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Recording the human brainstem frequency-following-response in the free-field

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HIGHLIGHTS

- A novel and reliable methodology for collecting human auditory brainstem frequency-following response (FFR) in the free field is proposed.
- It is possible to collect FFRs using free field stimulation.
- The FFRs collected using free and close-field stimulation are comparable in terms of the intrinsic, acoustical and reliability properties of the neural signal.

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ABSTRACT

Background: The human auditory brainstem frequency-following response (FFR) is an objective measure used to investigate the brainstem's encoding ability of sounds. Traditionally, FFRs are recorded under close-field conditions (earphones), but free-field stimulations (loudspeaker) have yet to be attempted, which would increase the applications of FFRs by making this technique accessible to those who cannot wear inserted transducers. Here we test the feasibility and reliability of measuring speech ABRs across free and close-field.

New method: The FFR was evoked by a 40-ms consonant–vowel (cv) /da/ syllable which was presented in the standard close-field conditions with insert earphones, and in a novel free-field condition via a loudspeaker.

Results: A well-defined FFR was observed for each stimulating method (free or close-field). We show that it is possible and reliable to elicit FFRs from a speaker and that these do not systematically differ from those elicited by conventional earphones.

Comparison with existing method: Neural responses were subjected to a comparative within-subjects analysis, using standard measures found in the literature in order to quantify and compare the intrinsic (*amplitude, noise, consistency*), acoustic (*latency, spectral amplitude*) and reliability properties (*intraclass correlation coefficients and Bland and Altman limits of agreement*) of the neural signal.

Conclusions: Reliable FFRs can be elicited using free-field presentation with comparable to acoustical, intrinsic and reliability properties as those elicited by standard close-field presentations.

1. Introduction

The human auditory brainstem frequency-following response (FFR; sometimes referred to as complex ABR) is an objective and non-invasive electrophysiological measure used to investigate the brainstem's encoding ability of spectral and temporal features of sound (Kraus and White-Schwoch, 2015; Skoe and Kraus, 2010). This technique originates from the clinically used auditory brainstem response and is increasingly being used in hearing research (Krizman et al., 2010; e.g., Russo et al., 2004; Sinha and Basavaraj, 2010). Moreover, clinically relevant outcomes such as reading skills (Banai et al., 2009), music abilities (Lehmann et al., 2015a; Liu et al., 2015) and learning difficulties (Johnson et al., 2005; Song et al., 2008) have now been linked to subcortical auditory function using FFRs. Since the neural recording closely mimics the stimulating

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waveform and is of very small amplitude (about 1 μV), it is very sensitive to electrical artefacts that can potentially creep into the recording via the acoustic transducer (Skoe and Kraus, 2010). For this reason, recording FFRs requires the use of insert earphones and careful magnetic shielding of the transducers' signal pathway, but the necessary shielding is not present in research systems, often built in-house by each laboratory. Akhoun et al. (2008) measured electromagnetic leakage on several types of close-field transducers and showed that shielded insert earphones were the only transducers that allowed artefact-free recordings, provided these would be linked to a common ground.

Presently, many auditory evoked potential (AEPs) research laboratories and audiology clinics use free-field stimulation in their neural recordings. Indeed, free-field stimulus presentation is routinely used for auditory cortical AEPs (Shafer et al., 2015; Teder-Sälejärvi et al., 1999; Wilkinson et al., 1966), however, it is currently unknown if it is possible to collect FFRs in the free-field. Compared to cortical potentials, brainstem responses have a much smaller amplitude (10–100 fold) and require higher temporal precision than the slower cortical waves (e.g. a 1 ms difference in wave V peak latency is clinically relevant to diagnose a hearing pathology, Jerger and Johnson, 1988). Compared to close-field stimulation, free-field presentation may distort the signal through reverberation and small head movements could introduce delays in arrival time at the ears. Furthermore, recording FFRs using free-field stimulation would allow assessing special populations that would otherwise not benefit from this technique. For instance, hearing-aid listeners and cochlear-implanted individuals, who require the use of their hearing device in order to measure its benefit and performance, cannot be tested using insert earphones. Other populations such as otitis media sufferers, collapsed ear canals or individuals with pinna malformations, where it is impractical (or impossible) to insert an earphone, would also benefit from recording this procedure in a free-field environment. Furthermore, individuals who do not tolerate the use of insert earphones (such as autistic and low-functioning individuals) could also profit from a free-field presentation of signals.

Here, we asked whether the human auditory brainstem frequency-following response can be measured using free-field presentation and how it compares to the traditional closed-field method. To do so, we recorded FFRs in response to a /da/ syllable. This consonant–vowel (cv) /da/ syllable from Kraus and colleagues (see Skoe and Kraus, 2010 for a review) is one of the most extensively studied speech syllables to date. To test the feasibility of collecting FFRs, we compared all aspects of the response when stimuli were presented using a commercially available loudspeaker (free-field) to the response acquired using a shielded insert earphone (close-field). More specifically, using a within-subjects design, we replicated the most widely used FFR paradigm in order to quantify and compare the intrinsic (*amplitude, noise, consistency*), acoustic (*latency, spectral amplitude*) and reliability properties (*intraclass correlation coefficients and Bland and Altman limits of agreement*) of the neural signal. This is the first study to date that attempts to record speech ABRs in free-field conditions, thus contributing to a wider inclusion of this technique in both research laboratories and clinics.

2. Methods

2.1. Participants

Twenty-three normal-hearing adults (6 males) aged between 19 and 40 (mean = 28 and SD = 5 years), with no history of hearing disorders participated to this study. All gave written informed consent and had thresholds lower than 20 dBHL at five frequencies (250 Hz; 500 Hz; 1000 Hz; 2000 Hz and 4000 Hz) as measured by air conduction pure tone audiometry and had no history of hearing loss. Data from three participants were excluded from the study due to noisy EEG recordings.

The project conformed to the World Medical Association's Declaration of Helsinki and was approved by the Research Ethics Committee of the Faculty for Arts and Sciences of the University of Montreal.

2.2. Stimulus

We used one of the most extensively studied speech syllables to date from Kraus and colleagues (Lehmann et al., 2015a; Skoe and Kraus, 2010), the 40 ms consonant–vowel (cv) /da/ syllable, created with a Klatt-based synthesizer. The neural response is characterized by a transient onset response peak that corresponds to the stop burst (/d/) and is associated with the consonant to vowel transition. The sustained response that follows is called the frequency following response (FFR) and results from phase-locked activity of the brainstem to the periodicity of the vowel (Johnson et al., 2005; or Kraus and White-Schwoch, 2015 for a review; /a/; Krishnan, 2002; but see Skoe and Kraus, 2010). This stimulus has been previously described in Skoe and Kraus (2010) and Song et al. (2011a,b), but shortly, the voiced transition has a fundamental frequency (F0) that rises linearly from 103 to 121 Hz with voicing beginning at 5 ms and the onset noise burst occurring during the first 10 ms.

2.3. Procedure

In each condition (free-field or close-field), four thousand repetitions of the /da/ stimulus were presented at a rate of 11.1 Hz, with alternating polarity (Lehmann et al., 2015a; Skoe and Kraus, 2010). Depending on the condition being tested, stimuli were delivered either via one loudspeaker (Genelec 8040A Bi-Amplified Monitoring System) placed directly in front at one meter away from the subjects' head, or binaurally via a pair of insert earphones (E-A-R Tone 3A, 3 M Indianapolis, IN). Participants sat comfortably in a reclining chair inside a faradized soundproof room and were instructed to relax and watched a self-selected subtitled movie (to prevent drowsiness and minimize motion; Skoe and Kraus, 2010) from a laptop computer running on battery power. The computer was positioned below and 10 cm behind the speaker frontal edge (to avoid shadowing of free-field sound). The order of the conditions (close-field and free-field) was counterbalanced across participants. The stimulus was driven by a programmable digital signal processor hardware (Tucker Davies Technology, Alachua, FL, USA), controlled by a custom Matlab routine (The Mathworks, Inc., Natick, MA).

2.4. Intensity and temporal calibrations

In both close and free-field conditions, sound was calibrated to be presented at 70 dB SPL at the level of each ear, using a Sound-Pro sound level meter (model DL 1/3 Octave Datalogging RTA) and using a 2-CC ear coupler for insert earphones calibration. Calibration measurements were done using a fast rate mode with an A-weighting frequency filter. Because travel time of the signal differs across presentation conditions (e.g. hardware response times, sound propagation through air or tubes, etc.), we measured the time difference between the occurrence of a digital trigger and the actual sound arrival at the level of the ear using Biosemi Analogue Input Box connected to a Sure SM 58 microphone. The system delay obtained for each condition was used to correct the time-axis of recorded brain signals accordingly. Since, we measure the system delay from the TDT hardware to the subject's ear via the two signal chains (earphone chain and loudspeaker chain), any delay caused

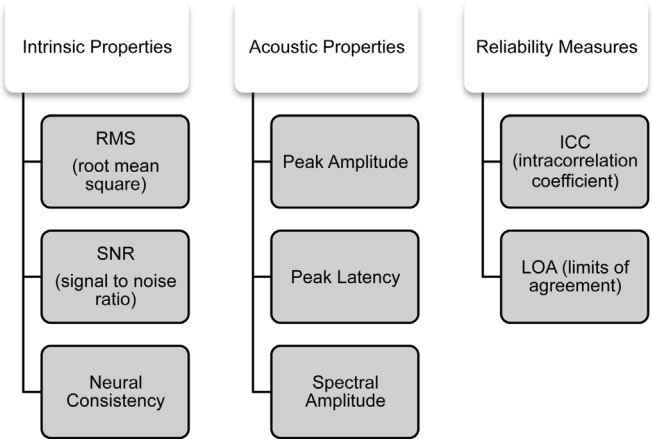

Fig. 1. Analysis of EEG data was done in three large areas (intrinsic, acoustic and reliability). Each area comprised some of the most common measures for treating speech ABRs.

by the circuitry, diaphragm size and air travel time was removed so that any temporal differences would result from neural activity in response to the external stimuli.

2.5. Electroencephalography (EEG) Recording

EEG was recorded using BioSemi active electrodes in a classical vertical montage of five sintered Ag/AgCl electrodes (central vertex as active and left and right mastoids as reference). The last two electrodes were placed between P03 and P0z (common mode sense; CMS) and P0z and P04 (driven right leg; DRL) and formed a feedback loop replacing the ground electrodes found in conventional EEG systems (BioSemi, Amsterdam, Netherlands). This active system has the first amplifier stage integrated within the electrode, performing an impedance transformation directly on site and providing a better solution for the problem of voltage cross-talking. For this reason, we did not control for electrode impedances but instead kept direct current offsets close to zero (under 50 mV) during the placement of the electrodes (Lehmann et al., 2015a). Signals from the electrodes was further amplified by a BioSemi ActiveTwo amplifier (BioSemi), sampled at 8192 kHz and stored using the BioSemi recording software ActiView for offline analysis.

2.6. Data pre-processing

Analysis of the FFR was conducted using custom routines in Matlab 2014a (The MathWorks Inc, Natick, Massachusetts, US), EEGLAB (Delorme and Makeig, 2004), bt_fftsc from the Brainstem Toolbox (Skoe and Kraus, 2010) and the ERPLAB plugin (Lopez-Calderon and Luck, 2014). Responses were re-referenced offline to the average of the recordings from both mastoid and filtered using a Butterworth filter with a 12 dB roll-off and a 100 Hz high pass filter and a 1000 Hz low pass filter. Signal timeline was corrected to compensate for the delays introduced by the two sound delivery methods. The data was then epoched into 90 ms windows (−10 ms to 80 ms relative to stimulus onset). Trials with activity greater than 35 μV were considered artefacts and rejected from further analysis.

2.7. Data analysis

Several statistical measures were administered to our data and divided into three groups for ease of presentation (Fig. 1). For each condition and each participant, sub-averages were computed from the epoched signals for each polarity. FFRs were obtained by averaging together those polarity sub-averages, in order to minimize the cochlear microphonic and stimulus artefacts (Lehmann et al., 2015a; Skoe and Kraus, 2010).

2.7.1. Intrinsic properties

From the individual FFR obtained for each condition, we computed the root mean square (RMS), signal-to-noise ratio (SNR), as well as the amplitude and latency of prominent peaks. The post-stimulus onset window corresponding to the steady-state portion of the FFR was 20 to 60 ms. This window duration was chosen in order to make sure that the entirety of the neural response was included in the analysis. SNR was computed as the ratio between the RMS of the FFR and the RMS of the noise in a window of −10 to 0 ms relative to stimulus onset. RMS and SNR measures were subjected to a paired sample *t*-test to test whether both measures were significantly different when recorded under different sound delivery conditions. We also performed the same analysis to the pre-stimulus window [−10 to 0 ms].

We also computed the neural consistency of individual FFRs. This measure assesses the extent to which the brainstem's representation of sound varies from trial to trial and has been linked to several cognitive abilities (Kraus and White-Schwoch, 2015; language proficiency Krizman et al., 2014; Skoe and Kraus, 2013; tapping to a beat Tierney and Kraus, 2013). We followed standard procedure in order to compute response consistency (Hornickel and Kraus, 2013); the FFR portions of the neural signal from each individual and for each condition were split into even-odd halves (also taking into consideration both alternate polarities). Even trials were then correlated to odd trials with *r* values close to 1 representing a more consistent sub-average. A paired *t* test was used to compare response consistency between close or free-field delivery methods.

2.7.2. Acoustic properties

For the latency analysis the prominent on-going peaks were identified in the grand average of the individual neural responses. We followed the nomenclature used by Lehmann et al. (2015a,b) to classify the peaks, but other nomenclatures can also be found in the literature (e.g. see Figure 1 of Skoe and Kraus, 2010; or Song et al., 2011a,b). Nonetheless, both nomenclatures acknowledge the existence of seven distinct response peaks: peak 1 corresponds to the neural response to the onset of the sound; wave 2–3 complex correspond to the transition between stop burst and the onset of voicing; peaks 4 to 6 correspond to the neural phase-locking to f0 and its harmonics; and peak 7 corresponds to the offset response. For each condition, the latencies of the grand average were then used to guide the peak detection performed for each subject by visual identification. A peak was coded 'not reliable, nr' if visual observation revealed that the peak's amplitude was not above the pre-stimulus amplitude and was removed from the analysis. Waves 1–7 were visually identified and their amplitudes and latencies were measured. A paired sample *t*-test was used to test if amplitude and latencies differ significantly between close and free-fields.

Response amplitudes in the spectral domain were computed for the FFR portion of the response (20 to 60 ms) using the function bt_fftsc from the Brainstem Toolbox (Skoe and Kraus, 2010). This function first obtains the Fast Fourier Transform of the FFR (using a Hanning window and zero padding) and then computes the average amplitude in the specified frequency range. Average spectral amplitude was calculated for four different windows of interest: f0 (90 to 140 Hz), first harmonic (H2, 200 to 300 Hz), second harmonic (H3, 305 to 395 Hz) and higher harmonics (HH, 400 to 750 Hz). A two-way factorial ANOVA with stimuli delivery condition (close or free-field) as the within subjects factor was used to analyse the differences between the two methods.

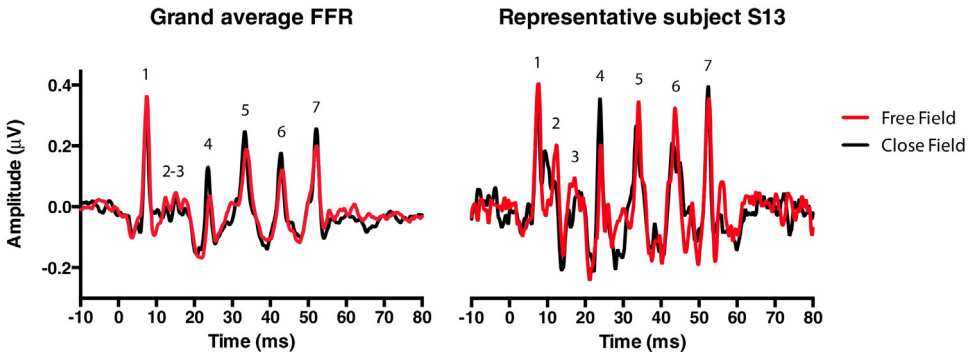

Fig. 2. FFR in free and close fields. Left: Grand average frequency following auditory brainstem responses to speech syllable /da/ in the time domain. Right: Average responses for a representative participant. A clear FFR was observed for all participants, comparable in free and close field. Peaks 1–3 is onset response and peaks 4–7 is the FFR offset response.

2.7.3. Reliability

Intraclass correlation coefficients (ICCs) and limits of agreement (LOAs) were used to examine the agreement between the two methods (Weir, 2005). First, to test the degree of agreement between the independent variables (close and free-field), the ICCs were computed (McGraw and Wong, 1996; Shrout and Fleiss, 1979; Weir, 2005). Broadly, ICCs are a measure of the amount of variance between two or more objects of measurement and are commonly used to assess agreement between two quantities. ICCs are a more suitable measure to compare neural data acquired under different stimuli conditions as the Pearson's correlation coefficient tests the strength of the linear relationship between two objects of measurements, and not their agreement. Thus, it is possible to have a strong linear correlation with poor agreement (Bland and Altman, 1986).

A two-way mixed effect model was used due to the fixed effect of independent variables. This corresponds to the case 3 model ICC[C,k] from McGraw and Wong (1996). Additionally, further analysis revealed that the intraclass correlation coefficients remained largely unchanged when other models were applied. This agreement between models is largely due to the relatively small differences between mean and standard deviations of the two objects of measurement (Tomarken et al., 1992). Because there is currently no standard to assess ICC scores, we used the criteria from Arnall et al. (2002): 0.69 or below is poor, 0.70–0.79 fair, 0.80–0.89 good and 0.90–0.99 high reliability.

ICCs take into account inter and intrasubject variability, however, it does not directly convey any information regarding the level of variability between subjects. Since knowing subject variability is clinically relevant to the practitioner, Bland and Altman (1990) limits of agreement (LOA) were calculated to complement the results from the ICC computations. Because stochastic portions of the neural response (e.g. noise) will decrease the agreement between measures, LOA were plotted for amplitude and latency measures of peak 1, the onset of neural response. These plots show the difference between methods against their mean, thus, being possible to observe if one method is over or underestimating the other, and to quantify it.

3. Results

A well-defined FFR was observed in each participant (see Fig. 2 shows the grand average of a representative participant [right] and of the entire group [left] in close and free-field conditions). Numbers 1–7 correspond to the peaks as classified by Lehmann et al. (2015b). Peaks 1–3 correspond to the onset response and peaks 4–7 correspond to the FFR offset response. The recorded responses appear remarkably similar between close and free-field conditions, a trend that was confirmed by the statistical analysis of all the aforementioned intrinsic, acoustic and reliability measures.

3.1. Intrinsic properties

The root mean square (RMS) values of the FFR was comparable between close ($M = 0.13$; SD = 0.04) and free-field ($M = 0.13$; SD = 0.05): $t(19) = 0.298$, $p = 0.77$. The RMS of the noise (prestimulus interval) was also identical in both free-field ($M = 0.3$, SD 0.01) and close-field 0.3, SD = 0.09), $t(19) = 1.98$, $p > 0.05$. Signal-to-noise ratio was also comparable across conditions (SNR; Fig. 3) with $M = 12.73$; SD = 4.06 and $M = 13.06$; SD = 5.26, respectively: $t(19) = 0.37$, $p = 0.71$. Brainstem responses showed similar inter-trial neural consistency (Fig. 3) for close-field ($M = 0.86$; SD = 0.14) and for free-field ($M = 0.88$; SD = 0.07): $t(19) = 0.57$, $p = 0.58$.

3.2. Acoustic properties

Both spectral and timing acoustic properties were successfully preserved in free-field.

Spectral encoding of the speech stimuli /da/ around f0 and subsequent harmonics (Fig. 4) does not seem to differ between deliver methods. There was no interaction, $F(3, 176) = 0.088$ $p = 0.97$. As expected, there was a main effect of harmonic band, indicating that the spectral power differed in each frequency band regardless of the stimulus being delivered in close or free-field, $F(3, 176) = 64.48$, $p < 0.0001$.

Peaks 1 and 7 were identified in 90% of our sample for both stimuli delivery conditions. The remaining peaks were only present in

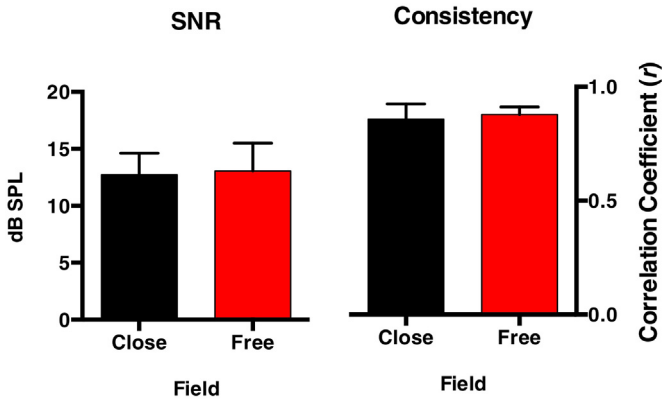

Fig. 3. Intrinsic properties of the brainstem FFR. Average signal-to-noise ratio (SNR; left) and neural consistency (right). No differences were found between free and close fields. Error bars are 95% CI.

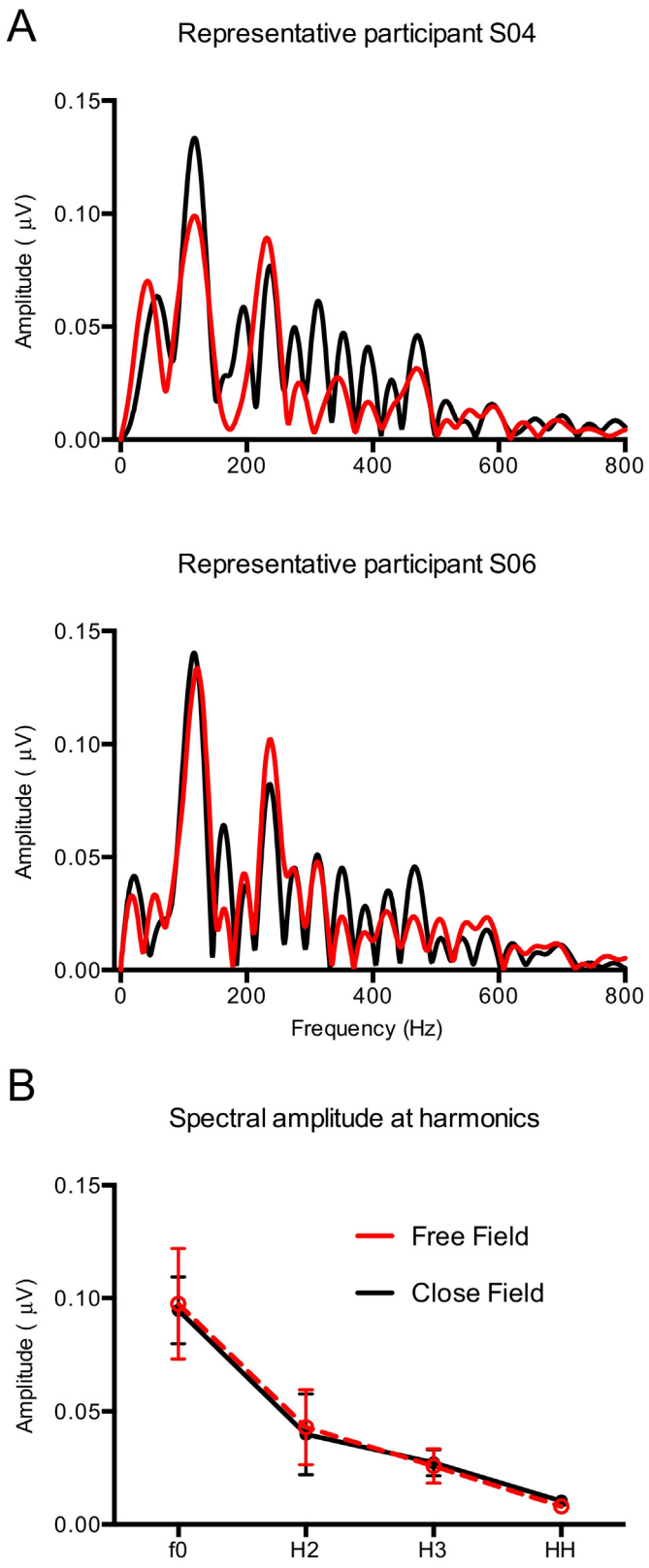

Fig. 4. Spectral amplitude. (A) Fast Fourier Transform (FFT) of average ABRs for two representative participants. (B) Mean spectral amplitudes around the fundamental frequency (F0), the second and third harmonics (H2 and H3) and higher harmonics (HH) are shown. Error bars represent 95% CI. Close field in solid grey line and free field in red (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

up to 80% of the participants; thus, acoustic properties were compared for peak 1 and 7 only (Table 1). The result of the Student's *t* statistic for close and free-field show that there was no significant difference found in amplitude (peak 1: $t[17] = 1.3$, $p = 0.23$; peak 7: $t[17] = 0.61$, $p = 0.55$) nor latency (peak 1: $t[17] = 0.95$, $p = 0.35$; peak 7: $t[17] = 0.58$, $p = 0.57$). There were also no significant differences in inter-wave latency between these two delivery methods ($t[17] = 1.1$, $p = 0.30$).

3.3. Measures of reliability

The ICC scores report a high degree of reliability and agreement between free and close-field conditions with the 95% confidence intervals indicating an excellent reliability between the repeated measures ($M = 0.94$, 95% CI [0.93, 0.95]). The limits of agreement (LOA) plot the difference between free-field and close-field in the ordinates and the mean values for free and close-field in the abscises (Fig. 5). The line of equality, a dashed black line that at 0 in the ordinates axis, should show for instance in the case of a true agreement, data points scattered closely around it (or on top of it in the case of zero variability between measures). For peak 1 amplitude (Fig. 5 left), the mean difference estimate is 0.039 μV, which could indicate that measurements under free-field measure on average 0.039 μV higher than measurement made under close-field. Hypothesis testing indicates, however, that such difference is not significant, thus, there is no need to correct values measured under free or close-field. The same is true for the LOAs for latency ($M = 0.075$ ms), which follows the trend that that free-field stimulation is comparable to close-field in all aspects, whether intrinsic, acoustic, or of reliability.

4. Discussion

The present study aimed to record FFRs in the free-field, and to compare the neural response to an already established close-field method of stimulation. We have shown that collecting FFRs in free-field is a viable solution: the obtained recordings are highly comparable to close-field recordings and there were no significant differences between stimulating fields. We have compared both methods in terms of derived intrinsic properties (*signal amplitude, noise and consistency*), acoustic properties (*wave latency and spectral amplitude*) and reliability (*intraclass correlation coefficients and Bland and Altman limits of agreement*). When considering the intrinsic properties of the neural recording, we show that free field recordings present identical noise and amplitude levels to those of close field. RMS was used to assess the overall response magnitude of the FFR with neural recordings in free and close-field presenting matching values. However, for the purpose of comparing the two methods, RMS amplitude is more relevant when compared to the RMS amplitudes of the pre-stimuli period (RMS of noise), since it is possible for two neural recordings to have equivalent RMS amplitudes but different noise levels. Thus, the SNR, expressed as the quotient between the RMS amplitude of the FFR portion and the RMS amplitude of the pre-stimulus baseline (noise), was calculated to establish if one method presents more noise than the other. The SNRs shown here are comparable and even superior to the typical range for speech ABRs seen in the literature (Bellier et al., 2014; 3–8 dB, Skoe and Kraus, 2010; Song et al., 2011a,b). Comparing the RMS amplitudes found in the present study to the ones reported in the literature, we show comparable and even superior RMS values (0.09 μV, e.g. Song et al., 2011a,b). The fact that there were no significant differences between both methods demonstrates that in terms of RMS amplitude and SNR, the two methods perform equally well. Furthermore, we report a high neural consistency score in the free-field that is not sig-

Table 1
Mean and standard deviations (SD) for amplitude and latency measured in peaks 1, 7 and inter-wave latency 1 to 7. Peaks were identified reliably in 90% of subjects.

	Amplitude (μV)				Latency (ms)			
	Close field		Free field		Close field		Free field	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Peak 1	0.36	0.091	0.40	0.039	7.3	0.31	7.4	0.32
Peak 7	0.31	0.078	0.29	0.15	52	0.27	52	0.80
Inter-peak 1–7	–	–	–	–	45	0.17	45	0.68

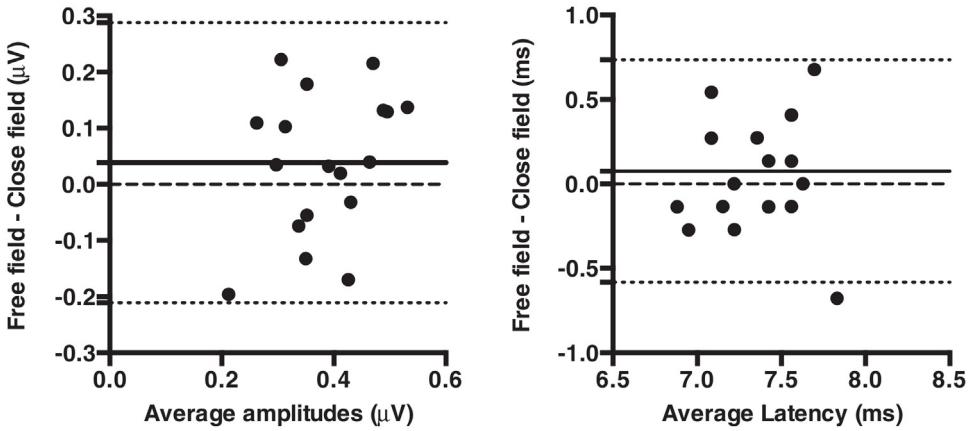

Fig. 5. Bland and Altman limits of agreement (LOA) plots for amplitude (left) and latency (right) of peak 1, the onset of the neural response. Solid line represents the mean difference estimate (0.039 μV for amplitude and 0.075 ms for latency). Dashed line represents the line of equality and dotted lines are the upper and lower 95% limit of agreement.

nificantly different from the consistency scores obtained in the close-field condition. We demonstrated that both methods have consistent sub-cortical responses that are equally reliable across trials. Since neural consistency is a useful marker to distinguish expert groups (such as bilinguals and musicians) from populations with biological disorders (e.g. dyslexics; Krizman et al., 2014; Skoe and Kraus, 2013), and has been credited in the past as the biological contributor to reading impairment between normal and dyslexic children (Hornickel and Kraus, 2013), extending the FFR acquisition to the free-field will increase the clinical applicability of this technique. Regarding the acoustic properties of the neural response, the FFRs recorded under free field were shown to have matching acoustic properties to the conventional shielded insert earphones. Spectral amplitudes around the fundamental frequency and subsequent harmonics (Fig. 4B) were highly comparable across delivery type. Furthermore, peak 1 latencies (M = 7.3 ms for close field and M = 7.4 ms for free field) and amplitudes (M = 0.36 for close field and M = 0.40 for free field) are equivalent and within the typical values found in previous studies (M_lat = 6.6 ms, M_amp = 0.31 μV Russo et al., 2004; M_lat = 7.02 ms Skoe and Kraus, 2010). This indicates that the spectrotemporal encoding at the brainstem is reliably preserved in free-field conditions and is within reported values. This has also been confirmed by the measures of reliability, such as the ICCs and LOAs, Fig. 5. When interpreted in combination, these two measures report an excellent agreement between the two methods, confirming the robustness of the FFR technique and suggesting that the FFR in the free-field is a viable option in situations where close-field stimulation is impractical or impossible. This study supports the notion that FFRs (whether recorded in free-field or close-field) are readily available, albeit, perhaps only in laboratories with expertise in signal processing. Further testing is required before the free-field method can be recommended for clinical use and should take into consideration that a high precision programmable hardware was used for stimuli production (Tucker Davis Technologies, FL) in the present study. It is possible that the relative and absolute peak latencies may differ if stimuli are played via a computer based system (which are known to introduce jitter; Skoe and Kraus, 2010). Furthermore, the present study was conducted in a sound-treated room to minimize the deleterious effects of room acoustics, such as reverberation. It is well known that reverberation hinders speech perception and has direct impact in the SNR by overlapping and masking the intended signal (Bidelman and Krishnan, 2010; Culling et al., 2003; Yang and Bradley, 2009). Most audiology clinics and hearing laboratories today are equipped with sound treated rooms; nevertheless, reverberation was further controlled in the present study with the subjects' distance to the sound source fixed at 1 m. Further investigations in different room environments would help understand the viability of speech ABRs in free-field.

In the past, FFRs recorded to the speech syllable /da/ have been found to be highly replicable, even over a one year period (Hornickel et al., 2012). In summary, reliable FFRs can be elicited using free-field presentation with comparable to acoustical, intrinsic and reliability properties as those elicited by standard close-field presentations. Taken together with the results of this study, the FFR can be thought of a very robust technique, replicable over time and across methodologies. But, it remains unclear if free-field recordings can retain the same temporal fine structure of faster responses, such as the clinical ABR (which is regularly recorded in the close-field). Future research would be necessary to investigate whether transient ABRs (elicited by clicks or tone pips), which requiring a higher temporal precision that speech ABR, can be reliably recorded using free field stimulation and up to which sampling rate. Answering this question could present a new approach to the traditional ABR recording, thus making it more accessible to populations who cannot use close field transducers. Furthermore, systematic comparisons between close and free-field were never attempted with cortical AEPs, thus, even though both methods of stimulation are commonly used to evoke the response (e.g. close-field, Näätänen et al., 2004; e.g. free-field, Winkler et al., 1998), it is open for debate

which method yields better recordings or even in which situation should a free-field recording be attempted over a close-field one, or vice-versa. Clarifying these notions could help standardize the collection of AEPs, which in turn would allow better comparisons of results between studies.

Conflict of interest statement

None of the authors have potential conflicts of interest to be disclosed.

Ethical standards agreement

I have read and have abided by the statement of ethical standards for manuscripts submitted to the Journal of Neuroscience Methods.

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