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Original Article

Comparison of Intensity Discrimination between Children Using Cochlear Implants and Typically Developing Children

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OBJECTIVES: Differential sensitivity of intensity is known to be important for the perception of the relative distance of sounds in the environment, emotions of speakers, and localize sounds. However, a few features in listening devices, such as cochlear implants, used by individuals with hearing loss alter the output intensity heard by them. This makes soft sounds loud and loud sounds soft. Hence, the aim of the present study was to compare the intensity discrimination of children using cochlear implants with that of typically developing children.

MATERIALS AND METHODS: Intensity discrimination of 30 children (15 using cochlear implants and 15 typically developing children) was obtained for three warble tones (500 Hz, 1000 Hz, and 4000 Hz) and three vowels (/a/, /i/, and /u/). The responses of the two participant groups, obtained using a 3-alternative forced-choice technique, were compared.

RESULTS: Children using cochlear implants performed significantly poorer than typically developing children for the 4000 Hz warble tone and for the vowels /a/ and /u/. However, there was no significant difference for the remaining stimuli.

CONCLUSION: The study indicated that the intensity discrimination threshold varies as a function of the frequency of the signals in children using cochlear implants. Intensity discrimination for high-frequency tones was significantly poorer for typically developing children, but not for low-frequency tones. In contrast, children using cochlear implants performed similarly to typically developing children for the high-frequency vowel but not for the mid- and low-frequency vowel.

KEYWORDS: Warble-tone discrimination, vowel discrimination, loudness perception

INTRODUCTION

Perception of intensity difference is essential, whether it is for speech or for non-speech stimuli. Intensity differences are reported to be utilized by normal hearing individuals to perceive the relative distance of sounds in the environment [1, 2], perceive emotions or the mental state of the speaker [3, 4], locate the source of sounds [5], and also for the perception of stress in speech [6-8]. Hence, for day-to-day functioning, individuals require to perceive the intensity of sounds heard by them and make judgments about their loudness.

Individuals with hearing loss are known to have difficulty in hearing, impairing their communication abilities through the auditory modality. Difficulty in hearing includes problems in perceiving the intensity of sounds around them. This may impair their ability to make judgments of the relative distance of sounds, identify emotions from a speaker's voice, localize sounds, and perceive stress patterns in speech. Cochlear implants are one of the devices used by individuals with hearing loss to overcome their difficulties in hearing sounds. Cochlear implants are reported to code a wide auditory dynamic range (120 dB) into a limited electrical dynamic range (10–30 dB) [9, 10]. All commercially available cochlear implants are noted to compress auditory signals during signal processing [11, 12]. Various signal processing strategies are reported to be used to enable individuals using cochlear implants to hear a range of intensities similar to what is perceived acoustically. These include adaptive dynamic range optimization [13-15], automatic gain control [16], microphone sensitivity[17], manipulation of the input dynamic range [18], and channel-specific gain [12].

Mertens and Punte [19] evaluated 54 individuals who had utilized their devices for at least three years to determine the perception of relative distance in post-lingual adults using cochlear implants. Individuals using cochlear implants were noted to have

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significantly poorer scores in almost all components of spatial hearing (direction, distance, and movement of sounds) and quality of sounds (segregation, recognition, clarity, and listening effort) than individuals with moderate hearing loss. The findings indicated that despite being able to perceive speech, cochlear implant users had difficulty in utilizing loudness cues for spatial hearing.

Dorman and Loiselle [20] compared horizontal localization abilities in bilateral post-lingual cochlear implantees with their interaural level differences. A compression ratio of 3:1 resulted in the interaural level difference being reduced above the knee point. The authors ascribed the errors in localizing in the horizontal plane to this reduced interaural level difference.

Use of amplitude cues for the perception of emotions by adult cochlear implantees was observed to be poorer than that by normal hearing adults, 1–2 weeks post-switch-on [21]. Improvement was seen in some participants who were evaluated 6 months and 1 year post-implant. This improvement was seen in the identification of emotions that varied in intensity (happy and sadness). However, cochlear implant users continued to confuse emotions that did not differ in intensity. Similar findings were noted by Luo and Fu [22] for sentences depicting different emotions.

Nikakhlagh and Saki [23] found differential limen for intensity of adult cochlear implantees to be poorer than that of normal hearing adults. This poor performance was considered to be mainly due to their inability to utilize the processing strategy of the cochlear implants.

The review indicates that intensity perception is adversely affected in individuals using cochlear implants. This has been noted to affect their ability to perceive relative distance of sounds in the environment, perceive emotions of speakers that have loudness variations, and localize sounds. Additionally, not having knowledge regarding loudness variations may affect their ability to carry out loudness matching and loudness growth measurement that are important steps while mapping cochlear implants. While studies have been conducted on adults, studies on intensity discrimination for acoustic stimuli in children using cochlear implants are sparse. Such information would indicate whether children using cochlear implants have similar difficulties in perceiving intensity variations as reported in the literature. Hence, the aim of the present study was to establish how loudness discrimination of acoustic stimuli varies between children using cochlear implant and age-matched typically developing children.

MATERIALS AND METHODS

Intensity discrimination ability of children using cochlear implants was studied using a standard-group comparison design. The performance of the group of children using cochlear implants was compared with that of typically developing age-matched children.

Participants

The study included 30 children aged 6–15 years. Children were divided into two groups, one consisting of 15 children using cochlear implants (mean age=10.60 years, standard deviation (SD)=3.01) and the other group consisting of 15 age-matched typically developing children (mean age=10 years, SD=2.80). Informed consent was obtained from the guardians of the participants in accordance with the ethical guidelines of the institute where the children were tested [24]. The receptive language age of both participant groups on the "Receptive Expressive Emergent Language Skills" test [25] was at least five years. All the participants also had normal Intelligence Quotient on the Raven's Progressive Matrices [26]. None of them had any history of a middle ear infection. The absence of a middle ear problem at the time of evaluation was confirmed by the presence of an A-type tympanogram. Additionally, all the typically developing children had pure-tone air conduction and bone conduction thresholds within 15 dB HL.

Children using cochlear implants wore monaural devices for at least 1 year and had stable maps at the time of testing. Their average aided warble-tone thresholds in the frequencies 500 Hz, 1000 Hz, and 2000 Hz were within the speech spectrum and ranged from 15 dB to 28.33 dB (mean=21.88 dB, SD=4.03). The participants wore their cochlear implant processor using the settings recommended by qualified audiologists. Further, 10 participants using cochlear implants wore hearing aids in their non-implanted ear. The demographic details of the participants and their devices are given in Table 1. CI: cochlear implant; ACE: advanced combination encoder; FSP: fine structure processing

Stimuli

Three warble tones and three vowels were used to evaluate intensity discrimination. The warble tones, generated using the Psycon v2.18 software (Columbus, Ohio) [27], had a duration of 1000 ms that included a rise and fall time of 10 ms. The 500 Hz, 1000 Hz, and 4000 Hz warble tones had a frequency deviation of 5% and a modulation rate of 5 Hz.

The vowels /a/, /i/, and /u/ were recorded by an adult female speaker, with a neutral Indian accent. The recording was done using a sampling rate of 44,100 Hz and 32 bits resolution. The recorded material was scaled such that the three vowels had similar average intensity. A 1 kHz calibration tone was inserted prior to the recorded vowels. The recorded vowels were played to 10 normal hearing adults to check the clarity of the recording. The stimuli were selected only if all 10 adults could correctly identify the vowels. The spectrograms of the recorded vowels /a/, /i/, and /u/ are depicted in Figure 1(a), (b), and (c), respectively.

Procedure

The children were tested in a well-lit, distraction-free, sound-treated two-room setup that met the requirement of the ANSI standards [28]. The stimuli were presented using the Psycon v2.18 software loaded in a laptop. The output from the laptop was routed through a loudspeaker (dB technologies M160, Bologna, Italy) and kept at a distance of 1 m from the head of the participants at 0° azimuth. Prior to the presentation of the stimuli, the volume control of the laptop was manipulated such that the output from the loudspeaker was 50 dB HL. The output level was measured using a sound level meter (Larson & Davis, Model 824, Depew, New York), with a half-inch free-field microphone.

Participants using cochlear implants were tested with their device set in the recommended settings. Participants who used hearing aids in the non-implanted ear were instructed to remove the device while being evaluated. Using an adaptive tracking procedure available in the Psycon v2.18 software, intensity discrimination thresholds were obtained utilizing a three-alternative forced-choice method. The three intervals were separated by a duration of 200 ms. Two of the intervals served as the anchor and one served as the variable interval. The intensity of the anchor tones was kept constant at 50 dB HL, and the intensity of the variable interval, which was selected randomly, contained

Table 1. Demographic details of the participants using cochlear implants

Participants	Chronological Age (Years)	Implant	Processor	Coding strategy	Number of years of CI usage
1.	13	CI24 RE	CP802	ACE	9
2.	11	CI512	CP810	ACE	7
3.	7	Nucleus 24RE	CP802	ACE	4
4.	8	CI422	CP910	ACE	4
5.	8	CI24 RE	CP802	ACE	4
6.	15	Freedom	CP910	ACE	9
7.	12	Freedom	Freedom	ACE	6
8.	6	Freedom contour advance	CP810	ACE	4
9.	15	Freedom	Freedom	ACE	7
10.	8	Freedom	Freedom	ACE	6
11.	11	Freedom contour advance	CI24RE	ACE	6
12.	9	Freedom	CP810	ACE	4
13.	11	CI512	CP810	ACE	8
14.	15	MedEl	Opus 2 Power	FSP4	12
15.	11	Digisonic SP	Saphyr SP	Crystalis XDP	6

CI: cochlear implant; ACE: advanced combination encoder; FSP: fine structure processing

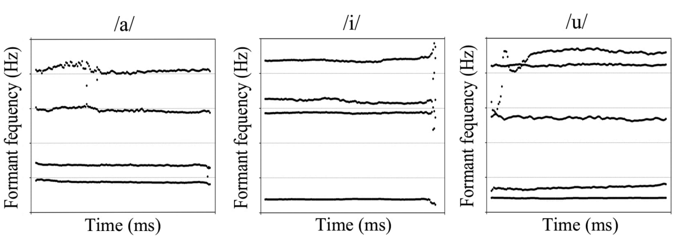

Figure 1. Formant frequencies of the vowels (a) /a/, (b) /i/, and (c) /u/.

the louder stimulus. The participants were instructed to indicate as to which of the three intervals in each set was louder by lifting one, two, or three fingers to represent the first, second, or third intervals, respectively. Prior to testing the participants, practice was given using live voice. The test stimuli were presented as soon as the child had understood the task. Initially, the variable stimulus was set 10 dB above the anchor stimulus. The intensity of the variable tone was altered using a 2 down/1 up rule, as proposed by Levitt [29], where it varied in 5 dB steps for the first two reversals and in 2 dB steps for the next four reversals. Breaks were given between the trials if a child showed signs of fatigue. The average of the final four reversals was calculated as the intensity discrimination threshold. This was done for all six stimuli.

Statistical Analysis

Data were analyzed using the Statistical Package for the Social Sciences version 21 (IBM Corp., Armonk, NY, USA) to measure intensity discrimination thresholds for statistical analyses. Shapiro–Wilk test was used for normally distributed data ($p>0.05$). Hence, parametric tests were conducted. Both descriptive and inferential statistics were performed.

RESULTS

The results, comparing intensity discrimination thresholds of typically developing children and children using cochlear implants, are provided separately for the three warble tones (500 Hz, 1000 Hz, and 4000 Hz) and the three vowels (/a/, /i/, and /u/). Data were compared between the two groups using two-way ANOVAs (2 groups×3 warble tones and 2 groups×3 vowels). The interaction between the stimuli and the participant groups was also determined.

Comparison of intensity discrimination thresholds for warble tones across participant groups

The mean and standard deviation of the intensity discrimination thresholds (Figure 2) were similar in the two groups of participants for the 500 Hz and 1000 Hz warble tones. However, children using cochlear implants had poor differential sensitivity for the 4000 Hz warble tone. A two-way repeated measures ANOVA was conducted to determine if a statistically significant difference exists between the groups. The frequency of the warble tones served as the within-subject factor, whereas the groups served as the between-subject factor. As Mauchly's test indicated that the assumption for sphericity was not met, a Greenhouse–Geisser correction was incorporated. A two-way repeated measures ANOVA revealed that there was a significant main effect of the participant groups ($F(1, 28)=9.48$, $p=0.005$, $\eta_p^2=0.25$). Additionally, a significant interaction between the warble tones and the participant groups was observed ($F(1.61, 44.97)=10.05$, $p=0.001$, $\eta_p^2=0.26$).

Separate one-way ANOVAs were conducted for each of the three warble tones as a significant main effect of the groups existed and there was an interaction between the groups and warble tones. There was no significant difference between the groups for the 500 Hz warble tone ($F(1, 28)=0.005$, $p=0.95$, $\eta_p^2=0.00$) and the 1000 Hz warble tone ($F(1, 28)=1.51$, $p=0.23$, $\eta_p^2=0.05$). However, there was a significant difference between the groups for the 4000 Hz warble tone ($F(1, 28)=19.02$, $p<0.00$, $\eta_p^2=0.40$).

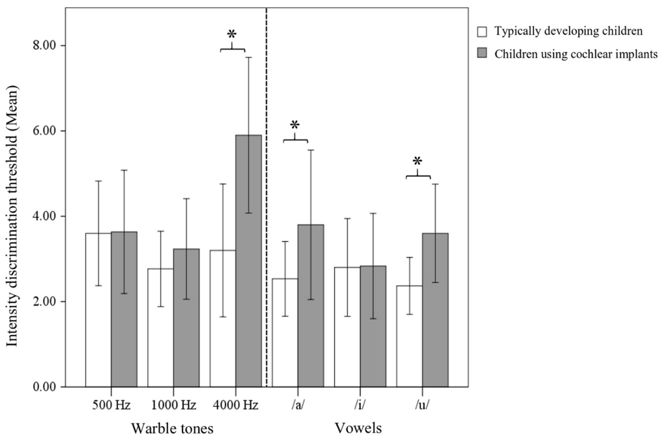

Figure 2. Mean and standard deviation (SD) of intensity discrimination thresholds for warble-tones and vowels of typically developing children and children using cochlear implants.

Comparison of intensity discrimination thresholds for vowels across participant groups

The mean intensity discrimination thresholds for vowels (Figure 2) were better in typically developing children than in children using cochlear implants for the vowels /a/ and /u/. Such a difference was not present for the vowel /i/. A two-way repeated measures ANOVA indicated the presence of a significant main effect of the group ($F(1, 28)=7.04$, p=0.013, $\eta_p^2=0.20$), as well as a significant interaction of the stimuli and group ($F(2, 56)=3.81$, p=0.028, $\eta_p^2=0.12$).

One-way ANOVAs, conducted separately for each vowel, revealed a significant difference between the two groups for the vowels /a/ ($F(1, 28)=6.28$, $p=0.018$, $\eta_p^2=0.18$) and /u/ ($F(1, 28)=12.86$, p=0.001, $\eta_p^2=0.31$). However, there was no significant difference for the vowel /i/ ($F(1, 28)=0.006$, p=0.939, $\eta_p^2=0.00$).

Thus, the results indicated that intensity discrimination was significantly different between typically developing children and children using cochlear implants. This difference was seen only for specific warble-tone frequencies and vowels.

DISCUSSION

The findings of the study are discussed to highlight the difference in intensity discrimination thresholds in 15 typically developing children and 15 children using cochlear implants. This information is provided for the three warble tones (500 Hz, 1000 Hz, and 4000 Hz) and the three vowels (/a/, /i/, and /u/).

Comparison of intensity discrimination thresholds between participants for warble tones

The findings of the current study indicated that children using cochlear implants performed significantly poorer than typically developing children only in the highest frequency that was tested (4000 Hz). This difference was not observed in the lower two frequencies (500 Hz and 1000 Hz). This indicated that children using cochlear implants needed greater difference in intensity at higher frequency to perceive the change in loudness than typically developing children. All the children using cochlear implants had used hearing aids for at least six months. This would have enabled them to have exposure to mid to low frequencies, which were audible with their hearing aids. This extended exposure to mid to lower frequencies probably would have resulted in them perceiving intensity differences better in these frequencies than in higher frequency. The participants would have been exposed to high frequencies only after using their cochlear implants.

Similar results were also noted by Drennan and Pfingst [30] using electrical stimulation. Their study noted that differential limen of intensity for electrode 16, which was responsible for stimulating low frequencies, was smaller than that for electrode 8, which coded high frequencies. The authors attributed this finding to more neuronal survival at low-frequency region, based on the findings of Nadol and Young [31]. They also ascribed to the proximity of electrode 16 position to the modiolus, as was earlier observed by Cohen and Saunders [32].

The finding of the current study regarding intensity discrimination is in line with the results noted by Nikakhlagh and Saki [23] in adult cochlear implant users. In contrast to the current study, their participants had poor intensity difference limens across all the frequencies tested by them (500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz). Although the authors did not mention the intensity of the pedestal tone, it is possible that they used a lower pedestal tone than that used in the current study. This would have resulted in their participants having difficulty in all the frequencies as at low presentation levels, intensity discrimination limen has been reported to be independent of frequency by Florentine and Buus[33].

Comparison of intensity discrimination thresholds between participants for vowels

The findings for vowels indicated that children using cochlear implant had significantly poorer intensity discrimination for the vowels /a/ and /u/ than typically developing children. However, this difference was not seen for the vowel /i/. The different formant structures of the vowels could have resulted in this variation in the findings. The first and second formants are relatively closely spaced in the former two vowels, as can be seen in Figure 1(a) and (c), in contrast to the vowel /i/ (Figure 1b). This could have resulted in the stimulation of closely spaced electrodes in the cochlear implant for the vowels /a/ and /u/, but the stimulation of electrodes that are far apart for the vowel /i/. Anzalone and Smith [34] noted that the slope of loudness growth curve increases as the electrode separation increases. Hence, the widely spaced formant frequencies of the vowel /i/, which would have stimulated widely spaced electrodes, would have resulted in a steeper loudness growth. Hence, a small change in intensity would have led to a loudness increment for the vowel /i/, but not for the vowels /a/ and /u/, which would have stimulated closely spaced electrodes. This rapid growth in loudness for the vowel /i/ would have enable cochlear implant users to perceive the vowel similar to typically developing children. In contrast, the gradual growth in loudness for the other two vowels would have hampered the loudness growth perception of cochlear implant users, resulting in them performing poorer than typically developing children.

CONCLUSION

The comparison of intensity discrimination thresholds between children using cochlear implants and typically developing children indicated that the former group had poor differential sensitivity for higher frequency warble tones. However, the thresholds were similar between the two groups for lower- and mid-frequency warble tones. Similarly, the intensity discrimination thresholds for vowels were significantly worse for children using cochlear implants for two of the vowels (/a/ and /u/). However, the sensitivity for the vowel /i/ was found to be comparable to that of typically developing children. The results indicate that children using cochlear implants are able to differentiate intensity cues of specific stimuli similar to that of age-matched typically developing children, but are unable to do so for some stimuli. Thus, it can be construed that the algorithms in different cochlear implant processors do enable children to discriminate intensity to a large extent for acoustic stimuli. However, it needs to be determined if similar findings would be obtained if electrical stimulation is provided.

Ethics Committee Approval: The ethical committee approval was taken from the Ethics Committee of the All India Institute of Speech and Hearing, Mysuru.

Informed Consent: A written informed consent was obtained from the patients and their parents.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – S.T., A.Y.; Design - S.T., A.Y.; Supervision – A.Y.; Resource - S.T., A.Y..; Materials - S.T., A.Y.; Data Collection and/or Processing – S.T.; Analysis and/or Interpretation - S.T., A.Y.; Literature Search - S.T., A.Y.; Writing - S.T., A.Y.; Critical Reviews - S.T., A.Y.

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REFERENCES

1. Ashmead DH, Leroy D, Odom RD. Perception of the relative distances of nearby sound sources. Percept Psychophys 1990; 47: 326-31. [CrossRef]
2. §Strybel TZ, Perrott DR. Discrimination of relative distance in the auditory modality: The success and failure of the loudness discrimination hypothesis. J Acoust Soc Am 1984; 76: 318-20. [CrossRef]
3. §Whiteside S. Acoustic characteristics of vocal emotions simulated by actors. Percept Mot Skills 1999; 89: 1195-208. [CrossRef]
4. Sauter DA, Eisner F, Calder AJ, Scott SK. Perceptual cues in nonverbal vocal expressions of emotion. Q J Exp Psychol (Hove) 2010; 63: 2251-72. [CrossRef]
5. §Blauert J. Spatial hearing: the psychophysics of human sound localization: MIT press; 1997.
6. Fry DB. Duration and intensity as physical correlates of linguistic stress. J Acoust Soc Am 1955; 27: 765-8. [CrossRef]
7. Fry DB. Experiments in the perception of stress. Lang Speech 1958; 1: 126. [CrossRef]
8. Lieberman P. Some acoustic correlates of word stress in American English. J Acoust Soc Am 1960; 32: 451-4. [CrossRef]
9. Zeng F-G, Shannon RV. Loudness-coding mechanisms inferred from electric stimulation of the human auditory system. Science 1994; 264: 564-6. [CrossRef]
10. §Shannon RV. Multichannel electrical stimulation of the auditory nerve in man. I. Basic psychophysics. Hear Res 1983; 11: 157-89. [CrossRef]
11. Wolfe J, Schafer E. Programming cochlear implants. United Kingdom: Plural Publishing; 2010.
12. Vaerenberg B, Govaerts PJ, Stainsby T, Nopp P, Gault A, Gnansia D. A uniform graphical representation of intensity coding in current-generation cochlear implant systems. Ear Hear 2014; 35: 533-43. [CrossRef]
13. Blamey PJ. Adaptive dynamic range optimization (ADRO): a digital amplification strategy for hearing aids and cochlear implants. Trends Amplif 2005; 9: 77-98. [CrossRef]
14. Dawson PW, Decker JA, Psarros CE. Optimizing dynamic range in children using the nucleus cochlear implant. Ear Hear 2004; 25: 230-41. [CrossRef]
15. Müller-Deile J, Kiefer J, Wyss J, Nicolai J, Battmer R. Performance benefits for adults using a cochlear implant with adaptive dynamic range optimization (ADRO): a comparative study. Cochlear Implants Int 2008; 9: 8-26. [CrossRef]
16. Boyle PJ, Büchner A, Stone MA, Lenarz T, Moore BC. Comparison of dual-time-constant and fast-acting automatic gain control (AGC) systems in cochlear implants. Int J Audiol 2009; 48: 211-21. [CrossRef]
17. James CJ, Skinner MW, Martin LF, Holden LK, Galvin KL, Holden TA, et al. An investigation of input level range for the nucleus 24 cochlear implant system: speech perception performance, program preference, and loudness comfort ratings. Ear Hear 2003; 24: 157-74. [CrossRef]
18. Spahr AJ, Dorman MF, Loiselle LH. Performance of patients using different cochlear implant systems: effects of input dynamic range. Ear Hear 2007; 28: 260-75. [CrossRef]
19. Mertens G, Punte AK, Van de Heyning P. Self-assessment of hearing disabilities in cochlear implant users using the SSQ and the reduced SSQ5 version. Otol Neurotol 2013; 34: 1622-9. [CrossRef]
20. Dorman MF, Loiselle L, Stohl J, Yost WA, Spahr A, Brown C, et al. Interaural level differences and sound source localization for bilateral cochlear implant patients. Ear Hear 2014; 35: 633. [CrossRef]
21. House D. Perception and production of mood in speech by cochlear implant users. ICSLP 1994.
22. Luo X, Fu Q-J, Galvin JJ. Vocal emotion recognition by normal-hearing listeners and cochlear implant users. Trends Amplif 2007; 11: 301-15. [CrossRef]
23. Nikakhlagh S, Saki N, Karimi M, Mirahmadi S, Rostami MR. Evaluation of loudness perception performance in cochlear implant users. Biomed Pharmacol J 2015; 8: 79-83. [CrossRef]
24. All India Institute of Speech and Hearing. Ethical guidelines for Bio-behavioural research involving human subjects. Mysore: All India Institute of Speech and Hearing; 2009.
25. Bzoch KR, League R. Receptive-expressive emergent language scale: Pro-ed; 1991.
26. Raven J. Raven progressive matrices. Handbook of nonverbal assessment: Springer; 2003. p. 223-37. [CrossRef]
27. Kwon BJ. AUX: A scripting language for auditory signal processing and software packages for psychoacoustic experiments and education. Behav Res Methods 2012; 44: 361-73. [CrossRef]
28. ANSI/ASA S3.1-1999. American national standard maximum permissible ambient noise levels for audiometric rooms. Standards Secretariate, Acoustical Society of America, R2013.
29. Levitt H. Transformed up-down methods in psychoacoustics. J Acoust Soc Am 1971; 49: 467-77. [CrossRef]
30. Drennan WR, Pfingst BE. Current-level discrimination using bipolar and monopolar electrode configurations in cochlear implants. Hear Res 2005; 202: 170-9. [CrossRef]
31. Nadol JB, Young YS, Glynn RJ. Survival of spiral ganglion cells in profound sensorineural hearing loss: implications for cochlear implantation. Ann Otol Rhinol Laryngol 1989; 98: 411-6. [CrossRef]
32. Cohen LT, Saunders E, Clark GM. Psychophysics of a prototype peri-modiolar cochlear implant electrode array. Hear Res 2001; 155: 63-81. [CrossRef]
33. Florentine M, Buus S, Mason CR. Level discrimination as a function of level for tones from 0.25 to 16 kHz. J Acoust Soc Am 1987; 81: 1528-41. [CrossRef]
34. Anzalone NM, Smith RL. The Growth of Loudness in Cochlear Implant Listeners; Possible Developmental Effects. Int Open Acce Otolary 2017; 1: 16. [CrossRef]