Acoustic match to electric pulse trains in single-sided deafness cochlear implant recipients

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Ten cochlear implant users with single-sided deafness were asked to vary the parameters of an acoustic sound played to their normal-hearing ear, in order to match its perception with that of the electric sensation of two electrodes (e14 and e20). The experiment was divided into 3 consecutive conditions in which the parameters of the acoustic sound varied. The participants had to vary i) the frequency of a pure tone (Exp. 1), ii) the center frequency and the bandwidth of a filter applied to a harmonic complex sound (Exp. 2), and iii) the based frequency (Fb) and the inharmonicity factor of a complex sound (Exp. 3). The results were averaged across participants, and compared within conditions. The pitch sensation for e14 and e20 was significantly different (Exp. 1). In Exp. 2, only the center frequencies of the band-pass filters were significantly different, not the bandwidth. In Exp. 3, the average F0s were not significantly different; The inharmonicity factor was 1.7 for both electrodes. The results of this study suggest that the sound sensation of different electrodes is more linked to a difference in timbre (brightness) than to a difference in pitch, and that the sound is more similar to an inharmonic complex sound than to a pure tone or a white noise.

INTRODUCTION

Cochlear implants (CI) can restore auditory perception in severely and profoundly deaf patients by bypassing the deficient auditory cells and electrically stimulating the auditory nerve. Over the years, technological upgrades and new coding strategies have improved speech perception and overall sound quality. Although CIs are nowadays widely used and can successfully restore speech perception, it is still unclear how the electric stimulation actually sounds like.

Vocoders have been developed to mimic the information provided to the CI user. Simulations with less than 8 channels presented to normal hearing listeners provide speech intelligibility scores in the same range as CI patients (Blamey *et al.*, 1984; Shannon *et al.*, 1995). Despite this good correspondence, some researchers argue that

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Proceedings of the International Symposium on Auditory and Audiological Research (Proc. ISAAR), Vol. 6: Adaptive Processes in Hearing, August 2017, Nyborg, Denmark. Edited by S. Santurette, T. Dau, J. C.-Dalsgaard, L. Tranebjærg, T. Andersen, and T. Poulsen. The Danavox Jubilee Foundation, 2017.

ISBN: 978-87-990013-6-1.

the vocoded information does not offer the same sound quality as that of CIs and suggest the existence of perceptual and informational discrepancies between CI stimulation and performance-matched acoustical simulations (Aguiar *et al.*, 2016; Mesnildrey *et al.*, 2016). Thus, similar level of performance obtained for both real and simulated CI may hide different patterns of errors, limiting the validity of acoustic simulations through vocoders to evaluate new coding strategies.

Some studies tried to match the perception evoked by the CI with an acoustic sound played to the non-implanted ear. Most studies focused on pitch perception (pure tone) in CI patients with residual hearing (bimodal rehabilitation) or normal hearing in the non-implanted ear (single-sided deafness) (for example Carlyon *et al.*, 2010; McDermott *et al.*, 2009), offering a valuable insight on the effect of mismatch between the frequency allocation table of the CI processor and the actual placement of the electrode-array along the cochlea. However, in the late 70s, Eddington *et al.* (1978) evoked that the sound sensation of an electric stimulation was rather a complex sound than a pure tone. Recently, this hypothesis was tested in CI users with residual hearing in the non-implanted ear (Lazard *et al.*, 2012). By modifying the fundamental frequency (F0), bandwidth, centre frequency, and the inharmonicity of the acoustic stimulus, it resulted that the percept given by the stimulation of a single apical electrode did not correspond either to a white noise or a pure tone, but more to an inharmonic complex signal. However, the “reference” ear being impaired (average hearing thresholds between the participants: 65 dB at 500 Hz), the matched acoustic sounds may have been distorted. With the emergence of patients implanted with a normal ear on the contralateral side, we had the opportunity to reproduce and extend to a more basal electrode this latter result. Our aim was to find a more precise and realistic acoustic match of a single pulse train played to an apical and a medial electrode, in patients with single-sided deafness, i.e., with a normal ear used as reference.

METHODS

Participants

Twenty-six adults with a dead ear were enrolled in a larger study about unilateral cochlear implantation. A sub-sample (n=10) was randomly selected from two French centres that participated in the whole study (Hôpital Rothschild, Paris, and Hôpital Ponchaillou, Rennes). The two projects conformed to The Code of Ethics of the World Medical Association (Declaration of Helsinki), and were approved by the Ethic committee of CPP Ile de France V. Each participant, enrolled in the present study, signed an informed consent form about the main project, and about this supplementary protocol. The experimental design of this study was largely inspired from Lazard et al. (2012).

The participants were all tested in a sound attenuated booth, they had normal or near-normal hearing in the non-implanted ear; The implanted ear was a dead ear responsible for severe tinnitus. The average hearing threshold of the non-implanted ear, calculated from the pure tone audiometric thresholds at 500, 1000, 2000, and 4000

Hz, was 24 dB ± 7 standard deviation. For six participants, testing was done after 3 months and 12 months of CI use. One participant performed the three-month session only, and the three remaining participants performed the twelve-month session only. All participants were users of Oticon Medical devices (internal part: Digisonic SP EVO, with the Saphyr Neo SP speech processor and Crystallis XDP sound-processing strategy).

Stimuli

All auditory stimuli were created using the software MAX (Cycling '74 ®), which also provided the experimental interface and enabled data collection. The CI sound processor was linked to a PC laptop via a direct connection. The electric stimulus was a pulse train with an overall duration of 900 ms, including a 100-ms ramp up and a 300-ms ramp down in level, delivered through electrodes 20 and 14 (e20 and e14), representing the most apical electrode and a medial electrode of the Oticon medical device. The stimulation rate was set to the user's regular rate of 500 pps. Each pulse was composed of an active monophasic and a balanced passive discharge using a multi-mode grounding stimulation mode (combination of 20% monopolar and 80% common ground). Acoustic stimuli were presented via insert earphones (EtymoticH, ER-4P) to the non-implanted ear. The acoustic and electric stimuli shared the same temporal envelope.

Procedure

The electric and acoustic stimulus were alternatively presented every second. The electric stimulus was fixed, and the acoustic could be varied by the participants. Their task was to find the acoustic sound that matched as similar as possible the perception of the electric stimulus. A graphical interface (Bamboo Fun pen, Wacom®) was used to adjust the acoustic signal parameters within a multi-dimensional space. The position of the pen (on virtual x and y axes) varied the incoming acoustic signal by simultaneously adjusting the values of one to two selected parameters (see below). The parameters selected at the end of one experiment were used to create the stimuli applied to the following experiment, within one trial.

The study was divided into three experiments during which different acoustic parameters were varied:

Experiment 1: Frequency of a pure tone

The participant were asked to match the frequency of a pure tone (range: 40-2200 Hz) with that of the electric stimulus. The axis (x or y) driving the F0 change varied across trials, the displacement along the other axis did not affect the tone or any other parameter.

Experiment 2: Harmonic complex tone bandpass filtered

An 11-harmonic complex sound was generated. Its fundamental frequency (F0) was the one selected during Exp. 1. This sound was filtered through a symmetrical bandpass filter. One axis controlled the centre frequency, CF, ranging from F0 to 10 times the F0 on a logarithmic scale. The other axis controlled the Q factor of this filter band, ranged from 1.4 to 100 on a logarithmic scale. The Q factor characterizes the bandwidth (Δf) of the filter relative to its centre frequency: Q = CF/Δf. Therefore, a high Q value results in a sound with a relatively small number of harmonics, whereas a low Q value results in a more complex sound.

Experiment 3: Inharmonic complex sound bandpass filtered

An 11-component complex sound was generated and filtered through the output filter selected at the end of Exp. 2. One axis controlled the based frequency (Fb) of the sound (range: 40 to 2200 Hz on a logarithmic scale), while the other axis controlled a parameter referred to as inharmonicity, i. The composite acoustic signal comprised components with frequencies defined by: $Fn=Fb*n^i$, where Fn was the frequency of each component (i.e., n was numbered 1-11), and i was the inharmonicity exponent, ranging from 0.5 to 2.8 on a linear scale. When i = 1 or 2, the sound was harmonic. Relative to this value, lower values of i resulted in a compression of the inter-component frequency spacing whereas higher values resulted in an expansion of the inter-component spacing.

Protocol

First, the presentation level of the electric stimulus was set to be comfortable by the experimenter. Then the level of the acoustic signal was adjusted to match the loudness of the electric stimulus and could be modified along the trials. Participants were first familiarized with the interface, and trained during one trial. Subsequently, Exp. 1, Exp. 2, and Exp. 3 were presented in that order, and repeated 3 times in total. In order to reduce any tendency of participants to return to the same spatial position on the interface and thereby bias the results, the settings of the interface were randomly modified before each trial of each condition by interchanging the axes (x becoming y and vice versa), and by adding offsets to the origin of the axes (up to 20% shift on each axis). The instructions were to modify the acoustic sound to create a perception similar to the perceived electric sensation. This procedure was repeated at 3 and 12 months after the first fitting, for the two electrodes.

RESULTS

Experiment 1: Frequency of a pure tone

Figure 1 shows all the individual matches for the first experiment. A mixed linear model was performed with all the individual matches as independent variables, the electrodes, the sessions and its interaction as fixed effect and the participants as random effects. Only the main effect of electrode was found significant [$F(1,7.369)=8.5391$, $p=0.021$]. On average the sensation induced by e20 matched a tone with a frequency of 506 Hz and that of e14 matched a tone with a frequency of 901 Hz. No significant effect was observed for the main factor session [$F(1,6.164)=1.8367$, $p=0.2229$] nor its interaction with the electrode [$F(1,4.951)=0.2509$, $p=0.6379$].

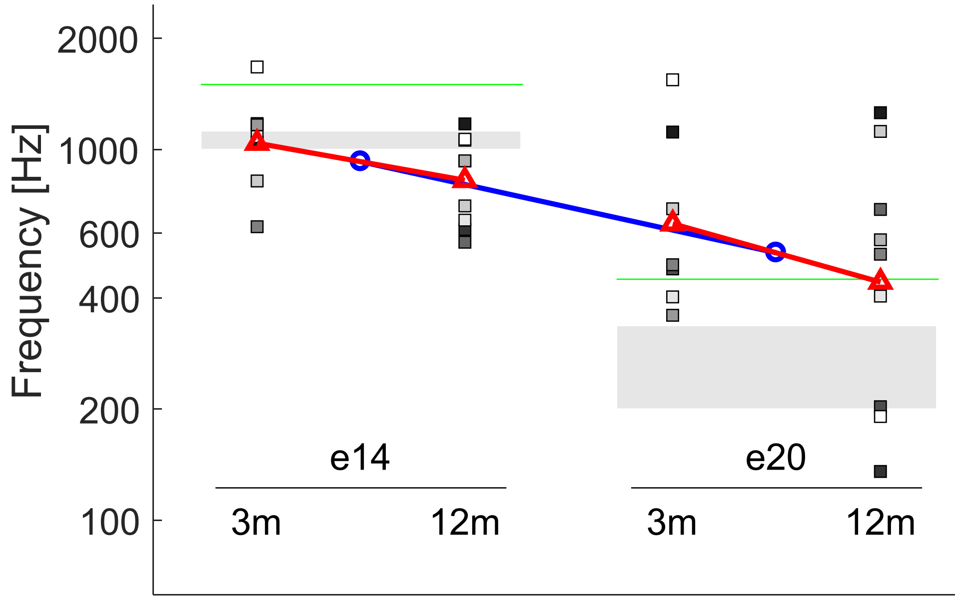

Fig. 1: Results of Exp. 1. Individual (squares) and average (red triangles and blue circles) results for the frequency matching, for e14 (left) and e20 (right) at 3 and 12 months after activation. The red triangles represent the average frequency per electrode and per session. The blue circles represent the average frequency of each electrode across both sessions. The horizontal green lines represent the supposed frequency based on the approximated place of the electrode (derived from the Greenwood function). The gray boxes outline the acoustic frequency band allocated to each electrode by the manufacturer.

Experiment 2: Harmonic complex sound bandpass filtered

The results of the characteristics of the filter applied in Exp. 2 are shown in Fig. 2. The average center frequency for the filter was 2850 Hz for e14 and 864 Hz for e20 (Fig. 2, left panel, blue circle). This difference was significant [$F(1,8.542)=18.5543$, $p=0.002$]. Similarly to Exp. 1, there was no session effect [$F(1,8.694)=0.92$, $p=0.36$], nor interaction with the electrode [$F(1,7.253)=0.001$, $p=0.95$]. The average Q factor was similar for the two electrodes, and between sessions ($p>0.05$): 5.97 and 6.21 (Fig. 2, right panel, blue circle).

Experiment 3: Inharmonic complex sound bandpass filtered

When the filter selected during Exp. 2 was applied to a complex sound**,** the task consisting of varying Fb gave similar results on average between e14 and e20 (Fig. 3 left panel, blue circles, Fb=433 Hz and 307 Hz, respectively, no statistical difference). However, an effect of session was observed, with a lower Fb for both electrodes between 3 and 12 months of CI use [$F(1,7,042)=6.7421$, $p=0.0354$]. The average results for the inharmonicity factor were also similar (n=1.77 and 1.74, respectively, no statistical difference).

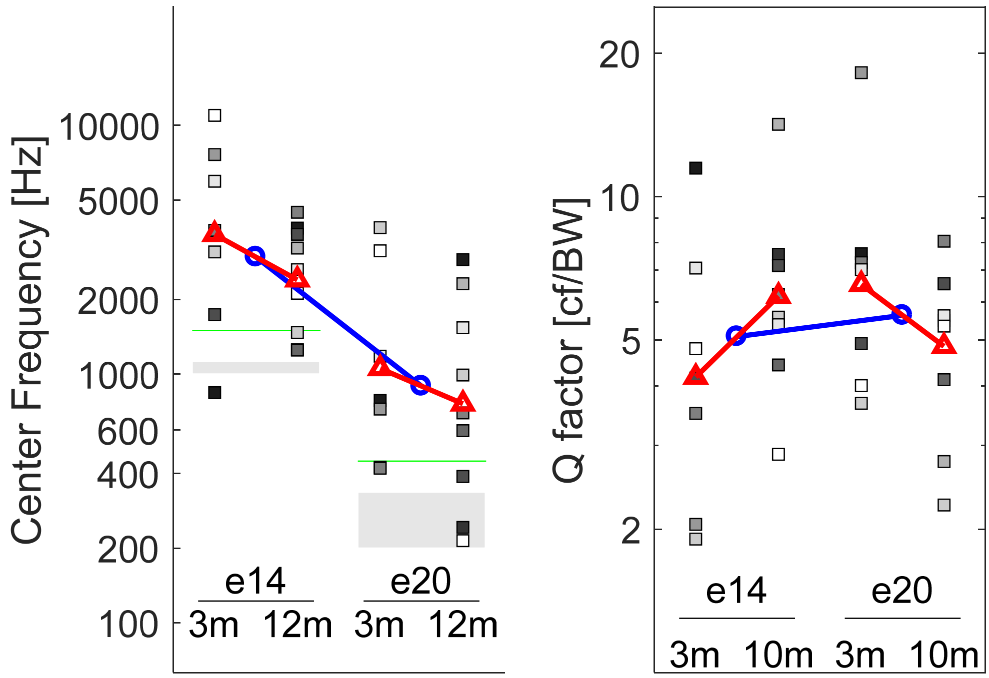

Fig. 2: Results of Exp. 2. Individual results for the center frequency and Q factor (left and right panel respectively) of the applied filter. See caption of Fig. 1 for more information.

DISCUSSIONS AND CONCLUSIONS

These experiments were designed to find an acoustic match for a single pulse train of an apical and a medial electrode. The results indicate that the best match was obtained with an inharmonic complex sound with a bright timbre for both electrodes. Exp. 1 indicates that electrode position influenced the match with a pure tone (the lower the pith, the more apical the position) and was stable after 3 months of CI use in our sample. Neither the Greenwood function nor the frequency allocation band correctly predicted what participants described. In Exp. 2, the average centre frequency of the filters matching users' perception induced by e20 and e14 was 864 Hz and 2850 Hz, respectively. As the centre frequency of a symmetrical spectrum can be considered a physical descriptor of the perceptual dimension of brightness (McAdams *et al.*, 1995), this result shows that a pulse train delivered at e14 was perceived with a brighter timbre than the same pulse train delivered at e20. In Exp. 3, the frequency of each component was set by the based frequency and the inharmonicity factor. As the resulting sound was inharmonic, the based frequency did not predict the pitch. Taken together however, the based frequency and inharmonicity influenced the tonality of the sound. Because no significant effect of electrode place was found for these parameters, it can be concluded that the electrode place influences the timbre rather than the tonality of a pulse train. This result challenges the concept of *place pitch* in cochlear implant.

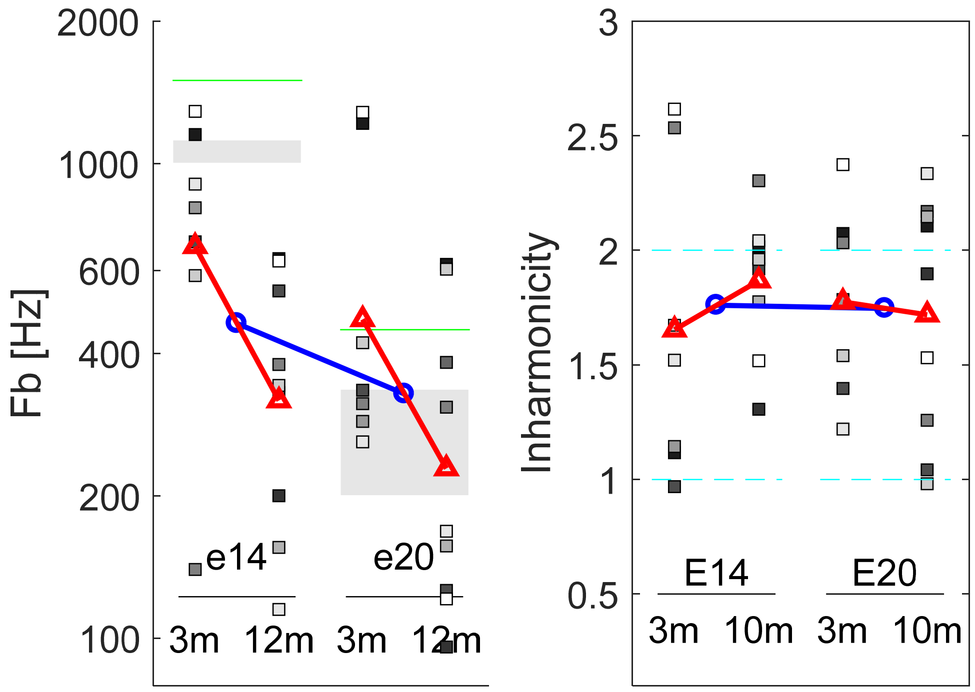

Fig. 3: Results of Exp. 3. Individual results for Fb and the inharmonicity factor (left and right panel respectively). See caption of Fig. 1 for more information. The doted lines indicate an inharmonicity factor of 1 and 2 (i.e., a harmonic sound).

ACKNOWLEDGMENTS

We would like to thank the participants for their time and enthusiasm, Dr. Christine Poncet, Prof. Bruno Frachet and Prof. Benoît Godey for giving access to their patients, and Bertrand Philippon for helping in the data collection.

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