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Research Article

Speech Perception, Sound Localization and Self-Assessment of Adult Users of Unilateral, Bilateral and Binaural Cochlear Implants

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Abstract

This study aimed to compare the performance of 13 adult users of unilateral, bilateral and Binaural® cochlear implants (CIs) and 5 normal hearing individuals. Speech perception was assessed through a recorded sentence recognition test, at a hearing level of 60 dB, in quiet and with contralateral competitive speech noise, in signal-to-noise ratios of +5 dB and 0 dB, at 0 and 180-degree angles. Sound localization was assessed with the use of a PA5® audiometer at 60 dB, 1000 Hz, in five directions. Self-perception was evaluated through the APHAB (Abbreviated Profile of Hearing Aid Benefit) questionnaire, in the CI condition. There was evidence of statistic difference between GBIN (Binaural® group) and GBIL (bilateral CI group) in speech perception with noise and in the APHAB Background Noise subscale. No remarkable difference was observed between GBIN and GUNI (unilateral group) on the speech perception test with noise and all of the APHAB subscales, as well as between CI groups during sound localization. All CI users showed difficulties in sound localization and there were no evidences that the Binaural® CI could be a similar alternative to bilateral implantation.

Keywords: *Cochlear Implantation; Audiology; Adult; Hearing Loss; Correction of Hearing Impairment; Sound Localization; Speech Perception*

Abbreviations

ANOVA: Analysis of Variance; APHAB: Abbreviated Profile of Hearing Aid Benefit; CI: Cochlear Implant; dB: Decibels; Hz: Hertz; HL: Hearing Level; SNR: Signal-to-Noise Ratio

Introduction

Cochlear implantation is known to bring many benefits, among them the development of hearing abilities, followed by the access to oral language, which can lead to a better sense of connection to the world, although hearing-related difficulties may still be experienced during daily life [1]. Sound localization, one of those hearing abilities, allows for spatial orientation and sound source identification, being crucial for a refined hearing performance and a better sense of balance, also preventing accidents [2]. This skill complements our perception of language sounds and provides clues on how a person acts on daily hearing tasks, where noise is constantly present [3]. There are currently different types of cochlear implant (CI) fitting, such as the unilateral CI (one CI device only), usually adapted with a hearing aid on the non-implanted ear (in this case called bimodal fitting) and the bilateral CI (2 CI devices, 1 for each ear). Past studies have discussed these options, approaching cost-utility and effectiveness [4]. Unilateral CI appears to be more financially beneficial however it usually presents low sound localization and speech perception performance, especially in noisy environments, when compared to the Bilateral CI [5]. Although the latter seems to show better results in speech perception and sound localization tests, it involves a higher cost and bigger risks, for instance, possible surgical complications [6]. An alternative solution was developed by CI manufacturer Neurelec/Oticon Medical (Vallauris, France), who launched a CI that electrically stimulates both cochleae with two arrays of 12 electrodes connected to one single internal receiver, the Digisonic Sp Binaural CI [7]. Although this device is no longer manufactured, very few studies put the hearing performance of its users to test [8] and there are patients around the world who did receive this implantation and are going through aural rehabilitation. Also considering the continuous need for technological resources that present better cost-utility and improve quality of life, we justify our search for clues and evidences that can benefit people with sensorioneural hearing loss, conducting a preliminary comparison of the Binaural CI next to unilateral and bilateral CIs, in order to understand their similarities and differences, and possibly gather evidences for future projects that aim to develop and improve binaural hearing technologies.

Materials and Methods

Participants

Eighteen adults, in the 18 to 59 age range, participated in this study, voluntarily. There was a male sex predominance (14 subjects were male, 4 were female). Thirteen of the subjects were post-lingually deaf individuals who underwent cochlear implantation at least 12 months before data collection, all part of the Hearing Health Program of a public institution from the state of São Paulo, Brazil, and 5 were normal hearing individuals. Subjects were invited to participate, before reading, fully understanding and signing a Written Informed Consent Form (WICF). We obtained appropriate Institutional Review Board approval before collecting any data.

The sample was divided into 4 groups: GU - 5 unilateral CI users group; GBIL - 5 bilateral CI users group; GBIN - 3 Binaural CI users group and GC – 5 normal hearing adults (control group). Exclusion criteria for this study were: diagnosed neurological alterations, middle ear abnormalities or obstructions of external auditory canal and sentence comprehension difficulties. We justify the small sample size since this study was conducted in a public hospital, where a limited number of Binaural CI surgeries occurred and a variety of brands and devices were used, in a way that no particular brand was prioritized, according to the federal law for public purchases.

Measurements

First we collected demographic variables of all subjects, followed by an external auditory canal inspection and a free field audiometry with the devices on. Speech perception was then assessed using Pereira and Schochat's material entitled "Processamento Auditivo Central: Manual de avaliação" [9], which comes with a Compact Disc (CD) and an evaluation manual. We used the sentence list 1A from track 6 - Sentences To Evaluate Speech Recognition, consisted of 25 sentences in brazilian portuguese recorded from a male talker. The evaluation was conducted in a silent condition, at 0 and 180-degree angles and then with contralateral competitive noise (Speech White Noise), also at 0 and 180-degree angles.

Subjects were seated in a quiet room at the center of two loudspeakers set at head height, 60 cm away, at 0 and 90 degrees each. The intensity level of the sentences was 60 dB HL and the noise was set at signal-to-noise ratio (SNR) of +5 dB (55 dB HL) and then 0 dB (60 dB HL). A 2-channel audiometer was used (MADSEN Astera equipment, from Otometrics company) and calibration was checked before testing. Subjects were instructed to repeat the sentences and their score was calculated as a percentage.

For sound localization, subjects would hear a pure tone of 60 dB HL, at 1000 Hz, from a PA5 (Interacoustics company) audiometer 40 cm away from head level, and had to identify the sound source as being one of the 5 following directions: left, right, front, behind or above. The task consisted in 5 rounds of 5 stimuli, in random order, and the subjects had their eyes closed during the procedure.

To assess CI users' self-perception of hearing performance during daily life situations, we used the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire [10], adapted to portuguese by Almeida [11]. In our study, participants only answered the CI listening condition, so we compared their current experiences with the CI, not the benefit brought by its use (unaided condition versus CI listening condition). To obtain percentage scores, Phonak's Fitting Guideline 8.6 software was used.

Statistical Analysis

First, data went through an exploratory analysis. Continuous variables were expressed in basic descriptive statistics and categorical variables were expressed in frequency and percentage. To compare the groups, we used the one-way Analysis of Variance (ANOVA) method; to find any association between the categorical variables and the groups, Fisher's exact test was used; to compare the results of the speech perception test, we used a linear mixed-effects regression model. A significance level of 5% ($p \leq 0.05$) was adopted for all analyses.

Results and Discussion

Table 1 presents the characterization of subjects according to age, CI-related information and mean hearing thresholds.

Group	Subject	Age	Sex	CI brand	Implanted Ear	Surgery Date	Activation Date	Currently on Hearing Therapy	Mean Hearing Threshold (dB HL)
GU	1U	42	Female	Neurelec®	Left	04/09/2014	15/10/2014	No	35
	2U	32	Male	Cochlear®	Left	17/02/2011	23/03/2011	Yes	25
	3U	33	Male	AB®	Left	12/12/2013	21/01/2014	Yes	45
	4U	44	Male	Cochlear®	Right	20/04/2008	23/05/2008	No	32.5
	5U	51	Male	Neurelec®	Right	03/09/2015	14/10/2015	No	52.5
GBIL	1BIL	33	Male	AB®	Both	10/09/2015	22/10/2015	Yes	37.5
	2BIL	33	Male	Cochlear®	Both	13/05/2015	25/06/2015	Yes	25.25
	3BIL	44	Male	Cochlear®	Both	06/01/2016	02/03/2016	No	27.5
	4BIL	30	Male	Medel®	Both	25/04/2014	11/06/2014	Yes	26.25
	5BIL	28	Female	Cochlear®	Both	18/02/2009	25/03/2009	Yes	28.75
GBIN	1BIN	54	Male	Neurelec®	Left	03/09/2015	14/10/2015	No	41.25
	2BIN	56	Male	Neurelec®	Right	06/08/2015	16/09/2015	No	47.5
	3BIN	58	Male	Neurelec®	Left	10/06/2015	16/07/2015	Yes	41.25
GC	1C	50	Female	-	-	-	-	-	7.5
	2C	31	Male	-	-	-	-	-	5
	3C	28	Male	-	-	-	-	-	7.5
	4C	50	Male	-	-	-	-	-	7.5
	5C	34	Female	-	-	-	-	-	6.25

Table 1: *Participant details according to age, CI characteristics and mean hearing thresholds obtained in free field.*

Speech Perception

Mean scores for each group were graphically plotted in figure 1. GC obtained the highest mean scores through all the testing conditions, while GBIN achieved the lowest mean scores for all conditions, except at SNR of +5 dB, at a 0 degree angle, the only condition where GU displayed the worst mean score. GBIL had the second best mean scores for all conditions, followed by GU. Table 2 shows a comparison of all 4 groups through the 6 testing conditions, by a linear mixed-effects regression model. There was a remarkable difference between GBIN and GIL for a SNR of +5 dB, at 0 (p = 0.0321) and 180 (p = 0.0271) degree angles, and SNR of 0 dB, at 0 (p = 0.0228) and 180 (p = 0.0111) degree angles. No significant differences were found between GBIN and GU. There was significant difference between GBIN and GC, as well as between GU and GC, for all conditions. GU and GBIL showed difference in the noisy condition, with a SNR of +5 dB, at 0 (p = 0.0010) and 180 (p = 0.0005) degree angles. GBIL was significantly different from GC in the silent condition and with SNR of 0 dB, in both angles.

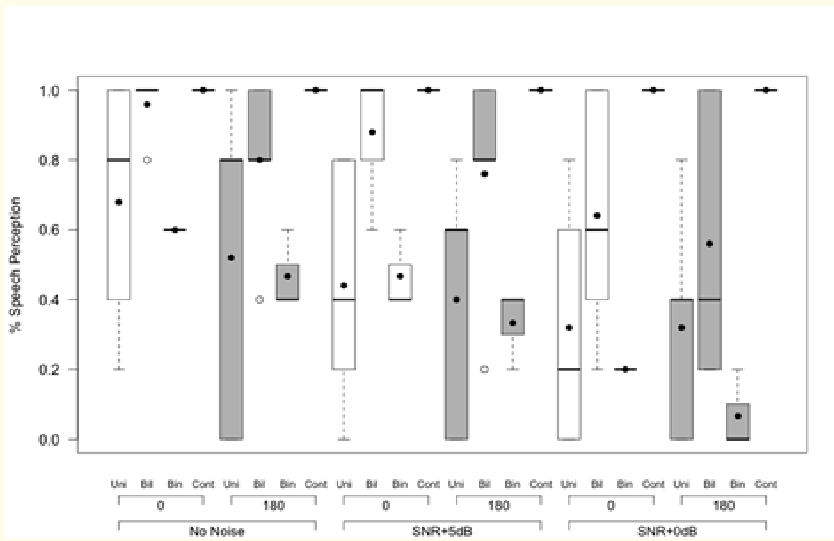

Figure 1: *Mean percentage scores achieved by the groups in each of the 6 conditions of the speech perception test, where Uni: Unilateral CI; Bil: Bilateral CI; Bin: Binaural CI; Cont: Control.*

Group	Right		Left		Front		Back		Above	
	Wrong	Right	Wrong	Right	Wrong	Right	Wrong	Right	Wrong	Right
GU	2 11.11	3 16.67	3 16.67	2 11.11	4 22.22	1 5.56	5 27.78	0 0.00	5 27.78	0 0.00
GBIL	0 0.00	5 27.78	0 0.00	5 27.78	1 5.56	4 22.22	3 16.67	2 11.11	2 11.11	3 16.67
GBIN	1 5.56	2 11.11	1 5.56	2 11.11	3 16.67	0 0.00	1 5.56	2 11.11	1 5.56	2 11.11
GC	0 0.00	5 27.78	0 0.00	5 27.78	0 0.00	5 27.78	0 0.00	5 27.78	2 11.11	3 16.67
p	0.2034		0.0686		0.0086*		0.0086*		0.1516	

Table 2: *Comparison of the Speech Perception Test Between the Groups.*

Sound Localization

Figure 2 illustrates mean, median and standard deviation values for each group. GC had the highest mean (3.32) scores, followed by GBIL (0.72) and GBIN (0.53). GU showed the lowest mean (0.24) for total score. Fisher's exact test was used to verify significant difference (p ≤ 0.05) between the groups for each direction tested (Table 3). There was significant difference between the groups for the positions

"Front" and "Back" (p = 0.0086 for both). Table 4 compares the total performance in the sound localization task between the groups, also through Fisher's exact test, which showed that there was significant difference between GC and all of the other groups, however with no significant difference between the CI groups.

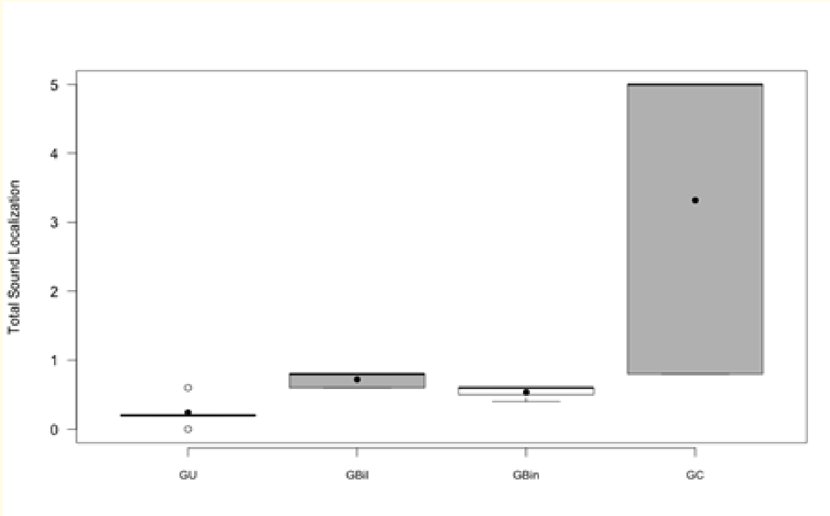

Figure 2: *Distribution of the groups' total score in the sound localization task, where 5 was the maximum score, correspondent to the 5 stimuli, and 0, the lowest.*

Groups	No Noise		With Noise (SNR + 5 dB)		With Noise (SNR 0 dB)	
	0º	180º	0º	180º	0º	180º
GU x GBIL	0.0916	0.0916	0.0090*	0.0312*	0.0546	0.1471
GU x GBIN	0.6734	0.7786	0.8882	0.7254	0.5276	0.1845
GU x GC	0.0046*	0.0045*	0.0010*	0.0005*	< .0001*	< .0001*
GBIL x GBIN	0.0609	0.0822	0.0321*	0.0271*	0.0228*	0.0111*
GBIL x GC	0.0312*	0.0090*	0.4659	0.1471	0.0312*	0.0090*
GBIN x GC	0.0379*	0.0062*	0.0062*	0.0007*	< .0001*	< .0001*

Table 3: *Comparison of the results for each direction in the sound localization task.*

Groups	Fisher's exact test *p*
GBIL x GBIN	0.8393
GBIL x GC	0.0050*
GBIL x GU	0.5495
GBIN x GC	0.0081*
GBIN x GU	0.7503
GU x GC	0.0015*

Table 4: *Comparison of total scores in the sound localization task between the groups.*

*GU: Unilateral Group, GBIL: Bilateral Group; GBIN: Binaural Group; GC: Control Group. *p ≤ 0.05*

APHAB

As seen on table 5, we calculated mean and median results of the CI groups for each subscale of the APHAB. GBIN had the highest mean scores in all settings and GBIL, the lowest, while GU fell in the middle of both. Using the ANOVA method, groups' scores were compared for each subscale (Table 6).

	EC		RV		BN		AV	
Group	Mean	Median	Mean	Median	Mean	Median	Mean	Median
GU	0.59	0.64	0.62	0.66	0.68	0.72	0.32	0.29
GBIL	0.27	0.18	0.41	0.41	0.41	0.31	0.39	0.45
GBIN	0.59	0.68	0.63	0.62	0.73	0.74	0.47	0.50

Table 5: *Mean and median scores of each group for APHAB's subscales.*

GU: Unilateral Group; GBIL: Bilateral Group; GBIN: Binaural Group; GC: Control Group.
**EC: Ease of Communication; RV: Reverberation; BN: Background Noise; AV: Aversion to Sounds.*

There was evidence of statistically significant difference between GBIL and GBIN (p = 0.0321) and between GBIL and GU (p = 0.0365) for the BN subscale. A remarkable difference was observed between GBIL and GU (p = 0.0332) for the EC subscale.

Discussion

All CI users in this study had their devices activated at least 12 months before taking part in the tests. GC showed the lowest mean hearing thresholds and GBIN, the highest. GBIN also had the highest mean age (M = 56), while GBIL had the lowest (M = 33.60). However, all candidates are within age range for appropriate listening responses, with few risks of age-related cognitive decline [12].

Concerning speech perception, there was no significant difference between GBIN and GU's performances, in all conditions. On the other hand, between GBIN and GC, there was a remarkable difference in all conditions, and between GBIL and GBIN, only in the conditions with competitive noise. This last result disagrees with Bonnard., *et al*. [8], who did not find any significant differences between Bilateral CI and Binaural CI, for speech perception. Between GU and GC, there was significant difference for all of the conditions, except for 0 degrees in silence. Between GBIL and GC, a notable difference was observed in the silent conditions and in the conditions with noise at SNR 0 dB. Between GU and GBIL, there was an important difference in the noisy conditions at SNR +5 dB. Our results agree with Smulders., *et al.* [13] and van Zon., *et al.* [14], who found that the bilateral IC performed significantly better than the unilateral CI, when noise came from a spatially separated source. GBIL's overall good performance (surpassed only by GC) is supported by the idea that, when signal and noise are presented in different directions, binaural advantages occur thanks to the head shadow effect, binaural summation and squelch [15]. Furthermore, Finke., *et al*. [16] defend that auditory-cognitive processing plays an important role in speech performance for CI users, so there may be a variability of outcomes between individuals, according to their cognitive and verbal abilities.

	EC	RV	BN	AV
	p value	p value	p value	p value
GBIL x GBIN	0.0596	0.2043	0.0321*	0.5789
GBIL x GU	0.0332*	0.1640	0.0365*	0.6056
GBIN x GU	0.9896	0.9555	0.6980	0.3249

Table 6: *Comparison of the APHAB subscales between the groups.*

*GU: Unilateral Group; GBIL: Bilateral Group; GBIN: Binaural Group; GC: Control Group; *EC: Ease of Communication; RV: Reverberation; BN: Background Noise; AV: Aversion to Sounds.*

The analyses of our sound localization task show that there is evidence of a significant difference between the groups for the positions "Front" and "Back", which reminds us of a study conducted by Kerber and Seeber [17], where 3 out of ten CI users had the perception that frontal sounds were coming from behind, suggesting a possible specific struggle or confusion when discriminating those 2 positions, to be further investigated. As we compared scores between the groups, there was evidence of statistically significant difference between GC and all of the other groups, however with no significant difference between the CI groups, which suggests a generalized difficulty in sound localization with CI, no matter what type of fitting. Although the studies conducted by Verhaert., *et al.* [18] and Bonnard., *et al.* [8] also did not find a remarkable difference between the Binaural CI and Bilateral CI for sound localization, they did not have a unilateral CI group for further comparison. Our results diverge from Verschuur., *et al*. [19] and Smulders., *et al*. [13], who found that the bilateral CI users had a better sound localization ability than unilateral CI users in this kind of task, although different testing settings cannot be easily compared. The poor localization performance of Bilateral CI users in this study could be explained by the ILDs (Interaural Level Differences) available to them, which are much smaller when compared to normal hearing individuals, as well as by individual differences, such as output-compression settings and different numbers of electrodes between ears [20]. One might argue that there could be sexual dimorphic differences among the groups, since studies have shown that there is a male advantage in the spatial abilities involved in sound localization with competitive noise [21,22]. However, all of the groups are predominantly male, so that difference should not influence the results.

Regarding the APHAB questionnaire, in all of the subscales (EC - Ease of Communication -, RV - Reverberation-, BN - Background Noise- and AV - Aversion to sounds), GBIN presented the biggest mean scores. On the other hand, GBIL showed the lowest self-perception in all settings and GU fell in the middle of both. Our findings partially agree with Litovsky., *et al*. [23], who found that bilateral CI users had better APHAB scores than unilateral CI for all subscales, except for AV. Comparing the groups, there was evidence of statistically significant difference between GBIL and GBIN, and between GBIL and GU, for the BN subscale. Relative to the EC subscale, there was evidence of significant difference only between GBIL and GU. Bonnard., *et al*. [8] didn't find any significant difference between bilateral and Binaural CI users for the APHAB scores, however they did calculate the benefit, and not only the current "CI condition". We were particularly interested in watching the performance of the Binaural CI, next to the unilateral and bilateral CIs, since, according to Dietz and McAlpine [7], there are not enough clinical evidences that show the Binaural CI could provide a true binaural hearing. The findings gathered here indicate that the Binaural CI could be significantly different from the bilateral CI in the following aspects: 1) Speech perception with noise; 2) APHAB's BN subscale (GBIN notices more difficulties in situations of communication with background competitive noise). Yoon., *et al.* [15] showed in their study that binaural hearing brought bigger benefits when there was competitive noise, and this can indicate that the binaural CI perhaps does not indeed correspond to real binaural hearing, since this binaural benefit is not noticeable. Additionally, the Binaural CI showed a similar performance to a unilateral CI, since: 1) There was no significant difference between GU and GBIN during speech perception with noise at different SNR levels; 2) There were no significant differences between GU and GBIN for all of the APHAB subscales; 3) They showcased similar mean scores.

The present study faces a number of limitations, such as sample size and not considering the speech code strategies used. Hence, further studies that could analyze those differences, with a bigger number of subjects, are necessary.

Conclusion

To conclude, individuals with the Digisonic SP Binaural® CI showed a similar performance to unilateral CI users in this study, when it comes to speech perception with noise and self-perception. All CI users experienced difficulties with sound localization and bilateral CI users had the overall closest performance to normal hearing individuals. None of our data or observations suggest that the Binaural CI could be a similar alternative to bilateral implantation.

Conflicts of Interest

There were no conflicts of interest throughout the development of this study.

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