its amplitude over the overall spectra and the spectrographic characteristics of the speech it processes (see Figures 1 and 2). Hence, by its technical specifications and the results provided herein, Forbrain® can be considered as a device that falls within the category of an AAF system. Previous studies have shown that delivering AAF in the amplitude/intensity domain, such as with the Lombard effect (Arciuli et al., 2013; Garnier et al., 2010; Stathopoulos et al., 2014), sidetone

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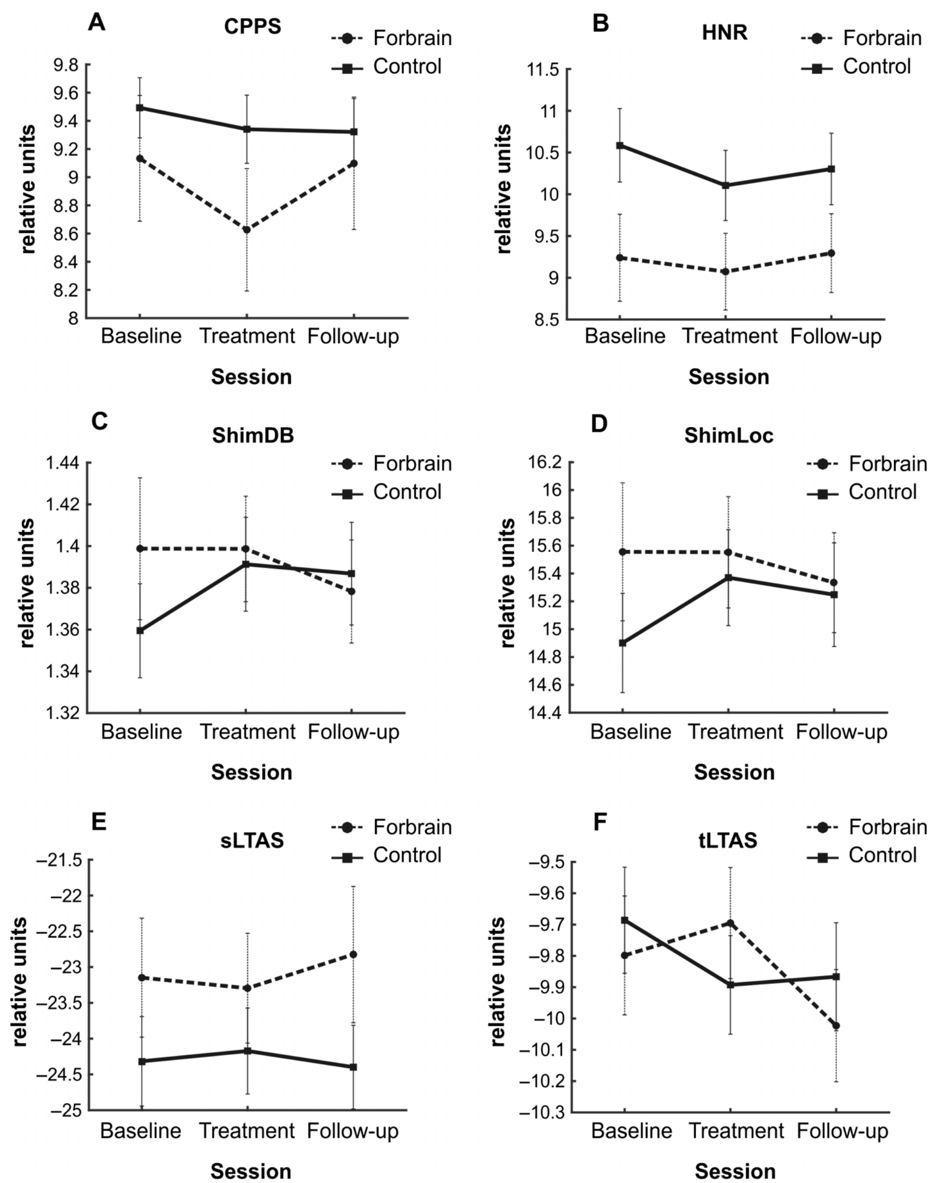
Figure 3. Voice quality measures. Participants' voice was recorded during reading aloud on three different phases: one serving as baseline (baseline; 7 min), one during the use of Forbrain® in the experimental group (treatment; dashed line) or during a placebo (same settings, Forbrain® device off serving as control; continuous line; 14 min), and one posttreatment (follow-up; 7 min). Six quantitative parameters of voice quality were determined for each of the reading phases: (A) the smoothed cepstral peak prominence (CPPS); (B) harmonics-to-noise ratio (HNR); (C) shimmer dB (ShimDB); (D) shimmer local (ShimLoc); (E) slope of the long-term average spectrum (sLTAS); (F) tilt of the trendline of the long-term average spectrum (tLTAS). Error bars show the standard error of the mean. Analysis of variance yielded a significant Group × Phase interaction for the tLTAS, and post-hoc analyses revealed that using Forbrain® enhanced tLTAS and attenuated CPPS, indicating that when Forbrain® is on, user's voice reacts to the device's feedback.



amplification (Bauer et al., 2006; Garber et al., 1976; Heinks-Maldonado & Houde, 2005), and feedback filtering (Burzynski & Starr, 1985; Garber et al., 1976, 1980, 1981), alters the speech of fluent speakers and those who stutter (Martin et al., 1984). Therefore, although not falling within the category of the most common and clinically used AAF manipulations, such as delayed auditory feedback, frequency-altered feedback, or masking noise, it is conceivable that Forbrain® provides some form of AAF capable to alter the speaker's voice and, hence, that it may have a relevant clinical utility as a general purpose AAF device. The purpose of this study was, thus, to gather some controlled empirical evidence on the potential effects of Forbrain®. We focused on fluent speakers and voice quality to avoid an effortful and costly study on a clinical population on a device not tested so far for effectiveness and to obtain a reliable and

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quantitative measure of fine-grained voice adjustment to challenge the potential effects of the device.

The participants in the present experiment were randomly assigned, in a double-blind manner, to either of two groups that underwent the same experimental protocol. This consisted of three runs of 7, 14, and 7 min, respectively, in which the healthy, young participants read aloud a text of their choice. All participants wore a Forbrain® headset during the whole experiment, the only difference between groups being that, for the long middle reading session (test phase), in half of the participants, the device was set on. Notice that for the other group of participants, the device remained off, yet a research assistant not involved in the data collection and analyses entered the room and manipulated the device with a similar handling as in the Forbrain group. This way, neither the participants nor the experimenters were aware of the condition being conducted (e.g., Forbrain® on or off). Participants' voice during the reading was recorded, digitized, and subsequently analyzed to derive six different quantitative parameters typically used in voice quality studies (Maryn et al., 2010; Maryn & Weenink, 2015).

The results obtained in this study were clear with regard to the effects of the use of Forbrain® during natural speech. Out of the six voice quantitative parameters analyzed, two of them yielded statistically significant results when comparing the two groups. Indeed, both the CPPS and the tLTAS resulted in significant Group × Phase interactions, indicating that, when using Forbrain®, participant's voice was significantly affected compared with baseline and postuse phases and with regard to the control group as well. Specifically, CPPS is a measure of the degree of harmony in a voice sample, so that it is larger when the voice signal is more periodic, and has been considered to indicate voice quality, particularly, breathiness (Heman-Ackah et al., 2002; Hillenbrand & Houde, 1996; Maryn et al., 2010). The results on CPPS revealed a attenuation in voice harmony and, hence, its breathiness, with time reading (significant effect of phase) across groups, as well as a further pronounced reduction in voice harmony in the Forbrain group when the device was turned on (signification Group × Phase interaction; see Figure 3A), indicating that Forbrain® further perturbed voice quality. Furthermore, results on tLTAS also revealed a specific effect of Forbrain®. The spectral trendline inclination tLTAS provides a measure that captures the average frequency distribution of the sound energy in a continuous speech sample (Maryn et al., 2010; Vaňková & Skarnitzl, 2014). In fact, it has been suggested that strong resonant voices present less differences between the strong and weak regions of the voice spectrum, whereas poor fluid voices present larger differences, and poor speaking voices have relatively lower sound level in the midfrequency range (1–3 kHz), whereas glottal closing speed has been related with less tilting slope of LTAS (Leino, 2009). Results regarding tLTAS revealed strong effects of phase across groups, with voice losing strength and becoming less fluid with time on reading across all reading phases. Remarkably, results also revealed a significant Group × Phase interaction, with Forbrain® users displaying a pronounced restoring of the tilt of the slope during the experimental phase, suggesting that Forbrain® use strengthened voice quality.

It is interesting to observe that the two effects of Forbrain® on voice quality obtained in the present experiment were in fact in apparent opposite directions. Indeed, the effects on CPPS, which reflects voice harmony, indicated reduced voice breathiness with the use of Forbrain®, whereas the effects on tLTAS, which is thought to reflect voice robustness, suggested strengthening of the voice during Forbrain® use. However, an interpretation of these effects in the context of the neural circuits of the phono-articulatory loop may help to clarify this apparent contradiction and, in fact, to support Forbrain®, together with its functionalities proved here, as a device that provides AAF. Indeed, there is increasing evidence that sensory processing is altered as a consequence of motor adaptation to altered visual, somatosensory, and auditory feedback (Ostry & Gribble, 2016), and conversely, motor output is fine-grained adjusted as a consequence of distorted sensory input (Hahnloser & Narula, 2017). These findings consist of the so-called *corollary discharge view* of motor control, according to which the motor (e.g., vocal) system sends an efferent copy or corollary discharge of the sound it aims producing, so that the encoding of the auditory input resulting from the self-produced sounds is attenuated in the auditory system (Scott, 2013; Wolpert, Ghahramani, & Jordan, 1995). This way, the auditory system implements a neurophysiological mechanism that allows it to recognize the self-emitted sounds and to disregard them from further processing, leaving the processing resources for the externally generated sounds (SanMiguel, Widmann, Bendixen, Trujillo-Barreto, & Schröger, 2013), with the obvious adaptive and communicative advantages. However, when the received input does not match the efferent copy of the motor command, a prediction error is generated (Hahnloser & Narula, 2017) that forces a system readjustment. The pattern of results obtained with Forbrain® in the present experiment nicely fits this model. Indeed, the effects observed on CPPS indicating reduced voice harmony support a perturbation of voice control caused by the altered feedback of the ongoing speech fed to the model, whereas the parallel increased voice strength during Forbrain® would indicate an attempt of the audio-vocal loop to compensate for the voice perturbation caused by the altered feedback. Although this is a conceivable interpretation of the data, future experiments should aim at identifying the underlying processes involved in this pattern of effects.

Conclusions

This study investigated, in a double-blind controlled design, the potential effects of Forbrain® on quantitative parameters of voice during natural speech, on a sample of normal-speaking adults. It was found that turning the device on induced changes in voice quality, in particular, a reduction in voice harmony paralleled by a strengthening of voice robustness. Based on its observed functionalities and the results obtained herein, it seems that it has been proven that Forbrain® provides AAF to its users and,

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therefore, that it could be considered as a low-cost option in treatments with AAF on a range of speech, language, and communication disorders. Further clinical studies should aim to validate its usefulness in clinical settings.

Acknowledgments

This research was supported by Sound For Life Ltd (Soundev) and partially by the Catalan Government (SGR2014-177), the Spanish Ministry of Economy and Knowledge (PSI2015-63663-P-MINECO/FEDER), and the ICREA Academia Distinguished Professorship awarded to Carles Escera. Natàlia Gorina-Careta and Carles Escera conceived the design. Fran López-Caballero performed the research. Fran López-Caballero analyzed the data. Fran López-Caballero and Carles Escera interpreted the results. Fran López-Caballero, Natàlia Gorina-Careta, and Carles Escera wrote the article.

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