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REPUBLIC OF TURKEY
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THE EFFECTS OF FINE STRUCTURE STRATEGIES ON PITCH AND SPEECH PERCEPTION BY COCHLEAR IMPLANT USERS

Yılmaz ODABAŞI

Audiology Program

MASTER'S THESIS

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ANKARA
2023

DECLARATION OF INTELLECTUAL PROPERTY AND PUBLISHING

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ETHICAL DECLARATION

In this thesis study, I declare that all the information and documents have been obtained on the base of the academic rules and all audio-visual and written information and results have been presented according to the rules of scientific ethics. I did not do any distortion in the data set. In the case of using other works, related studies have been fully cited in accordance with scientific standards. I also declare that my thesis study is original except for cited references. I was produced by myself in consultation with my supervisor (Assoc. Prof. Hilal DİNÇER D'ALESSANDRO) and my co-supervisor (Prof. Patrizia MANCINI) and written according to the rules of thesis writing of Hacettepe University Institute of Health Sciences.

Yılmaz Odabaşı

ACKNOWLEDGEMENTS

I would like to acknowledge and thank:

My supervisor Assoc. Prof. Hilal DİNÇER D’ALESSANDRO, for her valuable advice, kind and professional attitude, worthy feedbacks, patience, and continuous teaching,

My co-supervisor Prof. Patrizia MANCINI, for giving me the chance to conduct my research in her department, valuable guidance, support, patience, and helpful contributions,

Prof. Gonca SENNAROĞLU, and all lecturers at Hacettepe University Audiology Department for their contributions in my education,

All colleagues at both Hacettepe University Audiology Department and Sapienza University of Rome, Umberto Policlinico I, Cochlear Implant Center,

And my loved ones for their support and joy.

ABSTRACT

Odabaşı, Y., The Effects of Fine Structure Strategies on Pitch and Speech Perception by Cochlear Implant Users, Hacettepe University Graduate School of Health Sciences Audiology Program Master's Thesis, Ankara, 2023. Cochlear implant (CI) users show close to normal speech understanding performances in quiet listening conditions. However, skills requiring the better use of Temporal Fine Structure (TFS) cues and low frequency (LF) resolution such as speech understanding in noise, pitch perception and music perception are more challenging. Some CI listeners show better performances in the Disharmonic Intonation (DI) test, which is used for pitch perception evaluation. CI users use two different mechanisms to discriminate pitch: Rate Pitch (RP) which is the ability to discriminate pitch changes within the same intracochlear electrode and Place Pitch (PP) which is to discriminate pitch changes by the change of coding place to an adjacent electrode. Most CI speech processing strategies don't convey TFS information, but Med-El's FS coding strategies provide the listener with the TFS information. Previous studies reported that most CI listeners perform poorly in the DI test, whilst there are also performers with normal/close to normal results. This can be related to speech processing strategies of the CIs. Participants were 15 unilateral and 15 bilateral postlingual adult CI users fitted with FS coding strategies. Pitch and speech perception are evaluated with the DI test, words and sentences recognition in quiet and in noise for +10 and +5 signal noise ratio (SNR) and the Matrix test. Overall group showed an average median just noticeable difference (JND) of 33 Hz in the DI test. RP performers had significantly better DI scores than PP performers, 9 Hz vs 148 Hz, respectively. DI scores within the clinical normal zone are achieved by 33.3% and only by RP performers. Group comparisons for RP/PP performers showed statistically significant differences for word recognition scores in noise and for the Matrix test. With the FS coding strategies, RP ability's positive effect on both pitch and speech perception is observed in this study.

Keywords: Cochlear Implants, Temporal Fine Structure, Pitch Perception, Speech Perception

ÖZET

Odabaşı, Y., Koklear İmplant Kullanıcılarında İnce Yapı Stratejilerinin Perde ve Konuşma Algısına Etkileri, Hacettepe Üniversitesi Sağlık Bilimleri Enstitüsü Odyoloji Programı Yüksek Lisans Tezi, Ankara, 2023. Koklear implant (Kİ) kullanıcıları sessiz dinleme koşullarında normale yakın konuşmayı anlama performansı göstermektedir. Ancak gürültüde konuşmayı anlama, perde algısı ve müzik algısı gibi temporal ince yapı (TİY) ipuçlarının ve düşük frekans (DF) çözümlemenin daha iyi kullanılmasını gerektiren beceriler daha zorlayıcı olmaktadır. Bazı Kİ dinleyicileri, perde algısı değerlendirmesi için kullanılan Disharmonik Entonasyon (DE) testinde daha iyi performans göstermektedir. Kİ kullanıcıları perde algısı için iki farklı mekanizma kullanır: aynı intrakoklear elektrottaki perde değişikliklerini ayırt etme becerisi olan *Rate Pitch (RP)* ve perde değişikliklerini kodlama yerinin bitişikteki diğer elektrota geçmesiyle ayırt etme becerisi olan *Place Pitch (PP).* Çoğu Kİ konuşma işlemleme stratejisi TİY bilgisini iletmez fakat Med-El'in Fine Structure (FS) kodlama stratejileri dinleyiciye TİY bilgisini sağlar. Önceki çalışmalarda bazı Kİ dinleyicilerinin DE testinde düşük performans gösterirken normal/normale yakın sonuçlara sahip dinleyicilerin de olduğu raporlanmıştır. Bu durum Kİ'lerin konuşma işlemleme stratejileriyle ilgili olabilir. Katılımcılar FS kodlama stratejileri ile ayarlanmış 15 unilateral ve 15 bilateral postlinguel yetişkin Kİ kullanıcısıdır. Perde ve konuşma algıları DE testi, sessiz ve +10 ve +5 sinyal gürültü oranlı (SGO) kelime ve cümle tanıma skorları ve Matrix testi ile değerlendirilmiştir. Genel grubun DE testinde medyan değeri 33 Hz olarak bulunmuştur. *RP* becerisi gösteren bireylerin DE skorlarının *PP* becerisi gösterenlerinkinden anlamlı ölçüde daha iyi olduğu gözlenmiştir (sırasıyla 9 Hz ve 148 Hz). Normal klinik aralıktaki DE skorları sadece dinleyicilerin %33.3'ü tarafından ve sadece *RP* becerisi gösterenler tarafından elde edilmiştir. *RP/PP* becerisi gösterenler için grup karşılaştırmaları gürültüde kelime tanıma skorları ve Matrix testi için istatistiksel olarak anlamlı farklar göstermiştir. FS kodlama stratejileri sayesinde *RP* becerisi gösteren dinleyicilerin hem perde hem de konuşma algısı üzerindeki olumlu etkileri gözlemlenmiştir.

Anahtar Kelimeler: Koklear İmplant, Temporal İnce Yapı, Perde Algısı, Konuşma Algısı

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LIST OF ABBREVIATIONS

AB	Advanced Bionics
ACE	Advanced Combination Encoder
A§E	Auditory Speech Sounds Evaluation
BE	Better Ear
CI	Cochlear Implant
CIS	Continuous Interleaved Sampling
dB	Decibel
DI	Disharmonic Intonation
EAS	Electroacoustic Stimulation
et al.	et alli
F0	Fundamental Frequency
FS	Fine Structure
FS4	Fine Structure 4
FS4-p	Fine Structure 4 - Parallel
FSP	Fine Structure Processing
HI	Harmonic Intonation
HDCIS	High-Definition Continuous Interleaved Sampling
HS	Head Shadow
HiRes	High Resolution
ILD	Interaural Level Difference
ITD	Interaural Time Difference
JND	Just Noticeable Difference
LF	Low Frequency
PP	Place Pitch
PTA	Pure Tone Average
RP	Rate Pitch
SD	Standard Deviation
SF	Sound Field

SNR	Signal Noise Ratio
SPEAK	Spectral Peak
SQ	Binaural Squelch
SRS_q	Sentence Recognition Score in Quiet
SRS+10	Sentence Recognition Score in +10 SNR
SRS+5	Sentence Recognition Score in +5 SNR
SRT	Speech Reception Threshold
SU	Binaural Summation
TFS	Temporal Fine Structure
WRS_q	Words Recognition Score in Quiet
WRS+10	Words Recognition Score in +10 SNR
WRS+5	Words Recognition Score in +5 SNR
%	Percent

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1. INTRODUCTION

The number of people who are benefiting from cochlear implants (CIs), which are implantable devices for patients with hearing loss, are increasing day by day. CIs are unarguably life changing and one of the most successful ones among currently available neural prostheses. CIs are not a “cure” for hearing loss but rather a rehabilitation method, helping people to restore functional hearing by electrically evoking the auditory system beyond the cochlea (1, 2).

Individuals benefiting from CI systems are showing great performances on speech understanding in quiet listening environments. This was an on-target achievement, considering the fact that when the CIs first became available, the principal aim was to help people to understand speech and to be able to communicate. However, providing the listeners only with the speech understanding capability in situations without noise is outdated. It’s known that daily listening conditions are not always ideal for CI users because there might be background noise and listening in competing noise is a rather hard task for them (3, 4).

Performances such as speech understanding in competing noise and music perception demanding higher spectro-temporal resolution can be troubling for the CI listeners. These performances require more detailed processing skills of acoustic information. Such skills are also linked to pitch, which is typically defined as the perceptual equivalent of frequency (4, 5). CI users discriminate pitch changes with two different mechanisms called Rate Pitch (RP) and Place Pitch (PP). RP refers to the ability to discriminate the pitch changes within the same electrode while PP refers to the ability to differentiate pitch, not in the same electrode but by the change of coding, or place, to the next closer electrode (6).

When the acoustic signals are picked up by CIs, the sound information gets digitalized and turned into electrical pulses. These processing mechanisms differ between CI systems, and they are called “sound processing strategies”. CI systems which use early processing strategies are insufficient on listening skills such as pitch perception, speech understanding in noise, and music perception (7).

The sound processing strategies continue to be improved and such developments help people to achieve a better listening quality. Med-El's (Innsbruck, Austria) Fine Structure (FS) coding, important for the objectives of the present study, consists of three coding strategies: FSP, FS4 and FS4-p. FS coding strategies use a set of acoustic information called Temporal Fine Structure (TFS) to achieve a better pitch perception (8, 9).

Auditory Speech Sounds Evaluation (A§E) test suite contains the Disharmonic Intonation (DI) test, which can be used to evaluate low frequency (LF) pitch perception (5, 10). It is well-known that CI users have poor pitch perception skills, however, previous studies show normal or close to normal performances in the DI test for some CI listeners (5, 11, 12). The reason why some CI users perform better than others is unclear. In these studies, inter individual variability is high, CI brands, processors and speech processing strategies are variant, and the sample size is too small to have an explanation why some CI listeners show better performances. One possible explanation might be that the speech processing strategies' effects on pitch perception. FS coding strategies are aimed to have more detailed use of LF cues and TFS information which are important for pitch perception. The effects of FS coding strategies on pitch perception, the use of RP or PP mechanisms and their relationship with speech perception were not evaluated in the previous studies. Therefore, the aims of this study were to investigate the effects of FS strategies on pitch and speech perception in unilateral and bilateral CI users. The hypotheses of the study were:

Hypothesis 1:

H0: CI users fitted with FS coding are not able to discriminate pitch changes by RP.

H1: CI users fitted with FS coding are able to discriminate pitch changes by RP.

Hypothesis 2:

H0: Pitch perception skills for CI users with RP ability are not better than those with PP ability.

H1: Pitch perception skills for CI users with RP ability are better than those with PP ability.

Hypothesis 3:

H0: Speech perception skills for CI users with RP ability are not better than those with PP ability.

H1: Speech perception skills for CI users with RP ability are better than those with PP ability.

Hypothesis 4:

H0: Significant performance differences for pitch/speech perception are not present between unilateral versus bilateral CI users fitted with FS coding.

H1: Significant performance differences for pitch/speech perception are present between unilateral versus bilateral CI users fitted with FS coding.

Hypothesis 5:

H0: Significant performance differences for pitch/speech perception are not present between BE versus bilateral listening mode, in CI users fitted with FS coding.

H1: Significant performance differences for pitch/speech perception are present between BE versus bilateral listening mode, in CI users fitted with FS coding.

Hypothesis 6:

H0: Speech perception test material/mode does not have significant effects on RP/PP correlations.

H1: Speech perception test material/mode has significant effects on RP/PP correlations.

2. REVIEW OF THE LITERATURE

2.1. Cochlear Implants

CIs are devices that aim to restore functional hearing by stimulating the auditory nerve electrically, in individuals with severe to profound hearing loss. Years before today's technology, Djourno and Eyriès implanted an electrode to a patient's inner ear who had bilateral profound hearing loss (13). They come up with a sound sensation when the patient's 8th nerve is stimulated. This could be considered as the first human CI (14, 15).

With the new developments, CIs can restore hearing functionally. In situations where there is an impairment in the auditory system, but the auditory nerve is still capable to carry acoustic signals, CI's can be an effective treatment tool. Hence, CIs bypass the impaired parts of the inner ear and electrically stimulate the 8^{th} nerve. The aim for this is to directly deliver the acoustic signals by evoking the nerve fibers. When this electrically coded sound information carried by the nerve fibers reaches the auditory cortex, "hearing" is achieved (1, 16-18). Such auditory sensation is different from acoustic hearing and the coding of environmental acoustic information may differ between CI technologies and processing strategies (7). During fitting sessions, some parameters of sound processing can be adjusted to optimize the patient's performance (19).

CIs have become a standard procedure for children born with bilateral severe to profound hearing loss and they can be considered as the most effective treatment for individuals with higher levels of hearing impairment (2, 16). Today, CIs are equipped with multiple electrodes to stimulate the different areas of the cochlea and to mimic its tonotopic organization. Current advances in CI technology allow novel types of acoustic information, such as loudness and pitch to be processed better progressively (9, 20, 21).

CIs have external (worn, carried behind the ear or another place on the body) and internal (implanted) parts. While the typical external components are the processor, transmitting coil and the cable between these two units; internal parts are the receiver coil, the electrode array and the ground electrode (16, 20). The processor's role is to pick up the environmental sound signals with the microphone(s) and to convert these acoustic signals into digital information by some algorithms called "sound processing strategies". This process will be explained in detail in a future chapter (2.3. Speech Processing Strategies). The processed form of the sound signal has to be transferred to internal parts of the CI, and this is provided by the transmitting coil. The signal is transferred electromagnetically to the receiver coil, which is right under the skin, where the external coil sits on with the help of the internal magnet of the receiver. After the signal arrives in internal parts of the CI, the cochlear electrodes are stimulated according to the processed information coming from the external part. The nerve fibers pick up these stimulants or "sound information" and send them to the auditory cortex (1, 16, 20).

2.2. CI Candidacy

When CIs started to become available as a rehabilitation method, bilateral profound hearing impairment was the requirement for the implantation. However, recently the indications for CIs have expanded enormously. As a result, the number of individuals with CI's are increasing faster compared to the first years of cochlear implantation. Nowadays, the age for implantation ranges from as young as 9 months of age to seniors with 70+ years of age (21, 22).

The importance of auditory information on a child's development is well-known and in many countries children with hearing loss can get implanted at a young age. Moreover, the benefits of binaural hearing have been discussed and proven previously as well (23-25). An implanted child with bilateral hearing loss can get a hearing aid to the contralateral ear to provide bimodal hearing and to benefit binaural advantages. Another option is a second CI in the contralateral ear and this approach is strongly advised for children with bilateral severe to profound hearing loss (23). A large retrospective study conducted by Blamey et al. (26) showed a significant advantage of bilateral cochlear implantation versus bimodal rehabilitation on speech understanding. When provided with systematic auditory therapy, bilateral implantation at an early age allows even profoundly hearing-impaired children to achieve age appropriate spoken language skills as they grow up (23, 27, 28).

Studies also show that adult CI users are much more social and productive than their non-implanted hearing-impaired counterparts. There is a considerable number of adults, who are socially active and satisfied with their lives thanks to their CIs (29, 30). Today, people from various age groups can receive a CI if they cannot benefit from their natural hearing or auditory prostheses such as hearing aids or other implantable devices, certainly if they match with the criteria that has been set by their healthcare system (21, 22).

The criteria for CI candidacy differ between countries/regions. Certainly, CI technology, fitting techniques and outcome benefits improved significantly compared to the very first years of cochlear implantation. This situation raises questions about the selection criteria that are still in rule today. The candidacy process should be carefully planned and highly individual, which is also the case in current practice. Thus, expanding just the limits of candidacy may not have a significant effect in resolving problems of inter-individual performance variabilities. Indeed, allowing professionals to evaluate each patient individually without limiting themselves with the selection criteria would positively contribute to further advances in CI technology, individual-based achievements and personal/social quality of life in general (21, 31).

2.3. Speech Processing Strategies

The healthy human cochlea uses tonotopic organization to code acoustic information gathered from the environment. The cochlea is believed in particular to be dominant for perception of pitch and loudness which are psychophysical attributes of the frequency and intensity information obtained from the physical acoustic environment (1, 32). However, pitch perception in CI users is considerably poorer due to CIs limitations in the number of electrodes, and the spectro-temporal and dynamic range processing capacities (7). Moreover, anatomic structures and physiological mechanisms of the auditory system in hearing-impaired individuals do not function as good as in healthy hearing people (1, 15).

Since the CIs can only partially restore hearing, CI users are believed to have insufficient sound coding (7). The maximum number of available intracochlear electrodes is 22 in CIs and intracochlear CI electrodes are not as precise as a healthy cochlea for tonotopic organization. Besides, CI's electrical stimulation has a much narrower dynamic range (10 to 20 dB) compared to the dynamic range of normal hearing (100 dB) (17, 18).

Despite their downsides compared to normal hearing, CIs are considered as a very efficient solution for hearing loss. Advances in CI technology such as the development of new speech processing strategies might be helpful for improving the auditory benefit in CI users. CIs provide the listeners with a set of alternatives for speech processing strategies. During individual fitting sessions, some parameters such as the strategy's spectral and dynamic range can also be adjusted to optimize a CI user's performance (19, 33).

2.3.1. Continuous Interleaved Sampling (CIS)

The Continuous Interleaved Sampling (CIS) is a strategy which sequentially stimulates the CI's electrodes, using bandpass filters to filter sounds, diverting the sound information into frequency bands. CIS was developed by Wilson et al. (34) in 1991. It is generally based on envelope information and does not contain TFS cues. The envelope information is delivered into electrodes according to their proper counterparts in cochlear tonotopic organization. After this envelope information is collected, it goes through a nonlinear mapping procedure in order to compress the sound signals. The reason for compressing is that the pre-processed environmental sound signals have a much bigger dynamic range compared to the CI listener's electrical dynamic range (7).

The theory behind this strategy was that higher stimulation rates, between 600 – 1800pps in CIS, may better transmit acoustic signals. Higher stimulation rates provide improved representations in temporal changes compared to the slower stimulation rates (7).

2.3.2. The n-of-m, Spectral Peak (SPEAK) and Advanced Combination Encoder (ACE)

The n-of-m strategy is used by Med-El while Spectral Peak (SPEAK) and Advanced Combination Encoder (ACE) strategies are used by Cochlear. Their common feature is that these strategies have a channel-selection design for stimulation. The channel-selection design uses the envelope information from the different channels. It determines n number of channels which have a greater amplitude in between m number of channels, before stimulating the electrodes, so that only these n number of electrodes can be stimulated. The theory behind this is when using only the high amplitude channels and eliminating others, the density of stimulation is reduced, this helps the listener by decreasing the masking and interference from low-amplitude channels. At the same time, more essential acoustic information is delivered from the high-amplitude channels, the listener benefits from this by receiving acoustic information with better signal to noise ratio (SNR) (7).

The n-of-m and ACE strategies are based on higher stimulation rate while the SPEAK strategy has relatively lower stimulation rate. They all use envelope information and do not transmit TFS cues. It can be said that n-of-m and ACE strategies are very similar and the only difference between them and the CIS strategy is the above-mentioned channel-selection procedure (7, 19).

2.3.3. Fine Structure Processing (FSP)

For the development of CI speech processing strategies, the main focus has been to improve speech understanding. It can be said that strategies such as ACE, CIS and n-of-m achieved this goal. However, for CI users, speech intelligibility in noise, pitch perception or enjoying music is often unsatisfactory with these strategies. The main reason for this is that the necessary information for such skills is not processed, or not on primary focus for these strategies. This can be explained by missing TFS cues (7).

TFS is a frequency modulated carrier and it can be defined as rapid amplitude variations on the zero crossing of the signal. Envelope is the slower amplitude fluctuations over time in speech sounds (32, 35). TFS and Envelope are decomposed from the sound signals, and they are important for processing acoustic information (11).

Previously mentioned speech processing strategies are mainly focused on envelope cues and they do not deliver TFS information. This results in CI users having trouble understanding speech in competing noise while having quite gratifying speech intelligibility performances in the absence of background noise (3, 4). Med-El introduced FineHearing Technology to improve CI sound processing by conveying TFS information in the relatively LFs of the sound signals picked up by CI's. These sound signals at LFs contain TFS cues, which are not possible to be transmitted in the envelope information zone. FSP, FS4, and FS4-p speech processing strategies by Med-El are known for representing TFS information by mimicking the phase-locking of LF nerve fibers with the incoming signal to improve decoding of temporal information (7, 8).

FSP is the first version of fine structure processing strategies. Unlike Med-El's previous CIS strategies which has an input frequency range between 250-8500 Hz, FSP has an input frequency range between 100-8500 Hz (36). The biggest motivation for this is to better represent fundamental frequency (F0) of the sound signal. TFS information can be found in FSP strategy up to 350-500 Hz, by first two or in other words, two of the most apically placed electrodes (37).

FS4 and FS4-p are evolved versions of FSP, they both convey TFS cues up to 750-950 Hz by using the first four or four most apical electrodes. The difference between them is while FS4 has sequential stimulation, FS4-p allows simultaneous stimulation of four most apical channels. Both for FS4 and FS4-p, when the upper frequency limit is fixed at somewhere below 950 Hz, the apical electrodes representing that range are used as TFS channels. On the other hand, when the total number of active electrodes are less than 10, the number of TFS channels reduce to three (7, 8).

FSP strategy consists of 1 to 3 FS processing channels, depending on the individual stimulation rate of the CI user.

In FS4, the first 4 channels in the default filter-bank configuration are used for FS transmission. In FS4-p, the number of FS channels and the frequency range is equal to FS4 and in addition, up to 2 FS channels are stimulated in “parallel” simultaneously in case the stimulation pulse patterns coincide temporally (7, 8).

A study which compares FSP, CIS+ and High-Definition CIS (HDCIS) found that FSP is better in discriminating vowels and monosyllabic words when compared to CIS+. All three strategies are similarly well in speech perception tests and an evaluation on experienced CI users suggest that for speech and music, users prefer FSP (9). An intra-individual comparison study by Arnoldner et al. (38) showed that CI users have significantly improved results on speech and music tests after their strategy is converted to FSP from CIS. Listeners showed most significant improvements in speech test in noise, which is considered the more difficult speech test and 78% of the listeners preferred the FSP strategy over CIS, regarding speech understanding (38). Another study by Riss et al. (39) also showed statistically significant improvements for the sentences at 10 dB SNR for CI users using FS coding strategy with Opus speech processor.

Research about the effect of LF filter assignment with the use of FSP coding strategy by Riss et al. (36) showed no statistically significant differences with the HDCIS coding strategy on speech perception. Another study comparing HDCIS and FS4 strategies revealed that FS4 strategy outperforms HDCIS in music perception (40).

A study conducted on CI users with FSP, FS4 and FS4-p strategies which also used FSP coding strategy previously, revealed that there were no statistically significant differences between three FS coding strategies on speech perception in noise (8). Recent study about FS coding strategies suggests that formant frequency discrimination thresholds were significantly better in FS4 strategy compared to FSP strategy, which is related to extension of FS range. Although speech perception in quiet and in noise did not differ significantly between the two strategies (41).

2.3.4. HiResolution (HiRes)

Similar to FSP, HiRes sound processing strategy introduced by Advanced Bionics (AB) also contains TFS information of the sound signal. HiRes has a high stimulation rate and a high cut-off frequency for envelope cues, which allows LFs to represent some TFS information (7).

HiRes with the Fidelity 120 or simply HiRes 120, which is a different variation of HiRes strategy, allows the spectral analysis of sound signals in each of the band-pass filters by using the leading spectral peaks. This strategy also allows peak frequencies to be in correlation with two adjacent electrodes. AB implants use 16 intracochlear electrodes which means that there are 15 in-between electrode zones. These combinations of relative currents are used to create virtual channels. The theory behind virtual channels is, when two neighbor electrodes are stimulated simultaneously, depending on the amount of current shared between them, the pitch grasped by the listener differs. For example, if electrode number 5 is stimulated alone, only the zone corresponding to electrode number 5 is receiving information. But if electrode number 5 is stimulated by %25 of the amplitude and electrode number 6 is stimulated by the remaining %75 of the amplitude simultaneously, another zone in between these electrodes, which is closer to electrode number 6, will receive the information. This allows the implant to have more stimulation zones and the number of stimulation zones can be increased by manipulating the amplitude shared between two neighbor electrodes. It is believed that by using these virtual channels, more precise spectral resolution can be achieved because of the increased number of distinguishable areas and neural activity (42, 43). In theory, more precise spectral resolution leads to more detailed pitch perception. Although this is not guaranteed, in this way the listener can distinguish smaller frequency differences, resulting in the speech and music perception to be affected positively (7).

HiRes 120 provides better temporal and spectral resolution of the sound signals, compared to early CI strategies. In HiRes 120, 15 in between electrode areas have 8 different virtual channels, these 8 different zones are created by sharing the amount of current between adjacent electrodes in different ratios as mentioned above, adding up to 120 stimulation sites in total. The simultaneous stimulation of two electrodes differs HiRes with Fidelity 120 from HiRes strategy (7).

2.4. Pitch and Speech Perception

2.4.1. Pitch Perception

The auditory system benefits from different components of sound waves to distinguish speech. Pitch is one of these important attributes of the acoustic signal. Pitch can be simply defined as the perceptual equivalent of the repetition rate of acoustic waveforms. Frequency contents of sounds can be associated with pitch, in the same way intensity of the sound can be associated with loudness (5).

Pitch has quite important contributions for sound quality, music perception and speech perception (4, 44). In music, pitch relates to melody and combinations of pitch relates to harmony while in speech, changes in pitch bring out prosody (11, 45). Pitch's effect on prosody can even change the meaning of the words in tonal languages such as Mandarin Chinese, Vietnamese, and Thai (46). It is known that pitch information is essential for music perception and appreciation (44, 47). Therefore, improving music perception in CI patients may also result with improved speech in noise performances and increased quality of life (47). Adult CI users usually describe their music listening experience with their implants as "disappointing" and "unpleasant" (48). It is challenging for postlingually deafened CI users to enjoy music as much as their natural hearing experience before implantation. Music comprehension requires simultaneous, multiple pitch perception and high spectral resolution (49). CIs generally have a mismatched tonotopic organization because of the placement of intracochlear electrodes. Moreover, CI systems rely on envelope cues for the pitch information and envelope cues are particularly limited for transmission of F0s in the LF region (7).

In daily listening conditions, especially in the presence of a competing background noise, differences in pitch can be helpful for listeners to discriminate the acoustic sources. A healthy cochlea does it by comparing the F0s of the competing sound sources. Therefore, for a CI to successfully accomplish the segregation of sounds, the F0s should be properly coded (7, 32). Oxenham et al. (50) found that when LF harmonics are sent to the high frequency regions of the cochlea, the listeners were not able to determine F0s of the sound signals. This highlights the importance of proper tonotopic representation for pitch perception. Another study conducted by Miyazono and Moore (51) conclude that discrimination of F0 can be related to TFS cues on low and intermediate harmonics while on higher end harmonics, it can be more related to envelope cues.

There are two underlying mechanisms for explaining cochlear spectral coding, or coding of pitch information. These are place coding and phase locking (52). These mechanisms are not strictly separated, so both can be present for pitch perception in the same sound signal, at the same time. For LF sound signals, phase locking mechanism is more dominant for pitch perception. Phase locking mechanism is time-related and uses the TFS information of the sound. This mechanism takes the frequency of the sound signal as a guide and ensures the firing rate of the auditory nerve fibers to be at the same frequency of the original signal. Lately, to improve pitch perception, TFS cues are attempted to be represented better in speech processing strategies. For high frequency sound signals, place coding mechanism is more dominant for pitch perception. Place coding mechanism relates to tonotopic excitation. Information carried by the sound signal is delivered not in a neural synchrony like in phase locking but with spatial alteration of nerve fibers (12, 36, 52, 53).

The concepts RP and PP should be explained to have a better understanding on the evaluation of pitch discrimination in CI users. When two acoustic signals are processed by the CI system, the signal’s corresponding frequency region is stimulated by the intracochlear electrode. In situations where the CI user’s electrode range covers frequencies of two different acoustic signals, the same electrode will be stimulated for both signals. On the contrary, when the frequency difference is larger than the electrode's frequency range, different electrodes will be stimulated for two signals. In this regard, RP refers to the ability to discriminate pitch changes in the same electrode while PP refers to the ability to distinguish pitch, not in the same electrode but by the change of coding, or place, to the next adjacent electrode (6).

In general, pitch information is not successfully conveyed by CIs. Dinçer D'Alessandro et al. (12) showed that the larger part of CI users has poor TFS processing, which is related to LF pitch perception. Considering the design of CIs, mimicking tonotopic excitation or creating a spatial alteration of nerve fibers in the cochlea is challenging. This incapability can be related with the number of electrodes being limited, poor spread of current and even the amount of surviving neural fibers on high frequency zones (4, 50). On the other hand, using a time-related mechanism and providing neural firing with the same frequency as the sound signal is more realistic because of the advanced electric stimulation abilities of CIs. Processing strategies like SPEAK, ACE and CIS have been of great use over time by using envelope information instead of TFS cues and accomplished good results in quiet listening conditions. Despite that, since the F0s needed for segregating competing sound sources which helps a better speech understanding in noise are related to TFS information, CI processing strategies using TFS such as FSP and HiRes can accomplish better outcomes in listening conditions in noise. As discussed, pitch perception is undeniably important for speech perception (4, 7, 19, 35).

2.4.2. Speech Perception

For speech intelligibility, envelope and TFS information are the major acoustic components. Envelope cues are usually related to acoustic structure; therefore, it is believed that envelope plays a big role in speech understanding (7, 54). This is the main reason why CI sound processing used envelope-based strategies for a long time (36).

Another important aspect for speech perception is binaural hearing. The auditory system is structured binaurally, and natural hearing occurs with two ears. The sound localization on the horizontal plane is based on interaural time differences

(ITDs) and interaural level differences (ILDs). ITDs can be basically defined as the difference of sound wave's arrival time between two ears while ILDs are the difference between the loudness of sound sources. ITDs are mainly used for localizing LF sounds and ILDs are more related to localization of high frequency sounds (25, 55). With important features like ITDs and ILDs, bilateral CI users are benefiting from higher quality of listening, better auditory sensitivity, sound localization and advanced speech in noise intelligibility compared to unilateral CI users (56, 57).

Speech perception skill in CI users has been improving over time. For years, sound processing strategies that are mainly based on envelope information like SPEAK, ACE and CIS were used, and CIs have been considerably successful devices for speech understanding with these strategies (7). The envelope carries important cues for speech and people with CIs have similar (or close to similar) performances to their normal hearing counterparts for speech perception in quiet situations (3, 35). But for a healthy speech perception, envelope information alone is not adequate. As discussed before, it is known that TFS cues are helpful for speech understanding in competing noises, pitch discrimination and music perception (4, 44, 47).

2.4.3. A§E Psychoacoustic Test Suite: Harmonic Intonation (HI) and Disharmonic Intonation (DI) Tests

Auditory Speech Sounds Evaluation (A§E) Psychoacoustic Test Suite consists of a set of psychoacoustic tests, using phonemes or speech sounds as test materials. This test suite allows professionals to evaluate listeners' ability of detection, discrimination, identification, loudness perception and localization. The test suite is specifically designed for use in people with hearing aids, CIs or any other auditory prosthesis. Most of the tests in A§E are suprathreshold and language-independent, they also don't require any extra equipment but a compatible multimedia speaker (10).

A§E Psychoacoustic Test Battery consists of five different sections. These are, Classics (1) which includes Phoneme Detection, Phoneme Discrimination and Phoneme Identification subtests, Prosody (2) which includes Sentence Intonation and Word Stress Pattern subtests, Synthetics (3) which includes Harmonic Complexes, Harmonic Intonation and Disharmonic Intonation subtests, Loudness Scaling (4) and Localization (5). Among these tests, HI and DI tests are suitable for assessment of LF pitch perception (5, 12, 58). Therefore, these two tests will be explained in more detail.

HI and DI tests developed by Vaerenberg et al. (5) consist of harmonic complexes, which are basically made of an F0 and its three harmonics, e.g., F0 of 200 Hz and its three harmonics as 400, 600, 800 Hz. In harmonic complexes, every harmonic's intensity is 6 dB lower than the previous one.

HI and DI tests are evaluating the ability of discriminating pitch changes of two tones, based on their harmonic or disharmonic frequency sweeping. In HI, frequency sweep is present at F0 of 200 Hz and its all harmonics while in DI the frequency sweep is only present at F0 of 200 Hz (5). Compared to HI, DI focuses more on LF changes because of the absence of sweeping at higher harmonics. Findings from both tests are affected by the TFS cues and LF resolution ability. This reasoning can be supported by research conducted on different groups with high or LF hearing loss by Vaerenberg et al. (5) and Heeren et al. (58), showing significantly poorer performance in patients with LF hearing loss for both tests, with considerably higher (worse) scores in DI test.

The test validation and test–retest reliability approves the verification for both HI and DI tests (58). In normal hearing adults, the median just noticeable difference (JND) values for HI and DI tests are 2.0 and 3.0 Hz, respectively (5). Another research by Dinçer D'Alessandro et al. (59) shows that also children with normal hearing have similar JND values, 2.0 Hz for HI and 5.0 Hz for DI. The study also suggests the fact that big part of CI users have inconclusive results in these tests, which highlights insufficient TFS coding of CIs. Although some CI listeners have similar results with normal hearing population in HI test, both HI and DI tests disclosed abnormal LF pitch perception when CI users are compared to normal hearing listeners (5, 11, 59). When CI only condition and electroacoustic stimulation (EAS) were compared for speech perception and TFS, statistically significant differences were observed for speech perception at a fixed +10 SNR (60). Previous literature also showed that both in children and adults, speech recognition in quiet was not in significant correlation with TFS sensitivity evaluated by HI and DI tests (11, 59).

Dinçer D'Alessandro et al. (12) suggested that the correlation between HI and STARR test proves listeners with CI, who are able to make use of TFS cues offered by relatively higher frequency and place cues are showing better speech understanding performances in noise. The study also highlights the positive effect of bimodal listening on DI. The bimodal users may have better listening results with the assistance that they gain from LF TFS cues provided by their LF residual hearing and contralateral hearing aid.

In DI test, F0 of 200 Hz sweeps 0 to 214 Hz while higher harmonics remain the same. Keeping the higher harmonics fixed while the F0 is sweeping, may cause beating. This situation may introduce a new cue other than actual coding ability, that could bias the results. That's why JND above 130 Hz were considered as PP. The technical calculation for this is reported by Vaerenberg et al. (5).

2.4.4. Speech Perception in Noise and the Matrix Test

Daily listening conditions include noisy environments as well as silent situations. CI users have significantly better performance of speech perception when background noise is absent, close to normal hearing listeners. But they usually have insufficient speech perception in noise (3, 4, 35).

Audiological assessments which are focused on understanding speech sounds in various listening conditions are frequently used in clinics. Providing the ability to communicate is the main goal of CIs and testing this ability in different scenarios is the realistic approach for everyday situations. The Matrix Sentence test is a useful test for this purpose (61, 62).

For the assessment of the listener's ability to understand speech, the most fundamental approach would be presenting words or sentences to the listener and asking them to repeat what they hear. Commonly used speech understanding tests usually have pre-recorded words or sentences which are phonemically balanced and well-known. The problem with these tests is that creating multiple word or sentence lists can be time consuming since the chosen words or sentences must meet the conditions and go through various adjustments before being able to use them as a reliable source for estimating speech understanding. The Matrix test overcomes this problem by using 50 well-known words, usually 10 names, 10 verbs, 10 numbers, 10 adjectives and 10 objects and randomly rearranging them in every presentation, which results with it being a closed-set speech performance evaluation test (62-64). The words always arrange in a way to have the same syntactic structure, and this makes a total of 10^5 possible sentences. This situation also makes sentences that have low semantic predictability to the listener (62, 63). The Italian Matrix Test is created by choosing 50 commonly known two or three syllabic words, recording the audio, generating background noise, applying level adjustments, and taking evaluation measurements (64).

In daily listening conditions, there are numerous scenarios, listeners can be in a quiet environment as well as in a situation where the background noise is too much. Matrix test sentences are presented with a background noise to match these listening scenarios. The intensity of the background noise changes depending on the performance of the listener, making it an adaptive test for evaluating speech perception in realistic listening conditions. Adaptive SNR availability feature of Matrix test allows it to be more realistic, compared to tests which use fixed SNR. The Matrix test takes the average dB SNR level where 50% of the sentences are correctly repeated by the listener (62, 64).

As of the time this study is conducted, the Matrix test is available in 20 languages worldwide, which makes it available for cross-language comparisons (65). The Italian version of Matrix test, which is developed by Puglisi et al. (64), is used in this study. The Italian Matrix test has average speech reception threshold (SRT) of –7.3 dB SNR for normal hearing native Italian speakers with 0.5 dB test–retest reliability.

The Matrix test can be considered as a challenging test for CI users since implanted patients show considerably poorer performances, even with the superior CI performers and bimodal listeners, when they are compared to their normal hearing counterparts (63, 66). The Italian Matrix test shows an average SRT of 4.15 dB SNR for CI-only condition, in bimodal native Italian speaking users and 2.85 dB SNR for bimodal listening mode, in a recent study conducted by Gallo and Castiglione (66). Another study on elderly Italian population by Mancini et al. (67) showed 12.5 dB SNR for CI-only mode and 8.1 dB SNR for bimodal listening mode on Italian Matrix test.

Names	*Verbs*	*Numerals*	*Nouns*	*Adjectives*	*English translation*
Sofia	compra	due	**scatole**	azzurre	*Sofia buys two light-blue boxes.*
Marco	vuole	poche	matite	piccole	*Marco wants a few small pencils.*
Anna	prende	quattro	tazze	normali	*Anna takes four normal cups.*
Sara	**dipinge**	cinque	pietre	nuove	*Sara paints five new stones.*
Chiara	vede	**molte**	tavole	belle	*Chiara sees many nice desks.*
Maria	cerca	sette	palle	bianche	*Maria looks for seven white balls.*
Luca	trascina	otto	macchine	grandi	*Luca drags eight big cars.*
Andrea	regala	nove	sedie	**utili**	*Andrea donates nine useful chairs.*
Matteo	possiede	dieci	bottiglie	nere	*Matteo owns ten black bottles.*
Simone	manda	venti	porte	rosse	*Simone sends twenty red doors.*

Figure 2.1. Italian Matrix test sentences. Bold words represent an example of one random sentence (64).

The effects of FS coding strategies on pitch perception, the use of RP or PP mechanisms and their relationship with speech perception were not evaluated in the previous studies. Therefore, the aims of this study were to investigate the effects of FS strategies on pitch and speech perception in unilateral and bilateral CI users.

3. MATERIALS AND METHODS

This prospective study was conducted in Sapienza University of Rome (Rome, Italy) as a Thesis for the Audiology Master's Programme at Hacettepe University, Institute of Health Sciences. It was carried out in accordance with the ethical requirements of the Helsinki Declarations, the Epidemiological Good Practice Guidelines of the International Conference of Harmonization, and the existing legislation in Italy and it was approved by the Policlinico Umberto I- Rome Ethics Committee (n. 259/2020).

3.1. Participants

Participant recruitment for the present study regarded the following criteria:

3.1.1. Inclusion Criteria

- Being adult (> 18 years),
- Being a native Italian speaker,
- Having bilateral severe to profound deafness with postlingual onset,
- Being unilateral or bilateral Med-El CI user, with at least six months of experience,
- Being an FS coding strategy user,
- Being able to perform psychoacoustic and speech perception tests,
- Not having diagnosed additional disability.

3.2.2. Exclusion Criteria

- Having general comorbidities that prohibit from participating in the study,
- Having any cochlear/auditory nerve anomalies (such as malformations, hypoplasia or aplasia),
- Being unwilling to participate in the study.

The participants in this study were 30 postlingually deafened adult CI users (15 female and 15 male) aged between 19 to 83 years (mean=58yrs, Standard Deviation (SD)=17) at the time of testing (referred as "age at test"). Fifteen of the subjects were unilateral (unilateral subgroup) and the other 15 of the subjects were bilateral (bilateral subgroup) users. Five of the bilateral CI users were implanted sequentially while 10 of them received their implants simultaneously. Study groups for demographic characteristics are shown in Table 3.1.

The whole study group consisting of 30 participants were assessed after a follow-up CI use of 0.5 to 15 (Mean=4.9yrs, SD=3.3) years. The duration of hearing loss was 0.5 to 64 years (Mean=23yrs, SD=15.2). Age at implantation (referred as “age at CI”) ranged from 14 to 77 (Mean=53.2yrs, SD=17.2) years. For sequential bilateral users, the time interval for the second implant was <4 (Mean=2.9yrs, SD=1.6) years. There were no statistically significant differences for duration of hearing loss, age at CI, age at test and follow up CI use between unilateral and bilateral subgroups ($p>0.05$).

Present study assessments were performed for a total of 45 ears including both unilateral and bilateral users whilst for the latter ones bilateral performance was measured as well. Both unilateral and bilateral CI users in the study had no residual hearing in the LF area. The pure tone averages (PTA) were above 85 dB for octave frequencies between 125 to 1000 Hz for both ears. For unilateral CI users, the average aided sound field (SF) threshold for octave frequencies between 125 to 8000 Hz was 30.7 dB HL (SD=7.3). For bilateral CI users. the corresponding values were 34.3 dB HL (SD=4.4) and 35 dB HL (SD=5.7) on the right and left side, respectively, whilst the average bilateral CI threshold was 28.3 dB HL (SD=3.1). Statistically significant differences were found between bilateral and left (p=0.001, effect size=0.85) and right only (p=0.001, effect size=0.85) as well as bilateral versus better ear (BE) (p= 0.002, effect size=0.88).

Implant characteristics are categorized by receivers, electrode types and processing strategies. Among a total of 45 Med-El implants (15 from unilateral users, 30 from bilateral users), two receivers (%4.4) were Combi40+, two receivers (%4.4) were Pulsar CI100, two receivers (%4.4) were Sonata and 39 receivers (%86.7) were Synchrony. Intracochlear electrode types were “Flex24” for four (8.9%) implants, “Flex28” for 28 (62.2%) implants and “Standard (31,5)” for 13 (28.8%) implants.

Strategies were FSP for six processors (13.3%) (one Combi40+, two Pulsar CI100 and three Synchrony processors), FS4 for 31 processors (69%) (one Combi40+, twenty-eight Synchrony and two Sonata 100 processors) and FS4-p for eight (17.7%) Synchrony processors.

Table 3.1. The study group for demographic characteristics.

CI Mode	**Duration of HL (years) Mean (SD)**	**Age at CI (years) Mean (SD)**	**Age at Test (years) Mean (SD)**
Unilateral CI (n=15)	26.9 (15.9)	59.1(13.1)	64.7 (12.4)
Bilateral CI (n=15)	22.3 (15.8)	50.8 (18.4)	54.9 (18.3)

		n of subjects (%)
Gender	M	15 (50%)
	F	15 (50%)
Receiver type	Combi40+	2 (4.4%)
	Pulsar CI100	2 (4.4%)
	Sonata	2 (4.4%)
	Synchrony	39 (86.7%)
Electrode type	Flex24	4 (8.9%)
	Flex28	28 (62.2%)
	Standard	13 (28.8%)
Strategy	FSP	6 (13.3%)
	FS4	31 (69%)
	FS4-p	8 (17.7%)

Reported variables are expressed as Mean and (SD). CI=Cochlear Implant, HL=Hearing Loss, R=Right, L=Left, n=number, M=Male, F=Female, FSP=Fine Structure Processing of the most two apical channels, FS4=Fine Structure Processing Strategy expanded to four apical channels, FS4-p=FS4 in parallel stimulation.

The individual implant characteristics are reported in APPENDIX-2, as CI side, number of active electrodes, FS coding strategy, and the channel's number/bandwidth corresponding to F0 of 200 Hz. For the overall study sample (N=45 ears), all but two ears had full-insertion of all 12 electrodes at surgery. Partial insertion of electrodes happened in two cases (participants B4 and B15). The participant B4 had 11 electrodes and the participant B15 had 10 electrodes inserted on their left sides during the surgery. The total number of active channels at the time of testing were 12 in 55.5% (n=25 ears), 11 in 20% (n=9 ears), 10 in 15.5% (n=7 ears), 9 in 6.7% (n=3 ears) and 8 in 2,2% (n=1 ears). All but two deactivated electrodes were the most basal ones. Deactivation of electrodes other than the most basal ones was observed only in two cases (participants B10 and B15). The participant B10 had the 5th electrode deactivated on the right side while the participant B15 had the 6th electrode deactivated on the left side along with the 12th electrodes. The numbers of FS channels were 4 in 82.2% (n=37 ears), 3 in 4.4% (n=2 ears) and 2 in 13.3% (n=6 ears). F0 of 200 Hz was corresponding to the 1st most apical channel in 42.2% (n=19 ears) and to the 2nd most apical channel in 57.8% (n=26 ears) of the cases. The lower frequency limits were 100 Hz for 84.4% (n=38 ears), 70 Hz for 8.8% (n=4 ears), 200 Hz for 4.4% (n=2 ears), and 150 Hz for 2.2% (n=1 ear).

3.2. Test Procedures

Each participant got a regular CI fitting session right before testing. All audiological assessments were conducted in a professionally designed sound-proof testing cabin in the Cochlear Implant Center at Umberto Policlinico I, University of Sapienza. During the tests, listeners sat on a chair, in front of a loudspeaker 1 meter away from them at 0° azimuth. No feedback was given to the participants during the testing process. Participants were encouraged to guess the answers if they were unsure of what they heard. Answers were collected by the test audiologist. Measurements lasted approximately 1 hour, and participants could request to take a break. The participants with bilateral Cis were tested bilaterally first and then randomly on the single sides.

For hearing threshold assessment, standard audiological testing was performed at octave frequencies from 125 to 8000 Hz. A warble tone from OTO-suite audiometer (Otometrics Taastrup, Denmark) with TDH39 professional headphones was used for unaided thresholds. CI thresholds were also measured for the same octave frequencies, with the same audiometer using the loudspeakers as the above-mentioned protocol (SF measurement).

3.2.1. Pitch Perception Tests

For evaluating pitch perception, DI test from the A§E psychoacoustic test suite is used. This test aims to determine the JND limen for pitch changes. DI test is useful for LF pitch perception which is thought to be linked to availability of TFS cues (5, 58).

The basic task for the listener in the DI test is to discriminate between two sounds. Listeners are informed that they will hear two consecutive sounds from the loudspeaker, and they are asked to tell the clinician whether the sounds they heard are the same or different. Again, listeners are requested to wear their implants in their daily listening settings.

In DI, the tone complexes of F0 at 200 Hz signal and its three harmonics are presented. The F0 of second sound shifts to 200 + Δ Hz towards the end of presentation. The Δ value is between 0 – 214, and changes adaptively according to the listener's answer, by the software. The harmonics of the F0 do not sweep. The harmonics' intensity gradually decreases compared to F0 (6 dB lower than prior, for every harmonic). The first tone complex is always F0 of 200 Hz and its harmonics at 400, 600 and 800 Hz. In the second sound, F0 sweeps according to the Δ value (e.g., if the Δ value is 12, F0 of 200 Hz will sweep to 212 Hz but the harmonics don't sweep and remain the same (5, 58). This situation creates a disharmony sensation, it is important to note that in the DI test, the difference is only in F0, in other words, in LF component of the presentation. The fact that harmonics remain the same and the only change is in the F0 of the signal, is the reason for DI to be considered as a valuable test for evaluating LF pitch perception (5, 12).

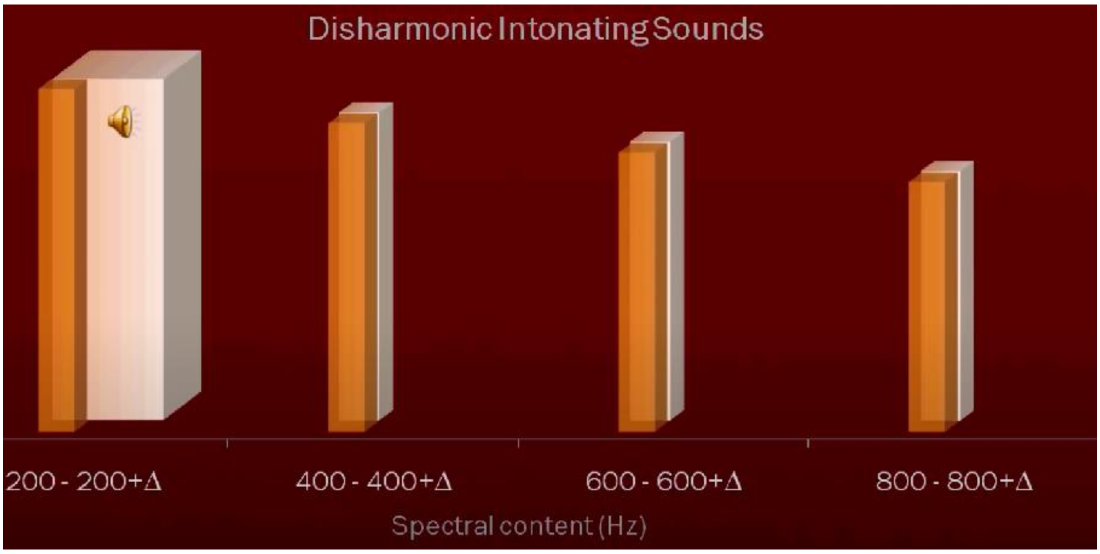

Figure 3.1. Disharmonic Intonating Sounds. The orange bars represent the F0 of 200 Hz and its harmonics. The white bars represent the F0 of 200+Δ Hz and its non-sweeping harmonics where Δ remains always at zero. The intensity of the signal drops 6 dB in every following harmonic. Source adapted from (68).

For the DI test, the tester must select the listener's answer on the test computer. When the listener successfully determines that the two sounds are different, Δ is decreased by software and the task becomes harder. When the listener fails to determine the difference and claims that two sounds are the same, Δ is increased by the software and the task becomes easier. There are also random presentations with two same sounds (or where the Δ value equals zero at F0) for preventing the listener from always answering "different" and for maintaining their attention. For the patients who are not able to discriminate between two tones, the JND (Hz) value is considered as 220 Hz, which is over the maximum Δ value at 214 Hz, available in the software.

In the DI test, the sweep begins at 330 ms after the start of the presentation and lasts for 120 ms. The total duration is 600 ms for each presentation. The two consecutive stimuli were separated with a 500 ms inter-stimulus interval. White noise was added to the stimuli (SNR+10.9 dB) resulting in the stimuli to sound more natural and intensity roving (±2 dB) was applied to avoid the use of loudness cues by the participants (5).

3.2.2 Speech Perception Tests

For evaluating the participant's speech perception performances both in quiet and in noise, listeners were requested to wear their implants and to use their daily listening settings. Speech recognition tests were performed through loudspeakers, using standard phonetically balanced bisyllabic words for Italian adult listeners (69, 70).

Word and sentence recognition tests in noise with a fixed SNR were performed with the speech signal fixed at 65 dB SPL, for +10 and +5 dB SNR, respectively. For the words and sentences, the scoring made by the software itself, 10 words/sentences are presented, and correct answers are converted to percentile scores.

The Italian Matrix test is used in the adaptive mode for evaluating the listeners' ability to recognize speech in noise (64). The Oldenburg software is used for presenting test material and scoring. Each turn, 30 random sentences are presented and the correct answers (in this case the individual words the listener correctly repeated) are selected by the clinician on the computer. The test continues adaptively, at the end the software gives the SNR where the 50% of the sentences are repeated correctly and the slope value.

3.3. Data Analysis

Data analysis was carried out with the Statistical Package for Social Sciences (SPSS version 25.0, IBM Corporations, Chicago, IL, USA). The Shapiro-Wilk and The Kolmogorov–Smirnov test of the main outcome measure showed that the data from DI and Matrix tests were not normally distributed ($p \leq 0.001$); hence, non-parametric statistical tests were adopted. Descriptive statistics were reported according to data distribution as median (min-max).

For each subject, the electrode location corresponding to the F0 of 200 Hz coding, which is usually the first or second electrode, is determined. Also, the DI discrimination scores (JNDs) are evaluated as either in the same, or in an adjacent electrode, depending on the electrode frequency range distribution. This led to grouping them as having RP or PP ability. The electrode RP value is actually a combination of the frequency range (the extension to lower frequency, i.e.,70 versus 100 Hz), number of active electrodes, and subjective ability to discriminate the electrode rate of discharge (6). Based on this, a univariate analysis was adopted to compare data between RP versus PP devices to discover if there was a significant difference between implanted ears in terms of speech perception. In the DI test, percentage of performers within the normal range are calculated according to Vaerenberg et al. (5)'s study, which scores ≤10 Hz are considered as within the clinical normal zone.

For speech perception in quiet, with fixed SNR +10 and fixed SNR +5, the percent value of correct responses was transformed to Rationalised Arcsine Units (RAUs) for avoiding the ceiling effect (71). For bilateral CI subjects, the BE for all cases but one was determined by the better DI score. For this bilateral patient who showed similar JNDs at 220 Hz for both ears, the BE was decided according to the better Matrix performance.

Mann-Whitney U test was reported for comparisons between unilateral versus bilateral, RP versus PP (for both pitch and speech perception tests); Wilcoxon test was reported for BE versus bilateral comparisons along with the effect size to define the magnitude of the relationship between variables (72-74). The cutoff level for statistical significance was set to 0.05. The effect size was calculated using Rosenthal formula $r = Z/\sqrt{N}$ (very low=0.00 to 0.20, low=0.20 to 0.40, moderate=0.40 to 0.60, strong=0.60 to 0.80 and very strong=0.80 to 1.00) (75).

Spearman bivariate correlations were performed to analyze the relationship between DI outcomes, demographics (age, age at implant, duration of deafness and duration of CI experience) and audiological (SF and speech perception) variables (75).

4. RESULTS

4.1. Pitch Perception Results

The average median JNDs from a total of 45 ears was 33 Hz (min=1, max=220 Hz). For ears with pitch perception ability within the same electrode (RP) or by a sweep to an adjacent electrode (PP), JNDs were 9 Hz (60%, n=27 ears) and 148 Hz (40%, n=18 ears), respectively. The individual implant characteristics with the RP/PP ability is reported in APPENDIX-2. As shown in Fig. 4.1., DI scores from implanted ears which discriminated pitch by RP were significantly lower (better) from those performing PP with a very strong effect size ($p<0.001$, effect size=2.8). For the overall group, DI scores from 15 ears (33.3%) were within the clinical normal zone (≤10 Hz), all from RP performers. This score corresponded to 55% of RP performance.

Table 4.1 and Figure 4.1. represent median DI JNDs including minimum/maximum scores and RP/PP perception ability from the overall study group (n=45 ears), comparatively with unilateral/bilateral subgroups.

Univariate analysis showed that DI scores from unilateral and bilateral CI subgroups did not significantly differ ($p>0.05$). For the bilateral CI subgroup, DI JNDs were not significantly different from BE scores ($p>0.05$). Demographic and audiological data did not show any statistically significant effects on overall DI results ($p>0.05$).

In the unilateral subgroup, RP versus PP performers were 66.6% and 33.3%, respectively. These performances in bilateral subgroup were 80% (RP on both sides or RP on one side and PP on the other side) and 20% (PP on both sides), respectively. For the BE alone RP versus PP performances were 73.3% and 26.7%, respectively. In the unilateral subgroup, performers within the clinical normal zone were 33.3%. Corresponding values in the bilateral subgroup and BEs were 33.3% and 53.3%, respectively.

Table 4.1. Descriptive statistics concerning median DI discrimination scores and FS coding channels.

Group	DI JND (Hz) Median (min-max)	RP (min-max) [n]	PP (min-max) [n]	FS coding channels [n]
Overall (N=45 ears)	33 (1–220)	9 (1–57) [27]	148 (19–220) [18]	4 [37] 3 [2] 2 [6]
Unilateral CI (n=15)	19 (1–220)	11 (1–57) [10]	220 (19–220) [5]	4 [10] 2 [5]
Bilateral CI (n=15)	7 (1–220)	9 (1– 57) [17]	109 (64–220) [13]	4 [27] 3 [2] 2 [1]
BE	9 (1–164)	7 (1– 57) [10]	122 (64–164) [5]	4[15]

Values are median (min–max) scores for pitch discrimination of the whole dataset. Rate Pitch refers to the ability to discriminate change in pitch in the same apical electrode (1st or 2nd), whilst Place Pitch refers to the ability to discriminate pitch due to shift into the next adjacent electrode. DI=Disharmonic Intonation, JND=Just Noticeable Difference, Hz=Hertz, RP=Rate Pitch, PP=Place Pitch, n=Number of participants, FS=Fine Structure, BE=Better Ear of bilateral CI users, which is determined by their scores at DI or Matrix test.

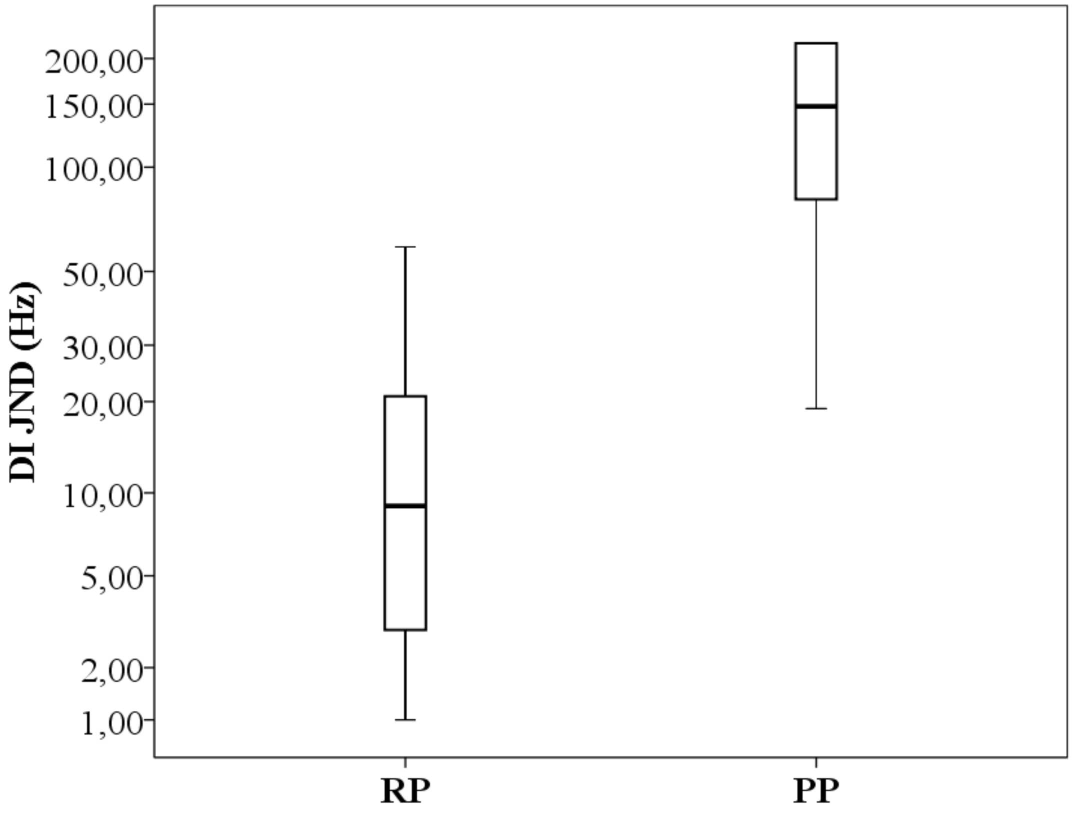

Figure 4.1. DI JNDs from the overall study group (N=45 ears) classified as RP (n=27 ears) and PP (n=18 ears) performers. Median values for RP and PP are 9 Hz and 148 Hz, respectively.

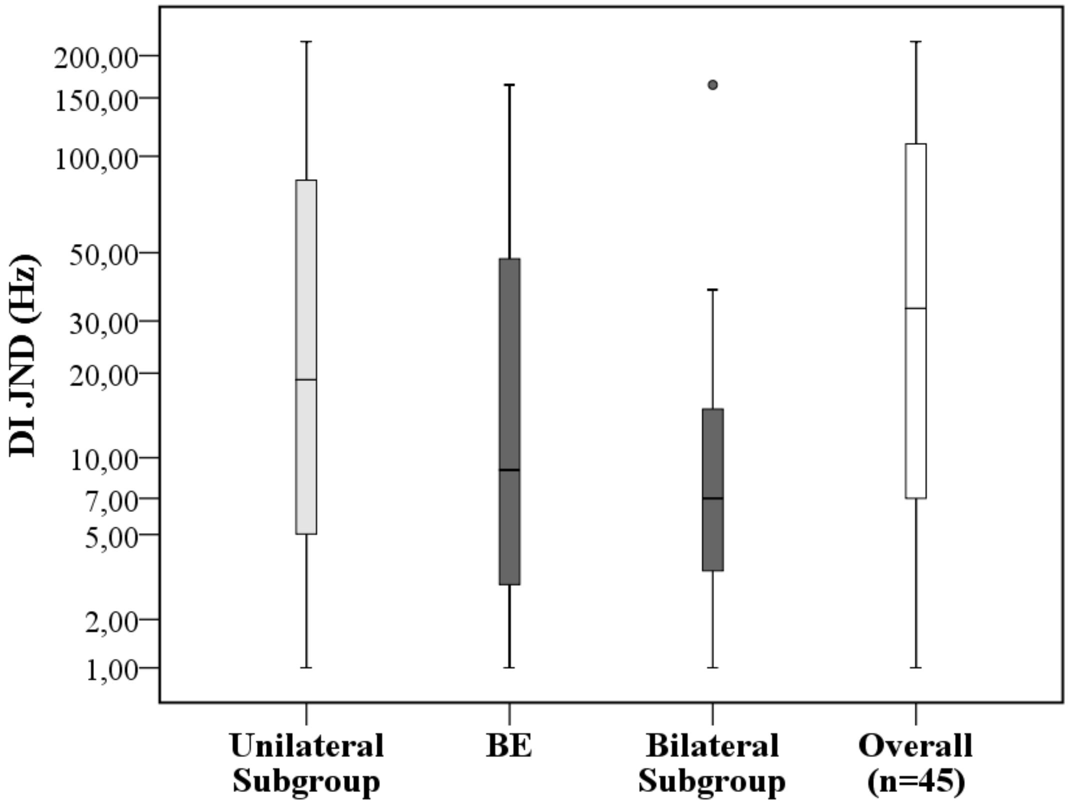

Figure 4.2. Average DI JNDs for listening modes. Unilateral (n=15), bilateral (n=15), better ear (n=15) and overall (N=45) median values are 19, 7, 9 and 33 Hz, respectively.

4.2. Speech Perception Results

Table 4.2 represents the median (min–max) speech perception scores for the overall group (N=45 ears) versus those for unilateral and bilateral subgroups.

For the overall group, the median speech perception scores were 76% for Word Recognition Score in Quiet (WRS_q), 42% for Word Recognition Score in 10 dB SNR (WRS+10), and 16% for Word Recognition Score in 5 dB SNR (WRS+5). The corresponding values for sentence recognition were 84% for Sentence Recognition Score in Quiet (SRS_q), 46% for Sentence Recognition Score in 10 dB SNR (SRS+10), and 17% for Sentence Recognition Score in 5 dB SNR (SRS+5). The median SRT score for the Matrix test was 7.0 dB SNR.

For the unilateral subgroup, the median speech perception scores for WRS_q, WRS+10 and WRS+5 were 80%, 41% and 12.5%, respectively. The corresponding values for sentences were 90%, 45% and 15%, respectively. The median SRT from Matrix test was 8.2 dB SNR. For the bilateral subgroup, these scores were 90%, 56% and 36.5% for words versus 90%, 70% and 40% for sentences, and 1.3 dB SNR for the Matrix test. BE scores were 79%, 44% and 20% for words versus 85%, 50% and 15% for sentences, with a median Matrix SRT at 4.1 dB SNR.

Group comparisons between unilateral and bilateral subgroups showed statistically significant differences for WRS+10 ($p=0.047$, effect size=0.8), WRS+5 ($p=0.024$, effect size=0.9), SRS+5 ($p=0.029$, effect size=0.9) and Matrix tests ($p=0.002$, effect size=1.3). Likewise, within-group comparisons of the bilateral subgroup (BE versus bilateral listening) revealed statistically significant differences for WRS+10 ($p=0.016$, effect size=1.0), WRS+5 ($p=0.021$, effect size=1.0) and Matrix test ($p=0.033$, effect size=0.8). Demographic and audiological data from the present sample did not show any statistically significant effects on speech perception scores ($p>0.05$).

Table 4.2. Speech perception scores for the overall group (N=45 ears) versus unilateral/bilateral subgroups.

Group		**WRS_q % (min-max)**	**WRS+10 % (min-max)**	**WRS+5 % (min-max)**	**SRS_q % (min-max)**	**SRS+10 % (min-max)**	**SRS+5 % (min-max)**	**Matrix (dB SNR) (min-max)**
Overall (N=45)		76(28–100)	42(10–88)	16(0–80)	84(40–100)	46(0–100)	17(0–90)	7.0(-4.2–20)
Unilateral CI (n=15)		80(52–95)	41(2–88)	12.5(0–50)	90(60–100)	45(10–100)	15(0–70)	8.2(-1.9–20)
Bilateral CI (n=15)		90(65–100)	56(38–88)	36.5(20–80)	90(80–100)	70(30–100)	40(0–100)	1.3(-4.2–7.2)
	BE	79(65–92)	44(10–70)	20(0–60)	85(60–100)	50(10–90)	15(0–90)	4.1(-3–9.5)

Median (min-max) scores are reported. WRS_q=Words Recognition Score in Quiet, WRS+10=Words Recognition Score in 10 dB SNR, WRS+5=Words Recognition Score in 5 dB SNR, SRS_q=Sentence Recognition Score in Quiet, SRS+10=Sentence Recognition Score in 10 dB SNR, SRS+5=Sentence Recognition Score in 5 dB SNR, dB=decibel, n=Number of participants, CI=Cochlear Implant, BE=Better Ear. The BE is considered the CI side with better DI or Matrix score in bilateral users.

4.3. Effects of Rate/Place Pitch on Speech Perception

Speech perception scores from the overall group of 45 ears were divided into two subgroups based on their pitch perception ability (RP versus PP performers) (see Table 4.3.). Figure 4.3. represents speech perception scores in quiet/noise for both words and sentences whilst Figure 4.4. illustrates Matrix results, classified as RP and PP performers.

Group comparisons for RP/PP performers showed statistically significant differences for WRS+10 (p=0.002, effect size=0.9), WRS+5 (p=0.001, effect size=0.9) and Matrix tests (p=0.03, effect size=0.6). Demographic and audiological data did not significantly differ for speech perception scores from RP and PP performers. Also, there was no statistically significant correlation found for participant demographics between RP or PP ability.

Table 4.3. Speech perception scores classified as RP and PP performers.

	RP (n=27 ears)	**PP (n=18 ears)**	**effect size (p)**
WRS_q (%)	80 (58–98)	80 (28–97)	0.40 (0.100)
WRS+10 (%)	50 (25–88)	30 (2–70)	**0.90 (0.002)**
WRS+5 (%)	20 (0–78)	0 (0–50)	**0.90 (0.001)**
SRS_q (%)	90 (60–100)	80 (40–100)	0.60 (0.060)
SRS+10 (%)	50 (0–100)	40 (0–80)	0.50 (0.200)
SRS+5 (%)	20 (0–90)	10 (0–70)	0.20 (0.700)
Matrix (dB SNR)	5.2 (-3.2–20)	10 (0.4–20)	**0.60 (0.030)**

Median (min–max) scores for speech perception. Bold values show statistically significant differences at p<0.05. RP=Rate Pitch, PP=Place Pitch, WRS_q=Words Recognition Score in Quiet, WRS+10=Words Recognition Score in 10 dB SNR, WRS+5=Words Recognition Score in 5 dB SNR, SRS_q=Sentence Recognition Score in Quiet, SRS+10=Sentence Recognition Score in 10 dB SNR, SRS+5=Sentence Recognition Score in 5 dB SNR, dB=decibel

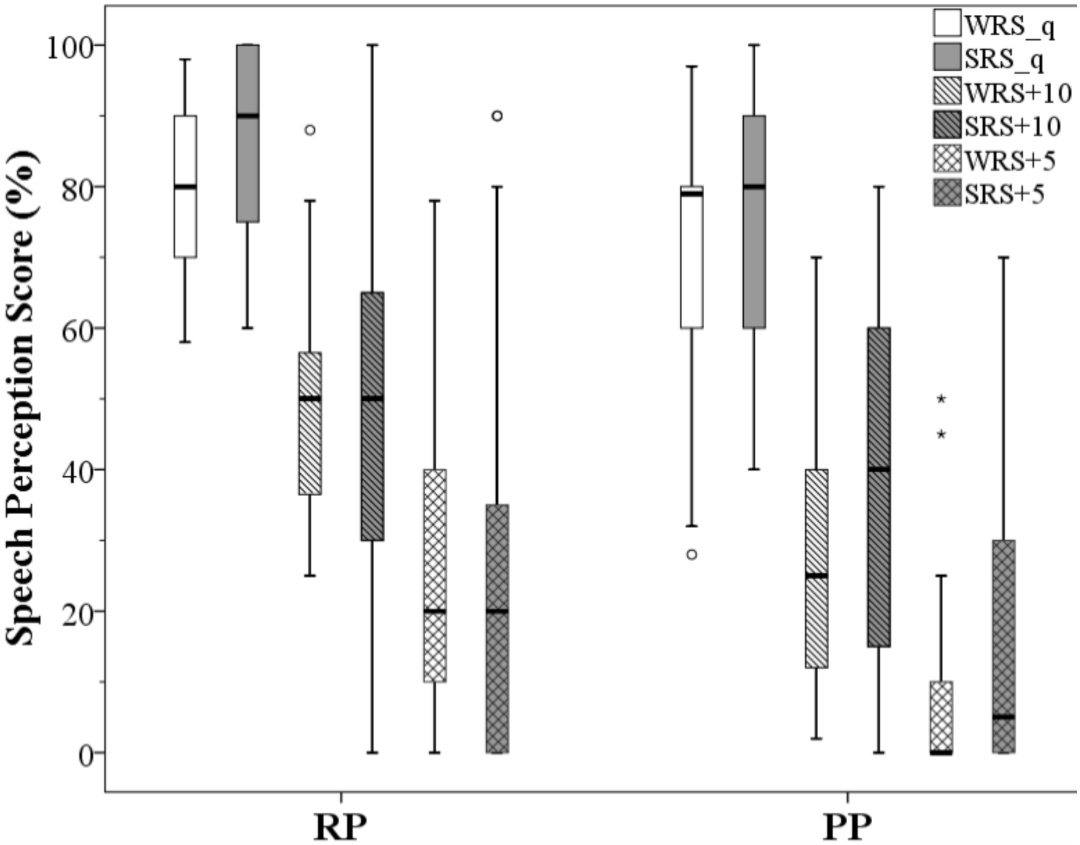

Figure 4.3. Speech perception scores in quiet/noise for both words and sentences, classified as RP and PP performers. RP=Rate Pitch, PP=Place Pitch, WRS_q=Words Recognition Score in Quiet, SRS_q=Sentence Recognition Score in Quiet, WRS+10=Words Recognition Score in 10 dB SNR, SRS+10=Sentence Recognition Score in 10 dB SNR, WRS+5=Words Recognition Score in 5 dB SNR, SRS+5=Sentence Recognition Score in 5 dB SNR

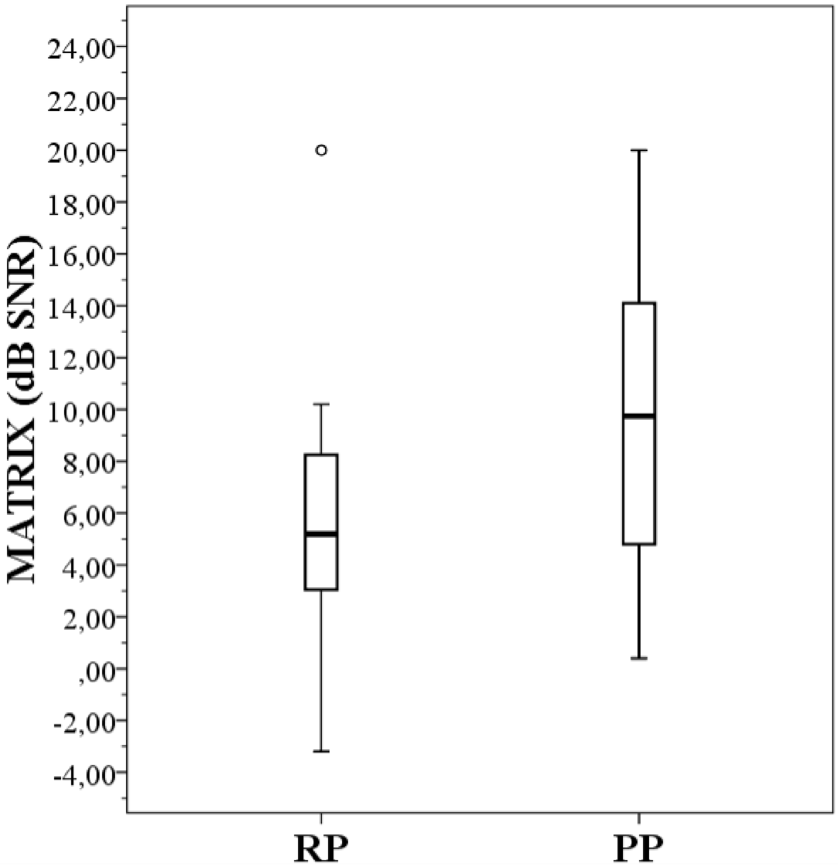

Figure 4.4. Matrix scores classified as RP and PP performers. Results are 5.2 and 10 dB SNR, respectively. dB=decibel, RP=Rate Pitch, PP=Place Pitch,

5. DISCUSSION

Over the past twenty years, numerous studies have proven CIs' efficacy as a rehabilitative solution for deafness (15, 21, 26). Such achievements are mainly because of considerable advances in CI technology, combined with systematic (re)habilitative support for auditory/spoken language skills (18, 26). The majority of children implanted at a very young age show age appropriate auditory-verbal communication ability (16, 21, 57). Moreover, CIs also help adults with postlingual onset of hearing loss to restore their functional hearing, necessary for their auditory/verbal communication (15, 21, 30). However, CI users still have big communication difficulties in comparison to people with normal hearing, especially when it comes to real life listening situations (3, 35).

The vast majority of CI users show excellent performance in quiet listening conditions, but their performance deteriorates remarkably for everyday-like listening situations where varying speech levels in the presence of background noise are leading to a big challenge. People with CIs report to have difficulties mainly for speech intelligibility in competing noise and music perception (3, 4, 44, 47). These abilities are shown to depend on acoustic signals' important attributes such as pitch and timbre. Pitch perception is significantly correlated with spectrotemporal discrimination ability linked to TFS processing, for which CI users show significantly poorer performance than people with normal hearing. Indeed, the majority of conventional speech processing strategies lack the ability to convey TFS cues. Although CI electrodes are designed to represent tonotopic organization of the inner ear, limited number of electrodes along with varying insertion depth usually results in place-versus-pitch mismatch (7, 45, 54).

While it's considered that CI users have poor pitch perception, some CI listeners show normal or close to normal performances in the DI test, which is also used for pitch perception evaluation in previous studies (5, 11, 12). The reason why some CI users perform better than others is unclear since in these studies, inter individual variability is high, CI brands, processors and speech processing strategies are variant, and the sample size is too small to have an explanation. Previous studies by Schauwers et al. (11) and Dinçer D'Alessandro et al. (12) evaluating the pitch perception reported that the CI users had a DI median value of 139 Hz (ranged from 1 to 220 Hz) and 147 Hz (ranged from 7 to 220 Hz), respectively. Interestingly, in the Schauwers et al. (11)’s study, when only the results from Med-El users are evaluated, a median DI score of 23 Hz (ranged from 1 to 220 Hz) is found. Also, some of the CI listeners were able to show performances within the clinical normal zone (5). One possible explanation for these findings might be that the speech processing strategies’ effect on pitch perception. Although Med-El's FS coding strategies are aimed to have more detailed use of LF cues and TFS information which are important for pitch perception and speech understanding in noise, the effects of FS coding strategies on CI performance are controversial. There are some studies in mixed groups of devices reporting that with the FS coding, CI users are showing better speech perception in noise and music perception (9, 39, 40). Comparisons between CIS and FSP strategies reveal significant improvements in speech tests in noise, which is considered as the more difficult speech test and a trend to use the FSP strategy over CIS regarding speech understanding is also reported by Arnoldner et al. (38). On the contrary, there are studies showing no significant improvements for speech understanding with the FS coding strategy (41). The effects of FS coding strategies on pitch perception, the use of RP or PP mechanisms and their relationship with speech perception were not evaluated in the previous studies. Therefore, the present study aimed to investigate the effects of better TFS processing on pitch and speech perception in 15 unilateral and 15 bilateral CI users fitted with FS coding strategies.

5.1 Pitch Perception

Normal hearing listeners discriminate pitch by changes in frequency. To have a better understanding of how the CI listener can discriminate pitch, electrode representations of frequency coding have to be observed. CI users’ pitch perception ability can be categorized as RP if they can discriminate two different tones within the same electrode or as PP if they are only able to distinguish pitch changes by channel shifts depending on the bandwidth where the corresponding frequency fall (6). CIs fitted with FS coding strategies are enabling one to four most apical channels to focus on TFS information which are indisputably relevant with pitch perception (8, 35, 36).

HI and DI tests are both useful for evaluation of pitch perception. In HI, frequency sweep is present at F0 of 200 Hz and all harmonics while in DI the frequency sweep is only present at F0 of 200 Hz (5). The reason why DI test is used in this study instead of HI is that in HI, sweeps in higher harmonics provide the listener with high frequency cues along with LF cues. However, the DI test only provides listener the LF cues to discriminate pitch. Since DI lacks sweeping in the higher harmonics, it does not allow the listener to use relatively higher frequency cues and conducts the use of TFS cues represented by their FS coding electrodes in the LF region. Also, the research by Dinçer D'Alessandro et al. (59), Vaerenberg et al. (5) and Heeren et al. (58) show that DI test is considered more sensitive for the LF area since people with LF hearing loss had significantly worse performances in both HI and DI test, however, the DI scores were considerably worse.

Since the DI test only allows the listener to use LF information to discriminate pitch, the listeners' JNDs for the F0 of 200 Hz in the DI test are evaluated. Thus, according to these JND Hz values being coded within the same electrode with 200 Hz or not, the CI listeners are categorized as RP or PP performers. In Med-El CIs, RP or PP ability for F0 of 200 Hz is related with the most apical, usually the 1^{st} or the 2^{nd} electrodes (7, 8, 37).

Overall group (N=45) in the present study showed an average median JND of 33 Hz (min=1, max=220) in the DI test. This finding supports the previous literature as CI users are shown to have poor performances in the DI test compared to normal hearing listeners (5, 12, 59). In the study by Dinçer D'Alessandro et al. (12) 49 individual ears from 23 unilateral, 6 bilateral CI users plus 14 CI-only responses from bimodal users showed an average median JND of 147 Hz and 8% of the outcomes were within the clinical normal zone. In Vaerenberg et al. (5)'s study, the CI group which consisted of 6 listeners, showed an average median score of 158.5 Hz in the DI test. Another study by Schauwers et al. (11) 21 CI users had DI median JNDs of 139 Hz and 9% of the listeners performed within the clinical normal zone. Compared to these previous studies, considerably less (better) DI JND median value was observed in the present study. This might be due to the effect of FS coding on better TFS information use and LF pitch perception.

When the overall group of 45 ears are categorized by their RP/PP ability, the noticeable difference with a very strong effect size for DI scores is revealed as the median JND was 9 Hz (60%, n=27 ears) vs 148 Hz (40%, n=18 ears) for RP and PP groups, respectively. This finding highlights not only that CI users with FS coding can actually be able to use RP to discriminate pitch but also the importance of better LF coding's positive effect on pitch perception since RP performers are considered as having better LF resolution. Such that the RP performers' median value was within the clinical normal zone (≤10 Hz) for the DI test while the PP performers' median value was closer to results from previous findings (5, 11, 12).

Another notable finding is that in the overall group, the DI scores from 15 ears (33.3%) were within the clinical normal zone (≤10 Hz), all from RP performers. Which also corresponds to 55% of the all RP performers. These findings also support the positive effect of FS coding on pitch discrimination ability since in the present study, not only the median JND values are significantly better than previous studies, but the percentage of people within the clinical normal zone is also noticeably higher. Also the RP ability's efficiency on pitch perception is obvious, because it covers all the clinical normal zone performances and higher percentage of RP performers showed scores within the clinical normal zone. But although the DI scores of CI users are better and the percentage of normal performers in the DI test are higher than the data obtained from CI users in previous studies, they still show poor performances compared to normal hearing listeners (5, 11, 12).

The FS coding strategies are focused on TFS cues and aim to have better LF representation. The extra benefit of LF information on pitch and speech perception is reported in previous studies conducted on CI listeners versus EAS listeners and CI-only listeners versus bimodal listeners (12, 60). The acoustic information used by EAS and bimodal listeners provided them with LF information, which resulted in significantly better performances for the DI test and speech understanding in noise. The similar effect of better LF information use with the FS coding strategies might be the reason why participants in the present study showed better DI scores and higher percentage of them were in the clinical normal zone.

The DI scores were not significantly different between bilateral and unilateral subgroups. For the bilateral subgroup, DI scores did not show any statistically significant difference from BE scores. This was expected since for bilateral listeners, the answer is believed to originate with a bigger contribution from the BE or in other words, the side that carries LF information more efficiently. In the bilateral subgroup, 80% of the participants showed RP in at least one side and 73.3% of the BEs showed RP, which suggests the benefit of BE in bilateral listeners since RP ability is resulting in better scores. In the bilateral subgroup, 33.3% performed within the clinical normal zone, while for BE, this value was 53.3%, showing again the important contribution of BE for pitch perception in bilateral listening.

Demographic factors like age at implant, age at test and duration of CI use can have significant effects on CI performance and this has been proven in the previous studies (21, 26, 27). But demographic data in the present study did not show any statistically significant effects on pitch perception. The absence of correlation with demographic factors is different from a similar study carried out by Moore et al. (52) in normal hearing subjects. This might be due to all participants being adults with a higher average age (58 years) and postlingually deafened with similar audiological profiles. While Moore et al.'s study reported evaluation of two subgroups of subjects for pitch perception, aged 34 years or less and aged 36 years or more, which showed the effect of age more clearly. Findings also showed that DI test can be considered valuable in terms of evaluating pitch perception ability.

5.2. Speech Perception

TFS cues, pitch perception and spectral resolution in LF region are all in close relations with speech understanding in noise (4, 5, 53). Thus, in the current study, words and sentences recognition in quiet and in noise as well as Matrix test are evaluated. The recorded speech materials used for word and sentence recognition were bisyllabic words for Italian adult listeners. The reason for using the bisyllabic words instead of monosyllabic words is the structure of the Italian language. The Italian language doesn't have several monosyllabic words and almost all words end with a vowel (69).

For the overall 45 ears in the present study, the median speech perception scores were 76% for WRS_q, 42% for WRS+10, 16% and for WRS+5. The corresponding values for sentence recognition were 84% for SRS_q, 46% for SRS+10, and 17% for SRS+5. The median SRT score for the Matrix test was 7.0 dB SNR. Previous literature reported that CI users are performing better in quiet listening conditions, a recent study with 20 postlingual adult CI users reported that the mean word recognition score in quiet from the participants was 68,5% (47). Another study conducted on bimodal elderly listeners (mean age=73) by Mancini et al. (67) found mean word recognition score in quiet from 17 patient's CI only condition as 58.9%. In another study with CI only and bimodal listeners, 49 CI ears' mean word recognition score in quiet was 77%, in the same study when 14 bimodal listeners evaluated in CI only and bimodal condition, corresponding scores were 73.6% versus 80.6%, respectively (12). The use of bisyllabic words might have affected the scores for words material positively in the present study since compared to monosyllabic words, bisyllabic words have longer duration and better acoustic cues. For speech perception in noise, a previous study by Gallo et al. (66) reported 4.15 dB SNR as median score for Matrix test in CI only listening condition in 45 bimodal listeners and in a different study by Mancini et al. (67), bimodal elderly patients showed an average median of 12.5 dB SNR on CI only listening condition. Another study with unilateral CI users also reported median Matrix SRT as 7.6 dB SNR while the average SRTs in normal hearing Italian listeners was –7.3 dB for the Matrix test (47, 64). Overall findings in the Matrix test for the present study support the previous literature as the average scores are close to other CI users and there's a significant difference with the normal hearing listeners. The findings for speech perception from the current study are coherent with the previous literature: although they show very satisfying speech recognition performance in quiet listening environments, it is known that CI users have poorer performance of speech understanding in noise (3, 35).

Group comparisons between unilateral and bilateral subgroups showed statistically significant differences for WRS+10 (p=0.047, effect size=0.8), WRS+5 (p=0.024, effect size=0.9), SRS+5 (p=0.029, effect size=0.9) and Matrix tests (p=0.002, effect size=1.3). These outcomes were expected since the effect of binaural hearing on speech understanding in noise have been proven several times (12, 23-25).

Binaural summation (SU), binaural squelch (SQ) and head shadow (HS) effects, which are three main benefiting components for binaural hearing, show their contributions in unilateral versus bilateral subgroups in speech perception tests (23, 76). Likewise, comparisons of the BE versus bilateral listening revealed statistically significant differences for WRS+10 (p=0.016, effect size=1.0), WRS+5 (p=0.021, effect size=1.0) and Matrix (p=0.033, effect size=0.8) test. Again, results can be considered expected because of the benefit of binaural hearing. BE dominated the answers in bilateral listening in DI test but it was not as effective in speech perception in noise since the advantage of binaural hearing is overpowering because unlike the task in DI, which can be considered more of a peripheral discrimination, speech understanding requires more central comprehension (1, 29).

The statistically significant differences between bilateral and unilateral subgroup for speech perception also contains SRS+5 mode along with words in noise and Matrix, the reason for sentence recognition to differ can be explained by that the more masking noise results with a harder listening condition and the listener becomes more dependent to the TFS cues and benefits of bimodal listening, since the difference in sentences is only in the lowest (hardest) SNR.

Although it's known that the factors like age at implant, age at test and duration of CI use can have significant influences on speech understanding, demographic data in the present study did not show any statistically significant effects on speech perception scores (p>0.05) (21, 26, 27). This might be due to all participants in the study being adults with a higher average age (58 years) and postlingually deafened with similar audiological profiles.

5.3. Effects of Rate/Place Pitch on Speech Perception

For RP and PP, the differences were statistically significant for WRS+10 (p=0.002, effect size=0.9), WRS+5 (p=0.001, effect size=0.9) and Matrix tests (p=0.03, effect size=0.6). The effects of better LF information use, resulting with better TFS coding on speech understanding in noise was expected owing to previous literature (7, 35). Studies with EAS and bimodal CI users showed better speech understanding in noise and this is explained by more detailed TFS information use, through extra acoustic sound contributions (12, 60). Similar effects can be observed with the use of FS coding strategies since FS coding strategies are also aimed to represent more detailed TFS information (36, 38, 39). RP performers can discriminate LF pitch better than PP performers. Hence, not only the findings from current study support the previous findings in the literature, but they also highlight the positive effect of RP with FS coding strategy.

Another important point is that the statistically significant differences are present in Matrix test and word recognition scores in noise rather than sentences. This situation also highlights the importance of TFS coding since speech understanding in noise is considered more difficult than in quiet and also word recognition is considered more difficult than sentence recognition because the limited duration of speech results with less predictability, TFS cues are becoming more crucial for these two tasks. Also, although it can be syntactically predictable, the semantically unpredictable nature of Matrix test prevents the listener to use auditory closure (62, 64).

Although it could be interesting to see the effects of age at implant, age at test and duration of CI use on RP/PP ability, there was no statistically significant correlation found for participant demographics, neither between RP or PP ability nor for speech perception scores from RP versus PP subgroups in the present study. This could be explained by that all the participants in the study were postlingually deafened adult listeners with similar audiological profiles and their average age was 58 with an average CI use of 4.9 years. Although factors like onset time of hearing loss and CI experience are known to affect the CI performance, having a postlingual onset of hearing loss and longer duration of CI use minimizes the differences in performances (26, 27, 29, 30).

5.4. Limitations and Future Research

The main limitations of the study were the small sample size and heterogeneity of the participants. The strategies used in the present study were FSP, FS4 and FS4-p, but their distribution was not even since the number of implants with these strategies were 6, 31 and 8, respectively. Although they were not the main focus of the present study as FS processing strategies, the uneven distributions were also present for electrode types, receivers and processors. Future research in larger and more homogeneous groups would be more helpful for the literature.

It’s known that DI scores are correlated with LF spectral resolution (5, 12, 59). Participants with incomplete insertion of CI electrodes or deactivated channels, which may affect the spectral resolution, were present in this study. Although their channel number and bandwidth for F0 of 200 Hz reported in APPENDIX-2, the detailed analysis and effects of the number of active channels on pitch perception and RP/PP ability was not investigated. Furthermore, it would be interesting to measure the degree of electrode insertion in the cochlea in order to verify if better DI values are correlated to deeper insertions.

6. CONCLUSION

1. Present study with 15 unilateral and 15 bilateral CI users showed that with the use of FS coding, benefits of better LF coding and TFS use, overall median JND value in the DI test is noticeably better than previous studies. Compared to PP performers, pitch perception skills from RP performers are noticeably better, such a point that they showed JND values within the clinical normal zone.

2. Demographic data in the present study did not show any statistically significant effects on pitch perception. DI test can be considered valuable in terms of evaluating pitch perception ability.

3. Between group comparisons showed that unilateral versus bilateral CI users do not show significant differences for pitch perception with FS coding, but there's a noticeable difference in speech perception between these groups, proving the advantages of binaural listening.

4. For within-group comparison between bilateral versus BE on the other hand, resulted with no significant difference for pitch perception since the answers are believed to originate from the BE. But the important contribution of BE for pitch perception in bilateral listening is observed. Distinct differences on word recognition in noise and Matrix tests are typically explained by the advantages of binaural listening.

5. Regarding speech perception, CI users who show RP ability are showing significantly better performances in words in noise and Matrix test, this is reasoned by the advantages of better TFS use provided by FS coding in harder speech perception tasks. RP ability's positive effect on both pitch and speech perception outshined for the current study.

Future research in larger and more homogeneous populations would be useful to better understand the role of FS coding strategies' effect on pitch and speech perception.

7. REFERENCES

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8. APPENDICES

8.1. APPENDIX-1: Ethical Approval

AZIENDA OSPEDALIERO-UNIVERSITARIA SANT'ANDREA · REGIONE LAZIO · SAPIENZA · AZIENDA OSPEDALIERO-UNIVERSITARIA POLICLINICO UMBERTO I

"SAPIENZA" ÜNİVERSİTESİ ETİK KURULU
22.04.2020 TOPLANTI TUTANAKLARI

22 Nisan 2020, saat 15.00'te Sapienza Üniversitesi Etik Kurulu aşağıdaki gündemle çevrimiçi olarak toplanmıştır:

- Başkanın Mesajları;
- Deneylerin tartışılması;
- Önemli Olan ve Olmayan Düzeltilerin Değerlendirilmesi;
- Diğer hususlar

İSİM	VASIF	P/A
Dott. Paolo Anibaldi	Direttore Sanitario AOU Sant'Andrea	AG
Avv. Alessia Amore	Esperto Di Bioetica	P
Prof. Marcello Arca	Internista	P
Dott. Antonino Bella	Biostatistico	P
Prof.ssa Raffaella Buzzetti	Endocrinologo	P
Dott.ssa Elisabetta Cortis	Pediatra	P
Dott.ssa Rosa D'Arca	Esperto In Materia Giuridica	P
Prof. Natale Mario Di Luca	Medico Legale	AG
Prof. Sebastiano Filetti	Internista	P
Dott. Carlo Lavalle	Cardiologo	P
Dott.ssa Maria Teresa Lupo	Farmacisti SSN	P
Dott.ssa Federica Mazzuca	Oncologo	P
Prof. Antonio Pizzuti	Esperto Di Genetica	P
Dott.ssa Gabriella Platania	Farmacista - Dispositivi	P
Prof. Francesco Pontieri	Neurologo	P
Dott.ssa Enrica Maria Proli	Farmacisti SSN	P
Prof. Dott. Alberto Deales	Direttore Sanitario AOU Policlinico Umberto 1	AG
Dott. Elio Rosati	Rappresentante Associazionismo Della Tutela Pazienti	P
Dott. Massimo Sabatini	Medico Di Medicina Generale	P
Dott.ssa Laura Tibaldi	Rapp. Professioni Sanitarie	P
Prof. Agostino Tafuri	Ematologo	P
Prof. Federico Venuta	Chirurgo	P
Prof. Bruno Annibale	Esperto In Nutrizione	P
Prof. Vito Cantisani	Radiologo / Esperto In Tecniche Diagnostiche E Terapeutiche Invasive E Semi Invasive A Chiamata	P
Ing. Raffaella Marchettini	Ingegnere Clinico	P

Etik Kurul üyeleri, doğrudan veya dolaylı çıkar çatışması olabilecek deneylere karar vermekten imtina edeceklerini beyan ederler.
Toplantının usule uygun olup olmadığı ve yeter sayının varlığı tespit edildikten sonra, Etik Kurul toplantısının saat 17.30'da açıldığı ilan edilir.
Roberto Poscia sekreterlik işlevlerini yerine getirir.

atlandı

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AZIENDA OSPEDALIERO-UNIVERSITARIA SANT'ANDREA · REGIONE LAZIO · SAPIENZA · AZIENDA OSPEDALIERO-UNIVERSITARIA POLICLINICO UMBERTO I

Ref. 5982 (herhangi bir yazışmada her zaman alıntılanması gerektiği unutulmamalıdır.) **Prot. 259/2020**

Araştırmacı: Prof. Patrizia MANCINI
Klinik Çalışma: Koklear implantın odyolojik ve nöropsikolojik sonuçlarının değerlendirilmesi
Organizatör: AOU Policlinico Umberto 1 - Roma Sapienza Üniversitesi
Etik Kurul aşağıdaki belgeleri değerlendirmiştir:

1. Araştırmacıdan gelen niyet mektubu;
2. 29/01/2020 tarihli Çalışma Protokolü versiyon 1;
3. Veri toplama formu veya vaka rapor formu (CRF) (29/01/2020 tarihli CRF versiyon 1)
4. 29/01/2020 tarihli çalışma bilgilendirme raporu versiyonu 1;
5. 29/01/2020 tarihli sürüm 1'i onam formu;
6. 29/01/2020 tarihli Gizlilik Politikası ve Onam Versiyonu 1;
7. Çalışmayı onaylayan Bölüm Akademik Kurulu Kararı (22/01/2020 Toplantısı)
8. Araştırmacılara ilişkin Mali Tablo ve Çıkar Çatışması Beyannameleri
9. Baş araştırmacının özgeçmişi

ONAY

atlandı

Ticari olmayan bir deney hakkında görüş talebinde bulunulması durumunda, AT, 17 Aralık 2004 tarihli Bakanlar Kararnamesi'nin gerekliliklerinin varlığını tespit etmiştir ve bu nedenle çalışmayı şu şekilde değerlendirmektedir:

1. Sağlık hizmetlerinin ayrılmaz bir parçası olarak klinik uygulamaları iyileştirmeyi amaçlamıştır EVET

Hatırlanması gerekenler:
Araştırmacı, ilk hastanın kaydını Etik Kurul'a bildirmekle yükümlüdür;
Araştırmanın sonunda, Araştırmacı nihai raporunu her çalışmanın sonunda Etik Kurul'a göndermelidir.
ayrıca, Araştırmacı yıllık raporu da göndermelidir.
Araştırmayı etkinleştirmek için beklenmesi gerekenler:
• Gerektiğinde AIFA Yetkili Otoritesi onayı;
• Gerektiğinde, anlaşma şartnamesi;
• Gerektiğinde, idari izin;
Etik Kurulu'nun iyi klinik uygulamalara (GCP-ICH) ve gerekli yükümlülüklere uygun olarak düzenlendiğini ve çalıştığını beyan ederiz.
Bakanlık Kararnamesi ekinden 15/07/97, Bakanlar Kararnamesi sonrasında 18/03/98, müteakip Kanun Hükmünde Kararname 24/06/2003, müteakip D.M. 12/05/2006, müteakip Bakanlar Kurulu Kararı 21/12/2007, Ö.M. 08/02/2013.

Roma, 27.04.2020

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8.2. APPENDIX-2: The individual implant characteristics with the RP/PP ability

ID	CI Ear	FS Coding Strategy	Channel's Number / Bandwidth for F0	n of active channels	RP/PP ability	ID	CI Ear	FS Coding Strategy	Channel's Number / Bandwidth for F0	n of active channels	RP/PP ability
U1	L	FSP	1st / 150 to 281 Hz	9	PP	B1	R	FS4	2nd / 198 to 325 Hz	12	PP
							L	FS4	2nd / 198 to 325 Hz	12	PP
U2	L	FS4	1st / 100 to 208 Hz	11	RP	B2	R	FS4	2nd / 198 to 325 Hz	12	RP
							L	FS4	2nd / 198 to 325 Hz	12	RP
U3	L	FS4	2nd / 198 to 325 Hz	12	RP	B3	R	FS4	1st / 100 to 208 Hz	11	RP
							L	FS4	1st / 100 to 237 Hz	9	PP
U4	R	FSP	1st / 100 to 221 Hz	10	PP	B4	R	FS4	1st / 100 to 221 Hz	10	RP
							L	FSP	1st / 100 to 250 Hz	8	PP
U5	L	FS4	1st / 100 to 208 Hz	11	RP	B5	R	FS4	2nd / 198 to 325 Hz	12	RP
							L	FS4	2nd / 198 to 325 Hz	12	RP
U6	L	FS4	2nd / 198 to 325 Hz	12	RP	B6	R	FS4-p	1st / 100 to 208 Hz	11	PP
							L	FS4-p	1st / 100 to 237 Hz	9	PP
U7	R	FS4	2nd / 198 to 325 Hz	12	RP	B7	R	FS4	2nd / 198 to 325 Hz	12	RP

							L	FS4	2nd / 198 to 325 Hz	12	RP
U8	R	FS4	1st / 100 to 221 Hz	10	RP	B8	R	FS4	1st / 100 to 208 Hz	11	PP
							L	FS4-p	2nd / 170 to 300 Hz	12	PP
U9	R	FSP	2nd / 198 to 325 Hz	12	RP	B9	R	FS4-p	2nd / 198 to 325 Hz	12	RP
							L	FS4	2nd / 198 to 325 Hz	12	PP
U10	L	FSP	1st / 100 to 208 Hz	11	PP	B10	R	FS4	2nd / 100 to 221 Hz	10	RP
							L	FS4	2nd / 198 to 325 Hz	12	RP
U11	R	FS4	1st / 200 to 265 Hz	12	RP	B11	R	FS4-p	2nd / 198 to 325 Hz	12	PP
							L	FS4-p	1st / 100 to 208 Hz	11	RP
U12	R	FS4	1st / 100 to 221 Hz	10	PP	B12	R	FS4	2nd / 198 to 325 Hz	12	RP
							L	FS4	2nd / 198 to 325 Hz	12	PP
U13	R	FS4	2nd / 170 to 300 Hz	12	RP	B13	R	FS4	2nd / 181 to 327 Hz	11	PP
							L	FS4	2nd / 170 to 300 Hz	12	RP
U14	L	FSP	2nd / 198 to 325 Hz	12	RP	B14	R	FS4-p	1st / 100 to 208 Hz	11	RP
							L	FS4-p	2nd / 198 to 325 Hz	12	RP
U15	L	FS4	2nd / 198 to 325 Hz	12	PP	B15	R	FS4	1st / 100 to 221 Hz	10	RP
							L	FS4	1st / 200 to 311 Hz	10	PP

8.3. APPENDIX-3: Turnitin Originality Report

The Effects of Fine Structure Strategies on Pitch and Speech Perception by Cochlear Implant Users

ORİJİNALLİK RAPORU

%9	%5	%9	%
BENZERLİK ENDEKSİ	İNTERNET KAYNAKLARI	YAYINLAR	ÖĞRENCİ ÖDEVLERİ

BİRİNCİL KAYNAKLAR

1	hdl.handle.net İnternet Kaynağı	%1
2	Hilal Dincer D'Alessandro, Deborah Ballantyne, Patrick J. Boyle, Elio De Seta, Marco DeVincentiis, Patrizia Mancini. "Temporal Fine Structure Processing, Pitch, and Speech Perception in Adult Cochlear Implant Recipients", Ear and Hearing, 2018 Yayın	%1
3	Patrizia Mancini, Hilal Dincer D'Alessandro, Ginevra Portanova, Francesca Atturo et al. "Bimodal cochlear implantation in elderly patients", International Journal of Audiology, 2020 Yayın	%1
4	link.springer.com İnternet Kaynağı	<%1
5	"Cochlear Implants", Springer Science and Business Media LLC, 2003 Yayın	<%1

8.4. APPENDIX-4: Turnitin Digital Receipt

turnitin

Dijital Makbuz

Bu makbuz ödevinizin Turnitin'e ulaştığını bildirmektedir. Gönderiminize dair bilgiler şöyledir:

Gönderinizin ilk sayfası aşağıda gönderilmektedir.

Gönderen:	Yılmaz Odabaşı
Ödev başlığı:	The Effects of Fine Structure Strategies on Pitch and Speech ...
Gönderi Başlığı:	The Effects of Fine Structure Strategies on Pitch and Speech ...
Dosya adı:	Yilmaz_Thesis_tt.pdf
Dosya boyutu:	1.11M
Sayfa sayısı:	53
Kelime sayısı:	14,432
Karakter sayısı:	72,784
Gönderim Tarihi:	23-Oca-2023 11:44ÖÖ (UTC+0300)
Gönderim Numarası:	1997608437


T.C.
REPUBLIC OF TURKEY
HACETTEPE UNIVERSITY
INSTITUTE OF HEALTH SCIENCES

THE EFFECTS OF FINE STRUCTURE STRATEGIES
ON PITCH AND SPEECH PERCEPTION BY
COCHLEAR IMPLANT USERS

Yılmaz ODABAŞI

Audiology Program
MASTER'S THESIS

ANKARA
2023

9. CURRICULUM VITAE (CV)

Personal Details

Education

Work Experience

Publications