PREPROCESSING STRATEGIES AND SPEECH PERCEPTION THROUGH COCHLEAR IMPLANTS — A SYSTEMATIC REVIEW

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This Dissertation is submitted as part

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September 2021

CERTIFICATE

This is to certify that this dissertation entitled **'Preprocessing strategies and speech perception through cochlear implants – A systematic review'** is a bonafide work submitted in part fulfillment for the degree of Master of Science (Audiology) of the student Registration Number: 19AUD015. This has been carried out under the guidance of the faculty of this institute and has not been submited earlier to any other University for the award of any other Diploma or Degree.

Mysuru

September 2021

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DECLARATION

This is to certify that this dissertation entitled **'Preprocessing strategies and speech perception through cochlear implants – A systematic review'** is the result of my own study under the guidance of Dr. N Devi, Assistant Professor, Department of Audiology, All India Institute of Speech and Hearing, Mysore and has not been submitted earlier to any other University for the award of any other Diploma or Degree.

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This Dissertation is dedicated to

Achan, Amma & Ettan

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ABSTRACT

Speech perception in the presence of competing noise is a challenging task for most individuals with cochlear implants (CI). Several advanced technologies are available in different cochlear implant systems to provide comfort in listening and enhanced speech perception in noisy environments without degrading the performance in quiet settings. The implementation of pre-processing strategy is an effective method for enhancing the signal quality in challenging signal-to-noise conditions. This study systematically reviews the articles published in the past nineteen years (2002-2021) regarding the various pre-processing strategies available in the major cochlear implant devices (Cochlear Ltd, Advanced Bionics, Med-EL, Digisonic). This review gives a broad overview of the device descriptions related to noise reduction strategies and the performance across listening environments. The studies concerning speech perception performance across adults and children were reviewed. Several pre-processing strategies are available in the cochlear implant devices, including Adaptive Dynamic Range Optimization (ADRO), Automatic Sensitivity Control (ASC), VoiceTrack, ClearVoice, BEAM, ZOOM, and SCAN. This review analyzed the speech perception benefits of each of these strategies and their performance in quiet and noise conditions. The evidence from the literature indicates that the enhanced performance with pre-processing strategies highlights the importance of incorporating appropriate noise reduction algorithms in CI devices.

CHAPTER 1

INTRODUCTION

A cochlear implant (CI) is a surgically implantable prosthetic device that provides optimal benefits for individuals with hearing impairment. A cochlear implant device directly stimulates the cochlea and provides sound and speech information to individuals with moderate to profound hearing loss (Schow & Nerbonne, 2017). Advanced cochlear implant technologies are incorporated with various signal enhancing strategies that contribute to the natural perception of speech. Nevertheless, speech perception with background noise remains a major challenge for the cochlear implanted population due to the loss of temporal and fine spectral resolution and a relatively narrow dynamic range of electrical stimulation (Kokkinakis et al., 2012, Spahr et al., 2007). An effective way to reduce the impact of competing noise on speech perception is through pre-processing strategies and multiple microphones. Currently available cochlear implant speech processors are equipped with pre-processing strategies (Brockmeyer & Potts, 2011) for improving speech perception. Pre-processing strategies will enhance speech quality by reducing the background noise, improving SNR, and improving speech intelligibility, thus help to provide maximum benefit from the cochlear implant.

Different cochlear implant systems use different default pre-processing strategies, and the names and features of each strategy vary according to cochlear implant models. Automatic sound management is used as the default pre-processing strategy by Med-EL device, Advanced Bionics uses ClearVoice, SmartSound by Cochlear Ltd, and VoiceTrack is used as default strategy Digisonic. Each of the manufactures offers multiple processing strategies concerning the speech processors.

The Cochlear Limited device offers pre-processing strategies that help to enhance hearing performance in challenging environments. These noise reduction strategies comprised various advanced versions of the SmartSound program with improved quality in speech perception. SmartSound algorithm incorporated a range of input signal processing technologies, including Automatic Sensitivity Control (ASC), channel-specific Adaptive Dynamic Range Optimization (ADRO), and both adaptive directional and moderate directional microphones (Patrick et al., 2006). The next version, called the SmartSound2 program in the Nucleus 5 system, was incorporated with an additional highly directional microphone technology (Wolfe et al., 2012). A further release available in the Nucleus 6 system is called SmartSound iQ, which includes an automatic scene classifier and a wind noise reduction technology. The most recent release, ForwardFocus (FF) in the Nucleus 7 speech processor, includes highly upgraded background noise reduction technology and improves listening quality in challenging SNR conditions. The Forward Focus was designed as a spatial post-filter technology and was implemented on unilateral conventional behind-the-ear sound processors (Goffi-Gomez et al., 2020). Each SmartSound option pre-processes sound differently to give optimum benefit under different listening environments (Yathiraj & Rao., 2013).

The noise reduction program available in Advanced Bionics is the ClearVoice algorithm based on the HiRes 120 strategy and has been designed to improve speech understanding in difficult listening environments by reducing the stationary noise and emphasizing the dynamic channels containing speech. In addition, the Advanced Bionics device providing an enhanced noise tolerance power to the listener. The ClearVoice program analyzes the incoming signal into distinct frequency channels and estimates the respective signal-to-noise ratio (SNR) or noise level using a digital signal analysis method. The gain is lowered for channels where noise is detected or when the SNR is low. As a result, there is more emphasis on dynamic channels which contain speech signals, and hence there is an overall improvement in SNR can be observed.

A study done at the Advanced Bionics research center (2012) indicates that ClearVoice significantly enhanced speech perception in steady-state noise in all the gain settings. Even though ClearVoice is meant to enhance speech understanding in a steady noise situation, this is also useful in fluctuating noise conditions. Two new sound processing strategies from Advanced Bionics include ‘SpecRes,’ a research version of HiRes with Fidelity 120, and “SinEx.” It incorporates a new high-resolution frequency estimator and a spectral masking model (Nogueira et al., 2009). The HiRes Fidelity 120 sound processing strategy is designed to deliver the pitch and timing of sound with great accuracy.

In the Med-EL cochlear implant system, Automatic sound management operates with automatic double-loop gain control, which continually adapts with the system's gain, adjusting the sound level at a range of loudness that can be comfortably heard by the listener and provides the optimal perception of speech. However, it is still proportionally soft or louder. The automatic sound management strategy regulates brief and intense intermittent sounds for various listening situations and provides a dynamic input range of 75 dB SPL for MAESTRO cochlear implant System users.

Voice track strategy in Digisonic SP cochlear implant system is to provide better speech understanding in noisy situations. This single-channel noise reduction system operates on modified wiener filter technology and works with 64 independent frequency bands. The modified wiener filter method effectively provides enhanced listening with significant improvements in their speech perception scores in quiet and noisy conditions.This is especially evident in environments such as speech intelligibility over the telephone and speech in noise settings (Guevara et al., 2016). Voice Track works by detecting the steady background noise and lowering its volume. It protects the important speech signal and shields the listener from other noise, thereby making conversation easier.

Directional microphones also play a vital role in the enhanced speech perception. It is used to improve listening in adverse conditions. The selectivity of the directional pattern can be substantially increased with multiple microphones. Across companies, there is a wide variety of microphone options available according to the model of the processor being used. The directionality of the microphone is specific for a particular model and the company. With the advance in technology, companies are coming up with newer placements for microphones to improve directionality and thus the speech perception in noise. Advanced Bionic has four different microphone options: Tele- Mic, two omnidirectional microphones, UltraZoom, StereoZoom and ZOOM Control. A study done at the Advanced Bionics research center (2013) indicates that UltraZoom showed remarkable speech perception ability in noisy situations. There was an improvement of 6 dB in speech recognition score when using UltraZoom compared to the standard omnidirectional microphone. Cochlear has two omnidirectional microphones, which provide dual-mic directionality and helps in beamforming. It operates in four modes, namely, Standard, ZOOM, FOCUS, and SCAN. The Med-EL uses two omnidirectional microphones, which act as advanced directional beamformers. It mainly has four modes: Omnidirectional mode, Adaptive directional, Natural, and Automatic. Spriet et al. (2007) indicated that using two microphones adaptive beamformers, a significant increase in speech perception was seen in various types of noise (multi-talker babble and speech weighted noise) and at various SNRs.

1.1 Need forthe Study

Several investigations evaluated various pre-processing strategies and their effect on improving Signal to Noise Ratio (SNR) in cochlear implant users. Gifford and Revit (2010) reported that recipients using FOCUS (ADRO+ASC + BEAM) in the Cochlear Ltd system have relatively lower speech recognition threshold than either ADRO alone or ASC plus ADRO in listening to noisy environments. The T-Mic or AUX-only setting is preferred for Advanced Bionics recipients for everyday situations and environments with a noisy background since it provides natural directivity without switching programs. Honeder et al. (2018) reported a significant improvement in speech recognition scores with the fixed and adaptive beamforming mode than in Omni-directional microphone in Med-EL implant recipient with SONNET audio processor. However, these research findings indicate that speech perception is closely associated with these pre-processing strategies, and combinations of different strategies can also benefit cochlear implant recipients.

The above literature results suggest numerous studies to discover the most effective pre-processing strategies to obtain enhanced speech perception in cochlear implant recipients. However, there is a need to effectively or critically integrate this current information in a systematic review and provide a comprehensive summary of various pre-processing strategies. Available literature findings indicate each input sound processing strategies are having unique features and operating mechanisms. Hence, this current study can compare different pre-processing strategies, identify which strategy provides better speech perception in the presence of background noise, and identify variability strategies.

1.2 Aim of the study

The present study systematically investigated various pre-processing strategies and their effects on speech perception in cochlear implants.

1.3 Research question

- How are various pre-processing strategies associated with speech perception in major cochlear implant companies such as cochlear, Advanced Bionics, Med-El, and Digisonic?
- Which pre-processing strategy provides better speech perception in background noise?

CHAPTER 2

MATERIALS AND METHODS

This study systematically reviewed original articles related to pre-processing strategies and speech perception throughcochlear implants. The review methods were described according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009). A systematic literature search was carried out for peer-reviewed articles published from 2002 to 2021.

2.1 Literature search:

The literature search was carried out after framing the PICO (population, intervention, comparison, outcome) question for defining the key variables. Studies were included if they incorporated human subjects with a history of hearing impairment and had undergone surgery for the cochlear implant with one of the major cochlear implant companies (Advanced Bionics, Cochlear Corporation, Med-EL, and Digisonic).

2.2 Eligibility Criteria

2.2.1 Inclusion criteria

- Published journal articles in the English language were selected
- The articles were considered for review based on the accessibility of full-length papers.
- Articles that were published in peer-reviewed journals over the past nineteen years were included.
- Original articles containing human subjects with appropriate samples and relevant statistics were considered.

- The population of the study includes individuals with hearing impairment, rehabilitated with a multichannel cochlear implant (Cochlear Ltd, Advanced Bionics, Med-EL,and Digisonic)

- Articles wereincluded regardless of the age range of implanted population, number of channels available in the implant, speech processor model, unilateral or bilateral stimulation, and type of noise exposure.

2.2.2 Exclusion Criteria

- Study populations with multiple disabilities or any other associated disorders were excluded.

- Articles with low methodological quality and language apart from English were excluded

- Systemic Review articles, case reports, case series, editorials, short communications, and letters to editors were excluded

2.3 Study design

Scientific study designs including, Cross-Sectional studies, Cohort studies, intervention studies, and case-control studies were included in this systematic review study.

2.4 Population:

Articles included both children and adults irrespective of the subject's age and surgically implanted with anymajor cochlear implant device using the pre-processing strategy technology. Subjects should not have presented any other disability.

2.5 Information source:

The following electronic databases were systematically searched to identify relevant studies: PubMed,Google Scholar, CINAHL, J-STAGE, Cochrane Library, Scopus, Web of Science and Shodhganga. Reference lists and citation tracking were screened to identify any additional relevant studies.

2.6 Search strategy

The search strategy was made using keywords, Boolean operators and medical subject heading (MeSH) terms and phrases such as the cochlear implant, pre-processing strategies, noise reduction algorithms in cochlear implants, speech perception, directionality and cochlear implants. The keywords were combined using the Boolean operators such as ‘AND,’ ‘OR,’ ‘NOT’. There was no language, publication year, or publication status restrictions. The articles from various databases were imported to Rayyan: intelligent, systematic review, software for managing bibliographic data, and enabling the removal of duplicate records.

2.7 Study selection

To ensure no bias during the selection process, two authors (first and second authors) evaluated the articles based on the inclusion and exclusion criteria of the study. The final article selection was made based on the consensus by the two authors. The search results were combined using the Rayyan QCRI (Qatar Computing Research Institute) and Mendeley desktop reference manager system, and the duplicate studies were eliminated. The abstracts and/or full texts for the identified studies were evaluated to select the relevant articles for the study. Additionally, the reference lists of selected articles were also screened to identify any relevant articles that met the inclusion and exclusion criteria of the study.

2.8 Data extraction

The authors extracted the following data: author, published year, title, research question, population, cochlear implant company, types of pre-processing strategies, tests used for assessing the outcome, results, main findings, implications, level of evidence, quality, country, journal type, validation, and evidence of effectiveness.

2.9 Quality assessment

The National Heart, Lung, and Blood Institute (NHLBI) –Quality Assessment Tool was used to assess the quality of each of the selected articles. Sources of bias (e.g., patient selection, performance, attrition, and detection), confounding factors, study power, the strength of causality in the association between interventions and outcomes and other factors included in the tool for evaluating potential flaws in study methods or implementation (*Study Quality Assessment Tools | NHLBI, NIH*, n.d.). The NIH tool consists of quality assessment checklists with 14 cohorts, cross-sectional and controlled intervention studies, and 12 items for case-control studies. The Quality assessment is based on the selection of "yes," "no," or "cannot determine/not reported/not applicable" in response to each item on the tool. This tool was selected because of its high reliability and could be used with various research designs and approaches. From the number of articles retrieved, none of the articles was omitted based on low quality (Appendix A). The finding of the present review has been shown in the result section in detail.

CHAPTER 3

RESULTS

3.1 Description of studies

A total of 32 articles were identified from the year 2002 to 2021 for the complete analysis. Most of the studies were based on cohort and cross-sectional design (26 studies), four studies on controlled intervention design, and two on case-control design. The population included both adult and child participants. All the participants were implanted unilaterally or bilaterally with one of the major cochlear implant devices. Speech perception skills were assessed with standardized tools, and outcomes weremeasured using different methodologies such as open-set and closed-set words and sentence lists in both quiet and noise conditions. A detailed PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow chart for the selection of the study is shown in Figure 3.1

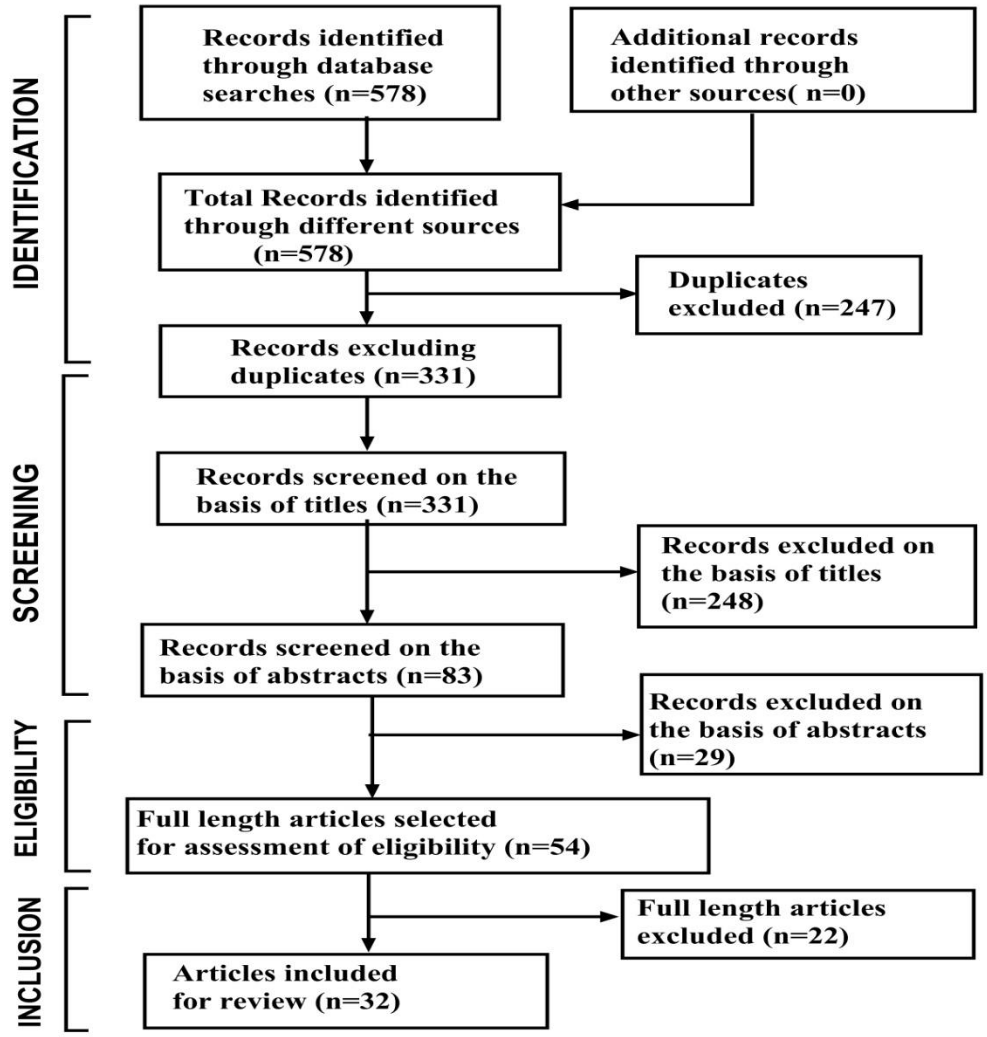

Figure 3.1: PRISMA flow diagram for the screening process of study selection

3.2 Study Characteristics

From figure 3.1, it is evident that 578 articles were identified through different database searching, and 247 articles are identified as duplicates. Title and abstract screening were done for 83 articles from multiple references. After the full-text screening, a total of 32 articles were selected for the current study. The final articles included were summarized and tabulated with the subheadings, including author and year, study design, research question, population(N), cochlear implant device, pre-processing strategy, the test used, results and implications.

A summary of the obtained literature studies were given in Table 3.1. (Summary table). When onsidering the purpose of this review, the following articles were selected which concerened the effect of pre-processing strategies in cochlear implant population: a total of 21 articles were identified on Cochlear Limited Company; 6 articles on Advanced Bionics; 2 articles on both Digisonic and Med-EL and one study which investigated the combined results of Cochlear Limited, Advanced Bionics and Med-EL devices.

Table 3.1. Summary of study characteristics of the selected articles

Sl No	Author & year	Research design	Research question	Study Population (N)	Cochlear implant	Pre-processing strategy	Outcome Measurement	Results	Implications
1	Wolfe et al.(2011)	Cross-sectional design	ADRO compared with ASC+ADRO	Children 11 subjects (aged between 4 years 4 months to 12 years) U/L or B/L CI.(8-bilateral implants 3-unilateral implants)	Cochlear Corporation	ADRO ASC	Speech perception in quiet assessed with monosyllabic word recognition test (PBK-50) and noise with BKB-SIN sentences	In quiet, word recognition score is at or above 90% correct for all the children. In noise, performance with ASC in combination with ADRO shows better scores than ADRO-alone	Better speech perception with ASC+ADRO

2	Goffi-Gomez et al. (2020)	multicentric prospective cross-sectional study.	Speech recognition was tested using a combination of automatic noise reduction algorithms with fixed microphone directionality.	Adults 47 subjects with post-lingual deafness (aged between 19 to 70 years). 7 subjects with bilateral CI and 4 subjects with the bimodal device.	Cochlear Corporation implants- Nucleus 5 (CP 810) and N7(CP1000)sound processor	Forward focus (Combination of ASC, ADRO, SNR/NR)	The SSQ assessed subjective listening outcomes and satisfaction. The evaluation involved the HINT Test with loudspeaker position at 0 degrees and 180-degree azimuth with the distance of 1 m from the subject, in four conditions with stimuli from the front direction: (a) quiet (b) fixed noise from the front direction, (c) fixed noise from the backside, and (d) adaptive noise ratios with	In quiet, no significant difference in scores.In noise, the N7 device provided better scores than the previous sound processor in all 3 settings. In fixed noise from the back direction, speech recognition was 62.9% for Nucleus 5 device with Beam and 73.5% for N7 with ForwardFocus.	The significant improvement observed using the N7 CI device with ForwardFocus

							noise from the front		
3	Guevara et al.(2016)	Cohort study	Evaluated quality of sound and speech perception in noise with a multiband single-channel noise reduction algorithm using modified Wiener-filter	Adults 13 participants with postlingual deafness (Aged as 51 ± 17 years.)	Oticon Medical Neurelec CI system with Digisonic SP in U/L	VoiceTrack	The outcome was measured immediately after the noise reduction strategy was enabled and after a month of usage duration. Pure-tone threshold measurement and vocal audiometry testing were done. The outcome was assessed in both	The noise-reduction strategy provided an improvement in speech perception skills in a stationary speech-shaped noise condition. Also,overall benefit with noise reduction strategy in subjective ratings for sound quality	Enhanced performance with a single-channel noise reduction system based on a modified Wiener-filter approach (Voice Track).

			approach				quiet and noise setting. A 10 item questionnaire was used to measure subjective sound quality		
4	Bergeron &Hotton. (2016)	Cohort study	Compared the performance of Voice Track and Crystalis to the standard processing strategy in terms of speech perception in noise and subject satisfaction	Adults 18 Participants (mean age: 62.0 years). Unilaterally implanted with Digisonic SP with a Saphyr processor.	Digisonic SP CI unilaterally	Crystalis Voice track	HINTest in quiet condition and noisy condition at +10, +5, and 0 dB SNR were measured. Subjective feedback related to the new strategy was also obtained	In quiet, no significant differences in performance, noise, and speech perception improved with the new processing strategy compared to the standard processing strategy. The subjective opinion indicates enhanced listening in more challenging situations.	The original Oticon Medical Device's high sensitivity to a degraded setting has decreased considerably with these more effective noise reduction processing strategies.
5	Yathiraj &Rao. (2013)	Cross-sectional	Investigated the effectiveness	Children 17 Participant	Nucleus CI: Nucleus	ASC ADRO	In Quiet, Speech identification scores were tested	A significant difference between the performance	when both the signal and noise from the front

		study	of noise reduction strategies in speech perception with background noise & speech perception differences between the noise reduction strategies (ADRO, ASC, and Beam) in different SNRs.	s (Aged between 5 to 13 years; mean age: 8 years 7 months)	24/512/Freedom implants with SPrint (N=5), Freedom (N=6), or CP810 (N=6) SP. all are used ACE strategy	Beam	with the 'Everyday' default setting activated, and also ADRO, ASC, and Beam with the speech in noise at two different SNR (+5 dB & +10 dB SNR)	scores in quiet and noise conditions. There is no significant variation between ADRO, ASC Beam at + 5 dB and +10 dB SNR and between the SNRs for all three pre-processing programs.	direction, no effect with the noise reduction strategies, and also indicates that when noise and speech are from the front of the listener, it did not matter whether they use processors with directional, omnidirectional, or a combination of directional and omnidirectional microphones.
6	Spriet et al. (2007)	Cohort study	Evaluated the speech understanding witha two-microphone adaptive	Adults (1 F/4 M) 5 subjects (aged between	Nucleus freedom. ACE strategy	Beam	At different SNRs, percent correct phoneme scores for CVC words and SRT with sentences	Compared to standard hardware directional microphones, the BEAM improved correct phoneme	For the Nucleus freedom CI system, the adaptive noise reduction algorithm BEAM may significantly

			beamformer in the presence of background noise	35 to 56 years)			were obtained in quiet and background noise. SSQ questionnaire was also administered	scores and SRT in noise. Subjective assessment and SSQ questionnaire are also recommending the use of beamformer in noisy conditions	improve speech perception in noisy environments
7	Hersbach et al.(2012)	Cohort study	The use of a noise reduction (NR) algorithm based on SNR estimation combined with different directional microphone settings.	Adults 14 Unilateral CI users (aged between 41 to 85 years)	Cochlear CP 810 processor	Standard, Zoom, and Beam with SmartSound directionality settings were all tested with and without NR.	In quiet, assessed with Word recognition test and in noise with sentence recognition test. Performance feedback from the subjects was taken through a questionnaire. SRT for 50% morphemes correct was used for the sentence recognition task. Competing talkers and	In noise, the use of a directional microphone shows better results in sentence perception. Over the Standard setting, an improvement of 3.7 dB and 5.3 dB in SRT was observed for ZOOM and BEAM, respectively. A further improvement in sentence recognition (1.3dB) in the presence of speech-weighted noise	In spatially separated noisy environments, an improvement in speech understanding was observed with multimicrophone directionality. The NR algorithm enhances speech intelligibility in the presence of speech-weighted noise without affecting the performance in

							speech-weighted noise were used as the interfering maskers. Music perception was assessed ina controlled environment.	maskers. Subjective feedback also suggests a benefit with the NR algorithm and the NR strategy not affected by the listening in quiet conditions, word recognition ability in quiet, and music perception.	quiet conditions.
8	Ali et al. (2014)	Cross-sectional study	Investigated the effect of ADRO on speech recognition in adverse listening environments.	Adults 10 subjects (aged between 54 to 80 years)	CI Nucleus multichannel implant ACE coding strategy	ADRO	Stimuli: 20 IEEE sentences. Ten testing conditions were provided: (1) Anechoic quiet, (2) reverberant, (3) noisy, (4) noisy reverberant, and (5) noisy reverberant settings (each condition with and without	The intelligibility scores decrease as the difficulty level increases, ranging from 96 % in a quiet setting to 23 % in a noisy reverberant setting. The non-ADRO program showed better performance than ADRO in the most challenging	There was no noticeable impact of ADRO processing strategy on speech intelligibility.

							ADRO strategy).	environments.	
9	Wolfe et al.(2015)	Cross-sectional study	1. In noise, the speech performance of N5 (default setting) compared with N6 (default setting) sound processor. 2. In noise, the performance of the default N6 setting compared with N6 sound processor with input processing	Adults & Children 93 Subjects (aged between 8 to 91 years; mean age- 52 years 10 months; SD-22 yr) With N6 processor (earlier users of N5 system)	Nucleus freedom, CI 422, CI 512 cochlear implants	For Nucleus 5 processor, standard directionality, ASC + ADRO, and for Nucleus 6 processo, ASC plus ADRO & SNR-NR with SCAN.	In noise, speech perception is assessed with AzBio sentences. The performance was assessed with the sound processor in the default setting, and the N6 processor was also tested with standard directionality and ASC plus ADRO, SNR-NR and SCAN disabled.	While compared to the default input signal processing of the N5 processor, there is a significant improvement in sentence recognition when using the default processing method of the N6 processor. When compared to the N5 processor in a noisy setting, the N6 default setting) showed a mean improvement of 27 % in sentence perception and 9 % in sentence perception with standard directionality, ASC	The N6 device with acoustic scene analyzer, automatic, adaptive directionality directionality feature, and speech enhancement characteristics provided a significant benefit over N5 processor in a noisy setting

			set to the same level of N5 (default setting) processor. 3.Assessed the benefits of the SNR-NR noise reduction program in N6 device.					plus ADRO and SNR-NR.	
10	Kordus et al.(2015)	Cross-sectional study	Localization ability and speech perception performance were assessed in dynamically changing listening environments with 3 device microphone	Adults 7 Subjects (bilaterally implanted, Aged between 27 to 68 years; mean age-54 years; SD-13.5 years)	Nucleus CI-24M device with Freedom Processor (ACE & SPEAK strategy)	SmartSound beam Omnidirectional Directional microphone	Localization ability assessed in both Quiet & Noise condition: closed-set test with 16 everyday sounds representing 4 sound categories: warning and information signals, vocalizations,	Neither in quiet nor in noisy condition, localization test showed an advantage of the beamforming over directional or the omni-directional microphone, four subjects accurately localized towards the center of the loudspeaker array,	There was no significant variance between the 3 microphone configurations. Compared to directional and Omni-directional microphone settings, a 3 dB SNR improved the beamforming configuration for 3

			configurations: beamformer, directional and omnidirectional.				instruments, and Effects are the targets. 70 dB (C) is the presentation level for localization test in a quiet setting, and 60 dB(C) with noise at 50 dB (C) is the presentation level for noise. Speech perception in noise: In the 'cued' SRT test, spondee words with female-male babble noise in background were presented.	while 2 subjects localized towards the side. Speech perception in noise: 50% level of spondees identification varies in SNRs by about 20 dB. For 2 subjects, 3 microphone setting comparison indicates slight improvement in the SNR for beamforming over directional or omni-directional microphone for beamforming vs. directional microphone comparisons, and for beamforming vs. omni-directional microphone comparisons.	subjects when the speech was given from the front direction. In dynamically changing listening environments, the benefits of using different microphone settings in cochlear implant devices vary depending on the acoustic environment.
11	Di Berardin	prospective,	A comparison	Children &Adults	Nucleus Freedom	ASC	Participants underwent a	In quiet, no significant	In noise, ADRO provides better

	o et al.(2021)	cross-sectional, observational blinded	between ADRO vs ASC + ADRO condition and assessed speech perception in a noisy environment with ASC in combination with ADRO.	(aged between 10 to 46 years; mean age-17.7 6.7 years) 2 monoaural and 16 sequential binaural)	or with a Nucleus 5 (CI512). CP810 speech processor & ACE speech coding strategy.	ADRO	speech-tracking (ST) test in noise. It also assesses the recognition of ongoing speech	differences were observed. in noise, word recognition scores (SNR at +5 dB HL) were significantly better in ADRO condition than ADRO+ASC condition and these objective findings are well correlated with the subjective reports	word recognition scores than ADRO+ASC condition
12	Dingemanse&Goedegebure. (2015)	double-blind crossover design	At various speech-in-noise ratios, the impact of ClearVoice" on noise tolerance and speech intelligibility in noise was evaluated. (2) Assessed wh ether low	Adults (aged between 37 to 85 years; mean age-65 years) 20 subjects	AB Harmony processor HiRes 120	Clear voice	ClearVoice was evaluated on speech intelligibility in quiet and noise tolerance ability with the ANL test and speech in noise for 3 performance levels. A spectral-ripple discrimination test was used for	No impact of Clear voice on any of the 3 speech in noise condition, and shows a substantial improvement in the ANL, with a reduction of 3.6 dB. Improved noise tolerance is correlated with higher maximal speech intelligibility in quiet. The noise	NRA is not affected by the speech intelligibility in noise The ClearVoice algorithm enhanced noise tolerance ability with a clear voice. Noise tolerance levels are not related to spectral-ripple

			spectral resolution may benefit from noise reduction strategies more than high spectral resolution.				assessing the effective spectral resolution.	reduction on ANL, speech intelligibility in noise, or speech-in-noise ratios were not associated with spectral-ripple discrimination thresholds. However, they were correlated with maximum speech intelligibility in quiet but not with speech reception thresholds in noise.	discrimination thresholds, speech intelligibility measures or SNR levels.
13	Koch et al.(2014)	rando mized crosso ver design	Evaluated speech perception effect with clear voice in quiet and noisy environments	Adults Unilaterall y implanted 46 Participant s (> 18 yrs of age)	AB CII/HiRe s 90K CI with HiRes Fidelity 120	ClearVoice	AzBio sentences are presented in three different settings: quiet, multi-talker babble, and speech spectrum noise. Speech perception abilities of ClearVoice low, medium, and high	ClearVoice strategy enhanced speech understanding in multi-talker babble and speech-spectrum noise setting without degrading the performance in quiet conditions was suggested for everyday listening and improved	ClearVoice strategy enhances speech understanding in noise without degrading the performance in quiet settings

							compared with the HiRes 120. A questionnaire was used to determine subjective preference.	listening in real-life situations.	
14	Honeder et al.(2018)	Cross-sectional study	Investigated fixed and adaptive beamforming technology on the perception of speech in noisy environments.	Adults 18 subjects (Aged between18 and 76 years; mean age-54.6 years) 12 bimodal, 2 B/L, 2 U/L and 2 subjects with single-sided deafness	Med-EL implant SONNET audio processor	(1)omnidirectional mode, (2) Fixed beamforming algorithm (FBF), and (3)Adaptive beamforming algorithm (ABF).	SRT measured with Oldenburg Sentence Test In continuous, speech-shaped noise. The stimuli presented from the front direction with noise sources at -135° and 135° angle direction. SRT differences obtained between SRT in 3 directionality settings considered as the outcome measures.	Directional microphones significantly Improved speech SRT. Compared to the omnidirectional setting, a 4.3 dB improvement for FBF and 6.1 dB improvement for ABF wereobserved. a benefit of 1.8 dB obtained for ABF compared to FBF	ABF and FBF provided Significant improvements in speech perception in a noisy setting

15	Mauger et al.(2014)	Cohort study	compared the performance of the N6 device to the N5 device and investigated the performance benefit with SmartSound iQ in a range of N5 and N6 programs	Adults 21 subjects (aged between 49 to 90 years) 4- bilateral 17- unilateral	Cochlear CI Nucleus 5 system (CP810), Nucleus 6 system (CP900 series sound processor)	ASC + ADRO Whisper zoom BEAM SCAN	5 test sessions were conducted. Assessed the CI performance in quiet, noise, and various spatial configurations. In quiet, stimuli presented at 50 dB SPL (Open set monosyllabic words). In noise, Speech understanding was assessed at 65 dB SPL using the Australian sentence test. Clinical comparisons across programs were conducted in; quiet, speech weighted noise, and 4-talker babble environment.	When compared to the subject's preferred program in the Nucleus 5 processor and a range of custom Nucleus 6 programs, the default Nucleus 6 program provides significant improvement in speech understanding	The SmartSound iQ provides significant improvement in speech recognition in various noise conditions and spatially separated noise settings by implementing various technologies according to the particular listening condition.

16	Kam et al.(2012)	Cohort study	assessed the speech understanding benefits in noise with a ClearVoice algorithm in the group of Cantonese-speaking CI users	Adults 12 Subjects (aged between 25.2 to 69.2 years; mean age - 50.3 years)	Advanced Bionics Harmony device with HiRes 120	ClearVoice	Performance of ClearVoice offsetting was compared with a ClearVoice on setting. After one week of usage, participants were assessed with ClearVoice medium and ClearVoice high setting. The speech perception outcomes were measured with Cantonese hearing in noise test and a subjective questionnaire.	In quiet, no significant difference was observed across the ClearVoice programs. In noise, the better performance was obtained with ClearVoice medium than the control program. In daily listening conditions, the majority of the participants reported that ClearVoice provided a high degree of satisfaction while listening.	ClearVoice provides better hearing in the noise condition
17	Holden et al.(2013)	Cohort study	Compared the performance between ClearVoice algorithm	Adults 15 Subjects 11U/L implant and 4 B/L	AB Harmony processor with HiRes 120	ClearVoice Low, ClearVoice Medium and ClearVoice	Sentences presented in R-SPACETM restaurant noise, speech-spectrum noise, 4 and 8	In the R-SPACE setting, ClearVoice and the HiRes 120 program noted a considerable variation in	For postlingual deaf adults, the use of a clear voice algorithm can enhance the listening comfort

			and HiRes 120 strategy for more modulated and less steady-state noise conditions. speech performance in a variety of listening environments , including soft presentation levels and conversation al speech levels, and also to find out the more beneficial algorithm among the 3 ClearVoice settings	implant (aged between45 to 75 years; mean age= 63 years; SD= 9 years)		High	talker babble, and connected discourse presented in 12-talker babble. In addition, A subjective questionnaire was used for comparing different ClearVoice strategies.	performance. ClearVoice High provided greater benefit than HiRes 120. No significant performance differences were obtained across the 3 clear voice programs. According to the subjective questionnaire- ClearVoice medium and high provide more benefit in speech perception.	and communication abilities in noisy settings

18	Rakszawski et al. (2016)	prospective, cross-sectional, observational study	Evaluated the speech recognition performance across different pre-processing algorithms	Children 11 subjects CI users (aged between 8.08 to 17.33 years; mean age=12.62 yr, SD=3.40 years) 6 B/L, 1 U/L, and 4 bimodal.	Cochlear Ltd	4 pre-processing conditions: no pre-processing, ASC, ADRO, and ADRO plus ASC	Monosyllabic words (CNC) were given at 50 and 70dB SPL in quiet condition, and HINT sentences at 60 and 70 dB SPL were presented with competing R-space noise	At 50 dB SPL, ASC + ADRO provided significantly better scores for CNC words. ASC scores are poorer when compared to ASC plus ADRO and ADRO. At 70 dB, SPL HINT sentences provided better scores with ASC and ASC plus ADRO compared to no pre-processing. Enhanced speech perception observed with ASC plus ADRO than ADRO alone setting. No substantial difference obtained between 70 dB SPL CNC and 60 dB SPL HINT sentences.	With ASC+ADRO, speech perception improved at both high and low levels of background noise. Subjective results demonstrate that the effective pre-processing strategy differs in terms of individual perform ance.
19	Dawson et al.	Cohort study	Investigated the	Children	Nucleus 24 CI	ADRO	ADRO and standard	In quiet at 50 dB SPL, BKB sentence	in quiet and noise, ADRO is

	(2004)		performance of ADRO in children	15 participants (aged between 6 to 15 yr)	with SPrint body-worn processor 11 using the ACE strategy, and 4 using the SPEAK strategy		(everyday) programs were compared with BKB sentence perception in quiet at 50 dB SPL and sentence perception in noise. In addition, subjects rated loudness of various environmental sounds and reported which program benefited from various everyday listening settings.	perception with the ADRO program was significantly better than the Standard program. The group average improvement was 8.60 %. Similarly, BKB sentences at 65dB SPL in multitalker babble shows an improvement with ADRO program. In 46% of listening conditions, the ADRO program was preferred, whereas in 26% of listening situations, the Standard program was selected and with ADRO, everyday sounds were not excessively loud.	benefiting for children with CI

20	Gifford et al. (2011)	Case-control study	Performance in speech perception with SmartSound strategies wasevaluated with an eight-loudspeaker (R-SPACE) setting	Children 22 experimental subjects with CI (aged between 5.6 to16.8 years; mean age=11.1 years) and 25 control subjects with NH (aged between 3.9 to17.0 years; mean age=9.6 years)	Nucleus Freedom or CP810 device with ACE coding strategy	ADRO ASC	SRT obtained with HINT sentences. Performance was measured in percent correct in a fixed +6 dB SNR for a six-subject subset. The effects of the SmartSound setting on the SRT in noise were studied using repeated-measures ANOVA.	ASC+ADRO strategy enhanced the speech perception in noise with a mean SRT improvement of 3.5 dB in the SNR required for threshold. ASC+ ADRO significantly enhanced the performance in higher levels of diffuse background noise	Improvement in speech perception with SmartSound strategies in a realistic semidiffuse noise environment. ASC+ADRO enhance the speech perception in everyday listening condition
21	Noël-Petroff et	Cohort study	Investigated the speech	Children (aged	AB CII or HiRes	ClearVoice	Two modalities of ClearVoice	The switchover to ClearVoice was	ClearVoice was beneficial for

	al.(2013)		perception benefits with ClearVoice strategy	between 6 and 14 years; mean age=9.7 years; SD=2.4)	90K CIs with Harmony processor (U/L implanted)		were randomly tested for one month each. CAP testing, APCEI profile, and pure-tone audiogram. Speech perception test in quiet and noise setting with HINT sentences in Canadian French. At the end of each session, parents and teachers were given a listening questionnaire.	uneventful for both modalities. Thresholds and comfort levels needed to be adjusted. The ClearVoice program was preferred by 7 of the 9 children. ClearVoice did not affectperformance in quiet conditions. Compared to the baseline program, an improved speech understanding in noise was observed with both modalities of ClearVoice, significantly with ClearVoice high. The questionnaires and discussions with parents and children also demonstrated outcomes	children in their daily life. speech perception in noise was improved with ClearVoice, without affecting the performance in a quiet setting

22	Runge et al. (2016)	Cohort study	Performance of SmartSound 2 in N5 CI device was assessed with AzBio sentences. A secondary objective was to compare the speech perception between the current and previous versions of the Minimum Speech Test Battery's tests (MSTB)	Adults 38 participants (aged between 18–89 years; mean age=63.6 years)	Cochlear limited	3 SmartSound2 programs with default settings of FOCUS (Beam, ASC+ADRO), EVERYDAY (Standard directionality, ASC+ADRO) and NOISE (zoom, ASC+ADRO)	In quiet, CNC word test and AzBio sentences (AzBioQ) and in noise AzBioN were presented at preoperative, 3-, 6-, and 12-month post-activation intervals. The HUI3 was used to assess the quality of life. For the secondary goal, Statistical models were utilized to evaluate the predictive capabilities of current and previously used MSTB tests.	Mean CNC scores were substantially higher than the N24 device at 3 months after activation; however, there was no difference at 6 months after activation compared to the Nucleus Freedom. The FOCUS and NOISE strategies provided better performance than the EVERYDAY program, with superior performance with FOCUS. Quality-of-life ratings increased substantially from preoperative to 6-month post activation. Preoperative CNC and AzBioQ, as well	The SmartSound 2 algorithm demonstrated a substantial benefit of FOCUS in noise. However, signal processing strategy preference did not correlate to the speech performance.

								as preoperative HINTQ and AzBioQ, were shown to have significant relationships.	
23	Razza et al. (2013)	Cross-sectional study	Compared the speech perception in noise for the Nucleus Freedom and CP810 processors with the use of different directional algorithms in SmartSound program	Adults& Children 31 subjects. 7 adults and 24 children (aged between 4 to 69 years; mean age=20.0 ±19.4 years)	Cochlear corporation Freedom & CP810 processor	ADRO, BEAM and ZOOM	In all three pre-processing strategies, SRT was performed in a free field layout with a disyllabic word list and interfering multilevel babble noise.	When compared to Freedom SP, CP810 significantly enhanced the SRT level after 1 hour of CI usage. However, there was no substantial SRT difference between the CP810 processor's ZOOM and BEAM strategies. The mean SRT values for the CP810 with ADRO + BEAM and ADRO+ZOOM programs were 2.55 ± 2.94 and 2.58 ± 2.92, respectively, whereas with the	CP810 showed better results with disyllabic word recognition in babble noise conditions when compared to the Freedom device. There were no significant variations in speech perception scores between the pre-processing strategies used in the CP810 device (ADRO + BEAM and ADRO + ZOOM).

								Freedom processor and the ADRO + BEAM were 4.40 ± 2.67.	
24	Büchner et al.(2019)	Case-control study	The impact of different microphone directionality settings on speech perception in the presence of noise wasassessed	Adults 20 subjects (aged between 28–81 years; mean age=57.9 years)	Med-EL Sonata, Concerto or Synchrony implant & SONNET audio processor with FSP or FS4 coding strategy and one subject with HDCIS.	omnidirectional, fixed beamformer, and Adaptive beamformer	Just Understanding Speech Test and Oldenburg Sentence Test were used to assess SRTs omnidirectional, adaptive, and fixed beamformer microphone settings. A listening effort required for speech understanding assessed with a Visual Analogue Scale in different SNR levels(−10, −5, 0, 5, 10, 15 dB SNR)	Compared to the omnidirectional setting, mean SRTs for the fixed (3.3 dB SNR) and adaptive (5.2 dB SNR) algorithms demonstrated substantial performance improvements. For -5 dB SNR and 0 dB SNR conditions, fixed or adaptive setting required substantially less listening effort than the omnidirectional setting.	Speech perception in noise improved with beamformer algorithm compared to an omnidirectional setting. the use of beamformer provided an enhanced and effortless speech perception in real-life environments

25	Dillier and Laiv.(2015)	Crossectional study	compared, zoom, and Beam strategies in noisy environments	Adults (Minimum age of 18 years) 9 German-speaking subjects (previous users of Freedom processor and were then updated to CP810)	Cochlear nucleus CI24RE device and N5 CP810 processor. (earlier users of Freedom processor)	ZOOM BEAM	Oldenburg sentences test used for comparing Zoom and Beam strategies. In noise, 50% speech intelligibility SRT obtained with sentences presenting at 65 dB SPL from the front direction with noise from the same speaker or 90-degree direction in either the ear with the sound processor (S0NCI+) or the opposite unaided ear (S0NCI-). Noise sources were set at 90, 180, and 270 degrees in the	In a spatially 37separated speech in noise conditions, SRT improved with BEAM and ZOOM settings. An average SRT improvement of 12.9 and 7.9 dB for single noise sources was observed using Beam for either ipsilateral or contralateral sound processors. Beam has an average SRT of –8 dB in a diffuse noise setting. When compared to the omnidirectional setting, ZOOM provided a substantial improvement of 5.9 dB in the diffuse noise setting	Enhanced speech perception in noise with the use of ZOOM and BEAM processing strategies.

							fourth noise condition. An adaptive procedure was used to adjust the noise level, resulting in a SNR where of 50 % words in the sentences were properly recognized.		
26	Potts and Kolb. (2014)	Experi mental study	Speech perception in noise wasevaluated in a simulated restaurant setting with the use of different noise reduction strategiesto find out the best noise	Adults 32 participant s (aged between 36 to 92 years; mean age=66 years) Unilateral	Nucleus 5 (CI512) or Cochlear Freedom Contour Advance (CI24RE). 25 subjects with Freedom processor and 7	Beam, Beam plus ASC, Beam plus ADRO, Beam plus ASC plus ADRO, Zoom, Zoom plus ASC, Zoom plus ADRO, and Zoom plus ASC plus	HINT sentences were given at 0° azimuth angle, whereas R-SPACE restaurant noise was presented from a 360° angle at 70 dB SPL. A one-way ANOVA measure assessed the difference between Beam, Zoom, and Beam	Poorer performance with Beam+ADRO compared to Beam + ASC, Beam, and Beam + ASC + ADRO. The Beam and Beam + ADRO algorithms differ by 1.6 dB. The Zoom + ADRO and Zoom only setting performed poorer than Zoom + ASC in the zoom algorithm. There	The optimal performance with pre-processing strategies varies across subjects, most of the CI recipient's preferred directional algorithm (ZOOM or BEAM) along with ASC strategy. However, ZOOM+ASC or BEAM+ASC is

			reduction algorithm	CI	with CP810 processor . ACE speech coding strategy	ADRO.	vs. Zoom settings.	was a 2.2-dB difference between Zoom+ASC and Zoom. The beam only showed an improvement in performance than zoom only. However no noticeable difference between Zoom + ASC vs. Beam + ASC, Zoom + ADRO vs. Beam + ADRO and Zoom + ASC + ADRO vs. Beam + ASC + ADRO.	recommended in a noisy, semi diffuse environment.
27	Wolfe et al.(2012)	Crossover with repeated measures design	In quiet and noise conditions, the speech recognition was compared between freedom and	Adults (aged between 21.2 to 84.9;mean age= 56.5 years; SD=15.5)	Nucleus 5 processor (earlier users of Freedom sound processor)	ZOOM ADRO ASC	In quiet, CNC monosyllabic words and in noise, sentences from BKB-SIN test used to assess the speech perception performance.	In quiet and noise condition, Improved speech perception performance with N5 process than with Nucleus Freedom device	In noise, speech recognition was significantly better with NOISE program (ZOOM+ASC+ADRO) in N5 processor than with Nucleus

			nucleus 5 processor and the "Everyday" and "Noise" programs in N5 and Freedom processor.	35 Subjects s with unilateral Nucleus Freedom implants					freedom (ASC+ADRO) processor. For adults, the, 'Everyday' and 'Noise' are beneficial in the N5 processor
28	James et al.(2002)	Cross-sectional study	The effect of ADRO on speech perception was investigated.	Adults 9 Participants (Age ranged between 42 to 77 years; Mean age 59 yr, 11 months.)	Nucleus 24 implant with SPrint body-worn processor. SPEAK and ACE coding strategies	Two versions of the ADRO algorithm: LowA & HighA.	In standard and ADRO a program, the speech perception performance was compared with CNC words, CUNY sentences, and closed set spondees in quiet condition. The stimuli level ranged from 70 dB SPL to 40dB SPL. Multi-talker babble with 10 dB SNR and 15	The ADRO increases the speech perception performance than the standard program. in quiet, at 50 dB the mean open set sentence scores performance increased by 16%, at 60 dB CNC words performance increased by 9.5% and at 40 dB spondees mean scores improved by 20%. There was no substantial	ADRO strategy can enhance the audibility and comfort in listening by adjusting the amount of gain in each channel.

							dB SNR was also used to present CUNY sentences. Questionnaires were used to measure the take-home experience.	difference between the sentence scores obtained with ADRO and standard setting. For 59 % listening conditions, subjects preferred the ADRO strategy.	
29	Buechner et al.(2010)	Cohort study	Investigated hearing in noise with the new signal enhancement algorithm: ClearVoice.	Adults 13 participant s (aged between 33.15 to 80.73 years; mean age=58.35 years)	AB with HiRes 120 During one immediat e session, the participa nts received the clinical HiRes12 0 program (standard)	2 different ClearVoice settings: moderate setting (-12 dB) and strong setting (-18 dB)	The clinical program and clear voice settings were assessed immediately after the session using the HSM sentence test in speech-shaped noise. the three programs were given in everyday listening environments, and participants rated the quality of listening and speech perception using the	ClearVoice moderate and high performed better than the clinical program in the HSM sentence test condition. The mean speech perceptions scores were also higher for the ClearVoice setting than the clinical program. most of the participants preferred the ClearVoice program for improved listening	Significant improvement in speech perception with the use of ClearVoice strategy

							APHAB questionnaire		
30	Mauger et al. (2012)	Crosse ctional study	Evaluated Speech perception and listening in a range of noise environments . Determined an optimized noise-reduction algorithm in CI and compared the performance to the Smart sound everyday program in a range of listening conditions.	Adults 12 Participant s (aged between 53 to 83 years; mean age= 71 years)	Nucleus CI users	3 smart sound programs: 1)'Everyda y program 2) NR (Everyday, with noise reduction algorithm. 3) CI-optimized noise-reduction (CI-NR) setting (Everyday, with CI-NR)	Performance assessed in quiet with EVERYDAY program and with CI-NR program and in noise with all the 3 noise reduction programs. SWN, 20-talker babble, and 4-talker babble were assessed in 3 sessions. The Australian Sentence Test in Noise (AUSTIN) was used to evaluate the EVERYDAY program. The SNR was determined by using an adaptive	Speech perception improved with optimized noise reduction thanstandard processing in speech weighted noise and babble noise conditions. CI-optimized noise reduction showed significant improvements in listening quality and noise annoyance, and there is an overall subjective preference for CI-optimized noise reduction	Improved sound quality and speech perception with the optimized noise reduction method

							SRT measure with 50% morpheme perception. Fixed level testing was then carried out for SWN and 20-talker babble at this SNR-1 dB, and for 4-talker babble at the same SNR. Monosyllabic word recognition and CNC word testing were used in the final session. A subjective quality rating was also done at the end of each session.		
31	Iwaki et al.(2008)	Cohort study	Compared the performance with ADRO and non-	Adults 6 post-linguistically	Nucleus 24M CI and SPrint processor	ADRO	Speech perception was assessed with Japanese hearing in noise test	Poorer scores were obtained for the JHINT test for two ADRO than two non-ADRO devices	In quiet and noise conditions, there was a considerable increase in the

			ADRO algorithms in Bimodal users	deafened subjects (aged between 36 to 78 years; mean age=61.0 years)	with ACE coding strategy		(JHINT) in quiet and 3 noise settings (noise from the front direction, from the implanted side, and non implanted side). Threshold estimated with a noise level at 60 dB SPL with varying the speech level. The JHINT measured the SRT with a 50% correct score. hearing aid measure of contrast (HAMOC) wasalso done to obtain the acclimatization level	in noise from the front and implant side conditions. Also, there is a substantial differencebetween ADRO and non-ADRO settings in noise from the non implanted direction. The HAMOC shows a subjective preference of ADRO setting in difficult listening conditions	audibility and speech intelligibility with ADRO strategy
32	Sivonen et	Cross-section	Compared the	24	AB Naída CI	omni/ moderately	In noise, SRT wasmeasured	The average improvement in SRT	Significant improvement in

	al.(2020)	al study	performance of adaptive directionality and fixed directionality to omnidirectional microphone setting on SRT in the noise condition	subjects (8 AB users 8- cochlear users and 8- Med-EL users) (The mean age was 61, 40, and 46 years)	Q70, Cochlear Nucleus CP910 and Med-El Sonnet sound processors	directional Processor, fixed directional and adaptive directional	with speech and noise signals from the front direction. The SRT with different microphone directionalities was measured with noise from 90 degrees in the horizontal plane to the horizontal plane from the side of the CI sound processor (S0NCI).	in noise for fixed and adaptive directionalities over the omnidirectional mode in the S0NCI condition. Depending on the CI system, the response ranging from 1.2 to 6.0 dB SNR and 3.7 to 12.7 dB SNR, respectively.	performance with directionality setting in all three CI devices

3.3 Quality assessment:

Critical appraisal of each article was done using The National Heart, Lung, and Blood Institute (NHLBI) tool. (*Study Quality Assessment Tools NHLBI, NIH*, n.d.). The checklist was assessed separately based on the type of study. Figure 3.2 depicts the Quality analysis rating of Observational Cohort and Cross-Sectional Studies, figure 3.3 depicts the Quality analysis rating of Controlled Intervention Studies, and figure 3.4 depicts the Quality analysis rating of Case-Controlled Studies. Though some of the studies failed to account for all the confounding factors, it cannot be considered a limitation. Rather, it accounts for the diversity of the population under study.

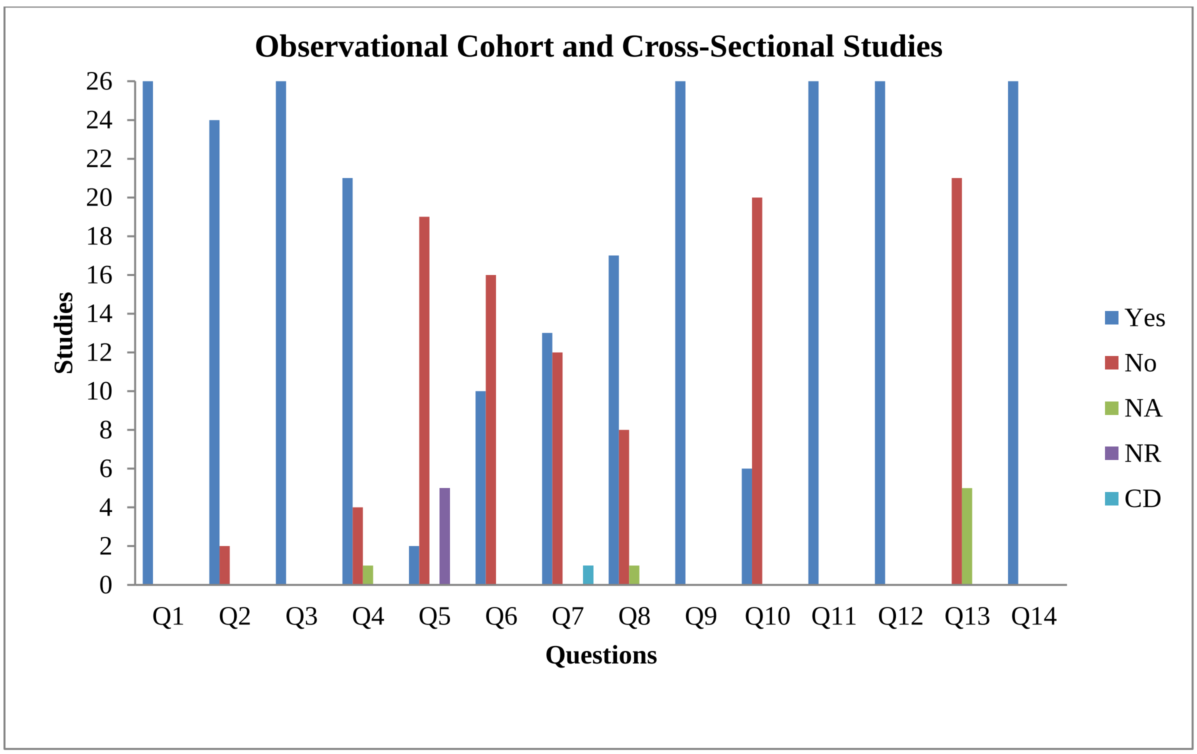

Figure 3.2. Quality analysis rating of Observational Cohort and Cross-Sectional Studies

Note: CD-cannot determine; NA-not applicable; NR-not reported

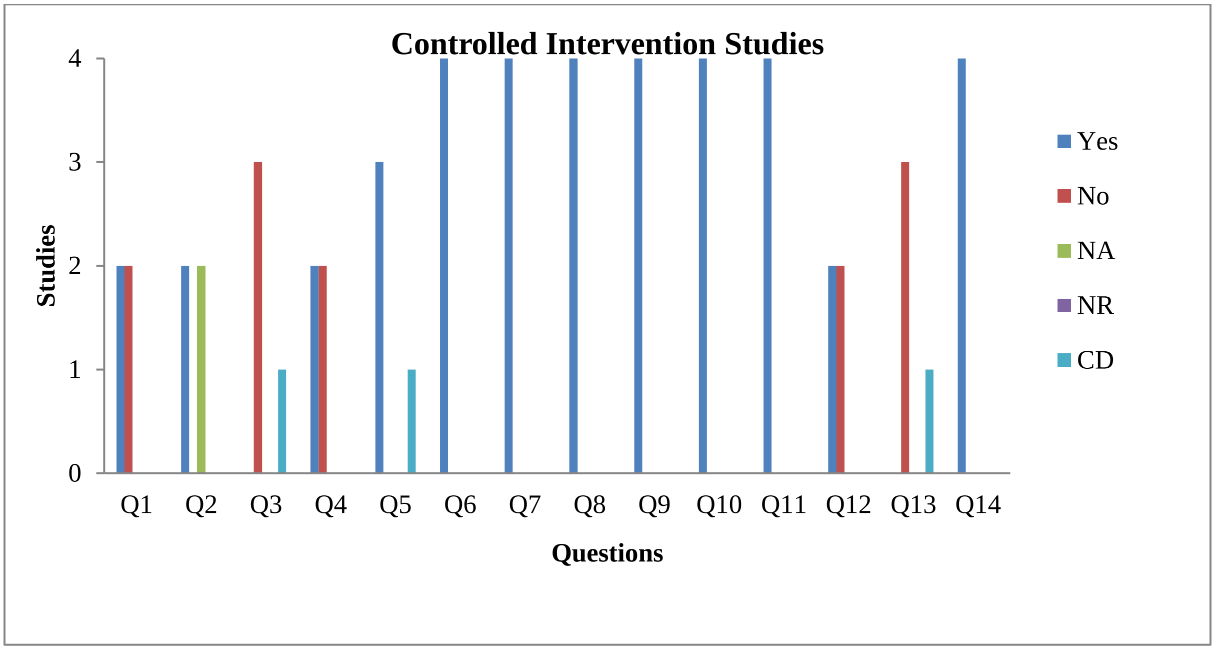

Figure 3.3. Quality analysis rating of Controlled Intervention Studies

Note: CD-cannot determine; NA-not applicable; NR-not reported

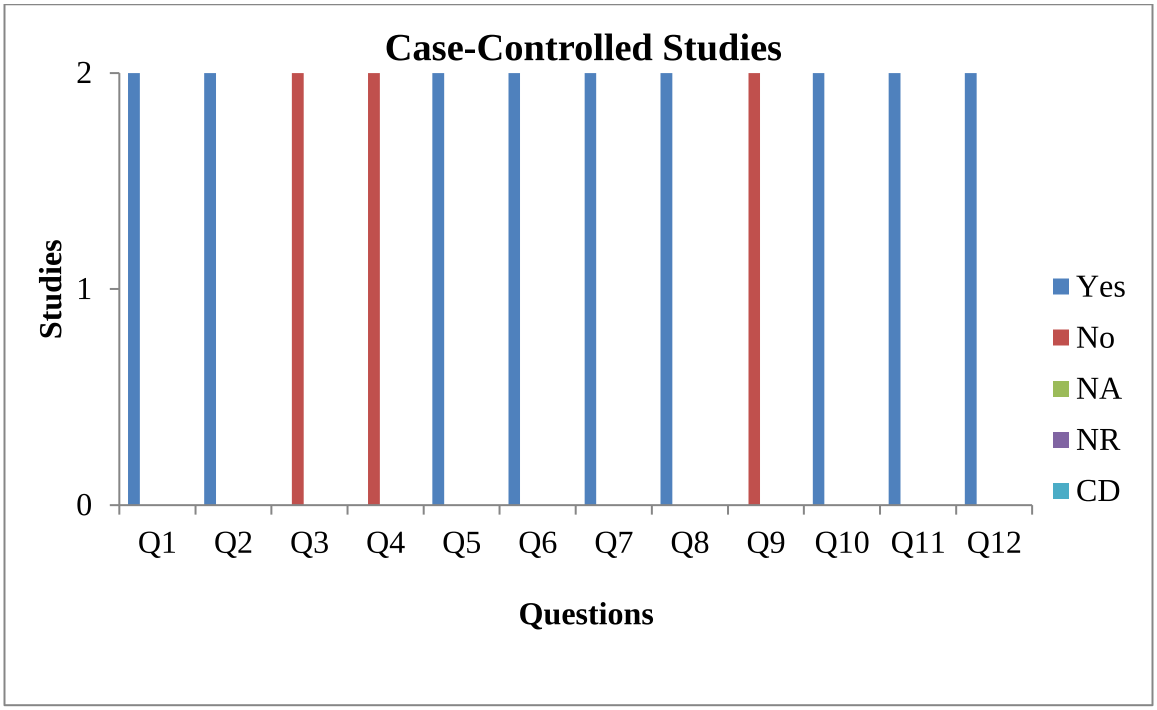

Figure 3.4 Quality analysis rating of Case- Controlled Studies

Note: CD-cannot determine; NA-not applicable; NR-not reported

A satisfactory rating was obtained from the above figures (3.2, 3.3 &3.4) for most assessed aspects. From the graphs, it is evident that all the studies were obtained with a good quality of analysis.

In cohort and crossectional studies (figure 3.2) nine out of fourteen questions were answered as 'yes' (question numbers 1, 2, 3, 4, 8, 9, 11, 12, 14) except for 4 questions (question numbers 5, 6, 10, 13) and for question number 7 a comparable response received for 'yes' and 'no'. Overall indicating a good quality of appraisal from all the studies. All of the participants who entered the study were accounted for at the conclusion in 26/26(100%). In comparison, the studies reported dropouts not accounted for at the conclusion. The timeframe for assessing the exact benefit from the treatment was not adequate in 13/26(50%)of studies. Independent variables were clearly mentioned for all the studies as 26/26 (100%). The outcomes of the study clearly specified for all the of the studies as 26/26 (100%)

In controlled intervention studies (figure 3.3), eight out of fourteen questions were answered as ‘yes’ (question numbers 5, 6, 7, 8, 9, 10, 11, 14). 2/4 (50%)indicating a good quality of appraisals. In all the studies, the research questions were clearly addressed, and all the participants included in the intervention group were treated equally, and the treatment effects were reported comprehensively.The participants were randomized in 2/4 (50%) studies. 3/4 studies (75%) reported blinding the participants and/or the investigator, while blinding was not clearly stated in the remaining 1/4 (25%) study. All participants who entered the study were accounted for at the conclusion in 4/4(100%). There were no dropouts of participants who encountered in the study (0/4).

In case control studies (figure 3.4), twelve questions were focused, and nine of them were answered as ‘yes’, (question numbers 1,2,5,6,7,8,10,11,12)indicating a good quality of the appraisal. The study objective and target population were clearly stated for all the studies 2/2(100%). The independent variables are clearly mentioned in the studies 2/2 (100%). All participants who entered the study were accounted for at the conclusion in 4/4(100%). There were no dropouts of participants who encountered in the study (0/4).The outcomes were clearly stated for all the studies 2/2 (100%).

CHAPTER 4

DISCUSSION

The purpose of this review was to assess the clinical effectiveness of pre-processing strategies on speech perception in cochlear implanted recipients. Literature on various recent advances in cochlear implant technology on noise reduction strategies and speech perception performance have been reviewed for the past 19 years. Different pre-processing strategies such as Smartsound iQ, ClearVoice, VoiceTrack, and various directionality settings were discussed and analyzed on their device descriptions and performance in quiet and noisy environments.

The research findings from different cochlear implant systems show that Cochlear Limited and Advanced Bionics havethe maximum number of studies. Literature gives significantly less information regarding the input processing strategies used in Med-EL and Digisonic devices. Speech recognition performance-based studies were reviewed for both adults and children. The number of studies carried out on the pediatric population is lesser when compared to adults. There are variations in performance observed among the available input processing strategies. Studies on various parameters of speech perceptions in terms of words, sentences, and continuous discourse in quiet and noisy environments were analyzed. It is found that a significant improvement in most of the speech perception outcome measures for all the participants regardless of subject age and type of cochlear implant device used.

Most of the studies found a relationship between the type of pre-processing strategies used and the quality of improvement in speech perception. Despite that, a definite conclusion regarding the usefulness of strategies cannot be drawn as a direct comparison is not possible due to variability's in the studies. These variables include age of subjects, age of implantation, type of device, language use, and implant experience. However, an attempt has been made to compare different studies using various strategies.

4.1 Pre-processing Strategies on Cochlear Corporation

Several approaches to signal management have been implemented in Cochlear Ltd devices, ranging from speech coding strategies development to new microphone features that represent the expressive improvement to CI recipients' outcomes. Recipients of cochlear implants (CI) show remarkable speech recognition performance in quiet and noisy listening environments.A major factor of these improvements was attributed to more appropriate coding strategies and new sound processor technology(Dillier & Lai, 2015).

In the pediatric population, it is necessary to enhance the speech perception skills in noise over the adult participants. Availability of the most comfortable and sound enriched environment during the developmental period can help to improve furtherlistening skills, language, and cognitive development. Therefore, incorporating appropriate noise reduction strategies can help to provide better listening in noisy and reverberant environments.

Different pre-processing strategies for noise reduction outcomes seem to affect speech perception significantly and are investigated in many studies. Wolfe et al. (2011) assessed speech perception ability in children using Cochlear Nucleus Freedom or Nucleus 5 device. Speech perception was measured in quiet with PBK-50 monosyllabic words and in noise with BKB-SIN sentences. When combining ASC and ADRO, there is an improvement in both quiet and noise settings. Similar studies were done by Rakszawski et al. (2016) and Gifford et al. (2011) in Nucleus Freedom or CP810 processors, indicating that ASC+ADRO pre-processing strategy provides significant benefits in the pediatric population. The ASC+ADRO significantly enhances speech recognition in challenging situations without degrading performance in any situations. Therefore, in the pediatric population, combining the ASC and ADRO provides equivalent speech recognition in quiet conditions and enhanced speech recognition in noisy environments.

Studies also describe the discomfort while listening to signal using ADRO in combination with ASC in both quiet and noisy environments (di Berardino et al., 2021). The major complaints associated with the ASC+ADRO algorithm were a loudness lowering of speech and fluctuations in voice perception. Therefore, which resulted ina significant reduction in speech perception scores in a noisy environment. On the contrary, for all the participants, there is a substantial improvement in SNR using ADRO alone in noisy settings and reverberant conditions.

The speech recognition benefits obtained with ADRO werenot directly related to the onset of hearing loss, duration of deafness, cochlear implant experience, number of channels available, and dynamic range (Dawson et al., 2004).Several studies have demonstrated an advantage in the use of ADRO alone.Berardino et al. (2021) compared the performance in speech perception with ADRO and ASC+ADRO in both adults and children who fitted with Nucleus Freedom or with a Nucleus 5 (CI512) device. Among this study, ADRO alone showed 83.34% better performance than with ADRO + ASC condition. The use of ADRO alone indicates an improvement in word recognition performance also. Similar findings were obtained by Dawson et al. (2004) in quiet and noise conditions with Nucleus cochlear implants using ADRO. A better response was obtained in the sentence perception test in quiet at a low input level of 50 dB SPL and 65 dB SPL in the presence of 8-talker babble. ADRO improves loudness comfort further and provides greater access to sound either via higher sensitivities or increased input range in unilateral, bilateral, or bimodal implant recipients (James et al., 2002; Iwaki et al., 2008). The improvement with ADRO processing can be due to modification in multiple channels and providing maximum comfort in each channel. Most of the studies indicated that ADRO provides enhanced listening tolow and medium input levels and a high level of loudness comfort and improved sound quality for high input levels.

Ali et al. (2014) pointed that, in some degraded listening environments, the use of the ADRO alone algorithm may not improve the quality of the signal for better speech perception, especially in challenging listening situations. However, research evidence are concluded that ADRO can be more beneficial when combined with other advanced pre-processing strategies or directionality settings such as ASC, BEAM, and ZOOM.

The BEAM and ZOOM strategies provide additional speech understanding, better localization, and improved functional performance. Only a few studies were done on BEAM and ZOOM strategies in the pediatric population. There is no significant difference between the ZOOM and BEAM settings were combined with the ADRO algorithm.

Substantially similar SRT scores were obtained for ZOOM and BEAM strategies. The mean SRT level of BEAM and ZOOM settings may depend on the listening environment. The ZOOM algorithm provides better results for the conditions, such as when the noise is coming from a fixed direction, whereas the BEAM works well in conditions such as when the noise source is moving. However, there is an improvement in speech perception performance in both pediatric and adult populations using ADRO+BEAM in Nucleus freedom implant, and with the use of ADRO+ZOOM and ADRO+BEAM algorithm in CP810 cochlear implant (Razza et al., 2013). It has also been reported that there was no significant difference in speech identification scores between ADRO+ZOOM and ADRO+BEAM in the CP810 processor.

Yathiraj and Rao (2013) reported on seventeen children using CP810, Freedom, and SPrint processors and assessed for the speech identification ability in quiet with ‘Everyday’ default setting and in noise at different Signal to Noise Ratio (+5 dB and +10 dB SNR) with ADRO, ASC, and BEAM processing. Here it is evident that in the presence of noise, the speech identification scores reduced compared to their performance in quiet. This reduction was noticeable across all three pre-processing strategies (ADRO, ASC, and BEAM) at the two SNRs (+5 dB and +10 dB) that were studied. No significant difference in speech identification scores was seen between the three pre-processing strategies studied.

In adults, along with the ADRO strategy, most studies concerned the directionality features (ZOOM, BEAM, and SCAN settings). The studies found a significant improvement with ADRO or ADRO combined with ASC, ZOOM, and BEAM strategy. Studies indicate that both ZOOM, BEAM and SCAN settings can considerably improve the SNR while listening in spatially separated speech and noise conditions.

Spriet et al. (2007) demonstrated that in the nucleus freedom CI system, the adaptive noise reduction algorithm (BEAM) might significantly increase the speech perception in challenging listening conditions. Several factors can affect the perception of signals with the BEAM processing strategy (Kordus et al., 2015). The most important aspect is the time required to process the beamforming signal to establish the location of the signal and noise. Errors can be made in this decision and the amount of time required to change the directionality settings of the beamformer algorithm. It was found that the beamforming system is expected to work best for side (90°) and back (180°) positions of background noise. This data may not always be statistically significant. The advantage of a beamforming system may be restricted in all conditions where background noise is diffused, such as in reverberant noise settings. Even so, enhancing SNR in background noise is highly correlated with microphone directionality in more realistic listening environments (Sivonen et al., 2020).

Differences in word and sentence recognition in noise with BEAM and ZOOM strategies with and without NR were reportedby Hersbach et al. (2012). The results indicated that the Microphone directionality in the cochlear implant device showed a statistically significant improvement in speech intelligibility in noise from STANDARD (Everyday program) to ZOOM (Noise program) and BEAM (Focus program) in all noise types. When averaged across all noise types evaluated in this study, the SRT benefit over the STANDARD setting was 3.7 dB for ZOOM and 5.3 dB for BEAM, demonstrating a strong benefit of directional processing in cochlear implants. A later study by Dillier and Lai (2015) also found that both ZOOM and BEAM pre-processing strategies improve the SNR in spatially separated speech and noise conditions.

When combining the BEAM and ZOOM with ASC and ADRO (Potts & Kolb, 2014), most recipients show significant improvements in speech perception, which is more evident when combining the advanced directional setting (ZOOM or ZOOM) BEAM) with ASC algorithm. When ASC was active in the R-Space environment, there were no noticeable changes between the BEAM and ZOOM settings. However, there was no significant difference between the BEAM+ASC and BEAM-only options. Signification difference was not obtained as it could be due to the additional noise cancellation features added to the BEAM option. In addition, the perception of the ADRO processing resulted in the poorest performances among the available strategies. Therefore in a loud semi diffuse environment, the use of either BEAM + ASC or ZOOM + ASC is recommended for improved speech perception. Also, it should be considered that there can be variations in best processing options across an individual's speech perception skills.

Wolfe et al. (2015) compared the default noise reduction programs in the Nucleus 5system (ASC + ADRO) and Nucleus 6 system (ASC + ADRO, SNR-NR, and SCAN). The findings showed that SNR-NR and the ASC + ADRO algorithm enhanced speech recognition in noisy environments. The findings indicate a significant benefit from the additional noise reduction features available in the upgraded cochlear implant device in terms of signal enhancement and better perception. The advanced pre-processing strategies available in the SmartSound 2 in Nucleus 5 and Nucleus 6 system were assessed by Runge et al. (2016) with three noise reduction programs, Everday (ASC+ADRO+standard directionality), Focus (ASC+ADRO+BEAM), and Noise (ASC+ADRO+ZOOM), each program using different approaches for noise management.

The findings showed that SmartSound2 signal processing features significantly benefit the Focus program when listening in noise settings.

A comparative study was done by Mauger et al. (2012) with three different forms of pre-processing strategies. The baseline program was set to 'Everyday listening, the second program was the same as 'SmartSound Everyday' setting with an addition of noise reduction algorithm (NR), and the third program was 'Everyday' setting with the addition of specifically designed optimized noise reduction algorithm (CI-NR) to react rapid changes in the noise spectrum. The results revealed that the CI optimized noise reduction method showed significant improvements in speech perception and listening quality than the baseline program and the current noise reduction method. An upgraded feature available in Cochlear Ltd called Smart Sound iQ provides a scene classifier technology called SCAN. This accurately classifies the surrounding sound environment into six scenes: quiet, speech, noise, Speech in Noise, Wind, and Music). Therefore, this advanced feature (SCAN) provides enhanced speech understanding in the presence of background noise (Mauger et al., 2014).

Finally, an advanced version of pre-processing strategy available in the Nucleus 7 speech processor is Forward Focus (FF), which is specifically designed to reduce the constant background noise and provide enhanced listening in challenging conditions. Therefore with these advanced technologies available in CI devices, a significant improvement is seen in the quality of speech perception, specifically listening in more degraded noise conditions (Goffi-Gomez et al., 2020).

However, studies comparing speech perception with and without pre-processing strategies reveal that pre-processing strategies significantly enhance speech. However, there is considerable variability among individuals for each of the algorithms. The choice of the most appropriate algorithm would have to be based on an individual's personal preference. Generally, the individual's performance using pre-processing strategies improves sound quality, localization, and speech perception in real-life settings.

4.2 Pre-processing strategies on Advanced Bionics

The ClearVoice algorithm available in Advanced Bionics devices recommends three levels of attenuation settings: low, medium, and high with a range of attenuation up to 6 dB, upto12 dB, and upto18 dB, respectively (Kam et al., 2012). The choice of selection can be customized based on the implant user's individual preferences and listening requirements.

Buechner et al. (2010) compared two versions of a ClearVoice strategy: a moderate (-12 dB) and a strong setting (-18 dB) with a standard clinical setting (HiRes 120 program) in adults using Advanced Bionics device with Harmony processor. Since ClearVoice has advanced noise reduction technology, a significant improvement in speech understanding was seen with ClearVoice conditions compared to the standard program.

Holden et al. (2013) investigated the noise reduction ability with HiRes 120 program in three ClearVoice settings (Low, Medium, High) and multiple listening settings. The sentences were presented in speech-spectrum noise, restaurant noise setting (R-Space), four and eight-talker babble, and connected discourse delivered in 12-talker babble.Participants also completed a questionnaire comparing different ClearVoice programs. The data indicated an advantage of ClearVoice High and Medium settings over the other noise reduction algorithms. Kam et al. (2012) did a similar study on Cantonese-speaking Harmony Cochlear implant users. Speech perception in noise and impacts of ClearVoice strategy on everyday listening conditions were assessed. The result indicates an improved speech recognition score for the ClearVoice medium setting compared to the standard program. However, there was no significant difference between the speech perception scores of the ClearVoice medium and ClearVoice high program. Therefore, the findings indicate ClearVoice medium setting with 12 dB gain reduction in the channels is sufficient for a better understanding of speech in noise than the ClearVoice high gain setting with 18 dB noise reduction. Even with CII/HiRes 90K cochlear implant, adults with six months of experience (Koch et al., 2014) showed improved speech perception in multi-talker babble and speech spectrum noise conditions. The ClearVoice was the preferred noise reduction strategy in real-life situations without compromising the listening in quiet conditions.

Schramm et al. (2011) tried to investigate the performance of ClearVoice in the pediatric population. The ClearVoice strategy was compared with the HiRes 120 program in twenty-four school-age children. When the ClearVoice strategy was activated, there was a mean improvement of sentence scores observed in a noisy setting compared to the HiRes 120 program. Therefore, most of the children showed a significant benefit from ClearVoice in their daily listening environments.

Noël-Petroff et al. (2013) studied the effectiveness of ClearVoice medium and ClearVoice high programs in the pediatric population. In addition to the speech in noise test, the participants, parents, and teachers were evaluated with a questionnaire related to the hearing performance in daily life in various noisy situations. Subject preference to the appropriate noise reduction strategy was also considered at the end of the session. The findings indicate that there is no impact of ClearVoice performance in a quiet setting. There is a significant improvement in speech understanding in a noisy setting compared to the baseline program, especially with the ClearVoice high setting. Also, Positive outcomes towards the ClearVoice were obtained from the questionnaires and discussions with parents and children.

However, Noël-Petroff et al. (2013) and Schramm et al. (2011) showed that in the pediatric population, the ClearVoice strategy provided a significant benefit in daily listening situations. There was a clear trend towards improved speech understanding in noise with ClearVoice, without affecting performance in quiet; therefore, ClearVoice can be used by children all day, without changing programs.

Besides speech enhancement in a noisy background, another important factor of noise reduction algorithms in improving aspects of listening comfort, such as noise tolerance and ease of listening. Dingemanse and Goedegebure (2015) evaluated the effect of the ClearVoice algorithm on noise tolerance on twenty adult users of Advanced Bionics. Acceptable noise level (ANL) test, speech in noise performance at three levels (SRT at 50%, 70%, and speech to noise ratio of SRT50% + 11 dB), and speech intelligibility in quiet were done. The findings indicate that the use of ClearVoice improves listening comfort in noise. Consequently, there can be enhanced noise tolerance ability at a higher noise level when listening to speech in background noise.

The effect of directional microphone technology also plays an important role in speech recognition in noise. The directional microphone activates immediately in optimal listening conditions and improves speech recognition performance by increasing the SNR between speech from the frontal direction and the surrounding noise. Sivonen et al. (2020) studied the acute effect of different microphone directionalities on SRT in noise with the noise emanating at 90° in the horizontal plane from the side of the CI sound processor (S0NCI). The results showed that microphone directionality significantly improves the speech perception outcomes in background noise and enhances the SNR level in more realistic listening environments.

Hence, preliminary research evidence indicates improved speech perception skills and comfortable listening with appropriate noise reduction algorithms in adults and children. A significant improvement with the ClearVoice algorithm over HiRes 120 while listening in noisy environments was observed, and it was significant with ClearVoice high setting and or with ClearVoice moderate setting.

4.3 Pre-processing strategies on Med-EL

The directionality features in the cochlear implant device have an important role in comfort listening and enhancing speech perception in challenging listening situations. When the directionality feature is added, the microphone is sensitive to the angle of an incoming signal and enhances the competency of the target signal. The beamforming feature can also enhance sound awareness and localization skills in difficult listening situations. The Med-EL SONNET has three directionality settings: Omni directionality, fixed directionality, and adaptive directionality. Perception of speech varied depending on the location of sound source and type of beamformer used.

Honeder et al. (2018) evaluated the effect of microphone directionality features on speech perception in noisy environments in eighteen adults' with Med-EL SONNET Audio processors. Speech Reception thresholds were measured using Oldenburg Sentence Test in continuous, speech-shaped noise with omnidirectional, adaptive beamformer, and fixed beamformer settings. The stimuli were presented from the front of the listener, and the noise sources were placed at -135°and 135°, respectively. The finding shows a significantly improved performance with the adaptive beamformer algorithm compared to the fixed beamformer and omnidirectional setting. The adaptive beamforming algorithm enhances the level of SRT regardless of the etiology of hearing impairment or CI experience. However, the use of an Adaptive beamforming algorithm provides an enormous improvement in listening skills. Because of the appropriate design, the system constantly detects the direction of the noise and adapts the polar pattern to attenuate the unwanted signal. Also, when comparing the performance of fixed beamformers with the omnidirectional setting, performance was superior for fixed beamformer algorithms in a speech in noisy environments.

These findings were also supported by the literature of Büchner et al. (2019), the fixed and adaptive directionality algorithm were compared with the omnidirectional mode. Significant improvements in mean SRT scores were observed with the use of fixed directionality and adaptive directionality settings. Thus, incorporating adaptive or fixed directionality settings in the cochlear implant provides less listening effort and enhances the comfort in listening.

It is important to highlight that the adaptive beamformer provides a significant enhancement in speech than the fixed beamformer setting. The fixed beamformer might not be able to provide focused listening in multiple listening conditions.

4.4 Pre-processing strategies on Digisonic

The cochlear implant device incorporated with the VoiceTrack algorithm initially detects the noise, and the unwanted signals are suppressed by using a frequency subtraction method in each band. The remaining signal can be fine-tuned according to the present ruler available in the fitting interface. Different noise suppressions are recommended, such as soft, medium, and strong levels; accordingly, the channel suppression levels are applied as 20%, 50%, and 70% of signal energy in this band. However, the undesired signals are attenuated and providing a comfortable and natural perception of the required signal (Bergeron & Hotton, 2016)

There are only limited studies explaining the perceptual benefit of pre-processing strategy in Digisonic Cochlear Implant. The available studies were explored which are related to speech perception in the adult population. Guevara et al. (2016) assessed the efficiency of VoiceTrack in a group of thirteen experienced CI users. Outcome measurement was done immediately after the noise reduction algorithms wereenabled and after one month of cochlear implant usage. The results indicate that, with the VoiceTrack system, there is improved quality in listening compared to unprocessed sounds. This effect is particular in two difficult listening conditions: speech in a noise setting and speech intelligibility over the phone.

Bergeron and Hotton (2016) assessed the speech perception efficiency in Oticon Medical Device with a Saphyr processor. The potential ability of the VoiceTrack algorithm was measured with a French-Canadian version of the Hearing in Noise Test (HINT) at a fixed level of 63dBA in quiet and in noise at +10, +5, and 0 dB signal to noise ratio. A significant improvement for speech perception in noise in all the 3 SNR levels and the subjective feedback also shows that the VoiceTrack algorithm adding a significant improvement for speech perception in more challenging conditions. Thus, it is necessary to incorporate appropriate signal processing strategies in the cochlear implant device to comfort listening and support speech recognition in acoustically degraded environments.

CHAPTER 5

SUMMARY AND CONCLUSION

The present study investigated various noise reduction algorithms in major cochlear implants (Cochlear Ltd, Advanced Bionics, Med-EL, and Digisonic). The study also compared the speech perception benefits across pre-processing strategies. Several performance variations across pre-processing strategies SmartSound, ClearVoice, VoiceTrack, BEAM, and ZOOM. Literature in various parameters of speech perception in quiet and different degraded environments were summarized. Information regarding the localization aspects and listening quality were also reported whenever available.From the findings of the study, recommendations can be made regarding the type of pre-processing strategy that should be used in typical listening situations

The present study revealed that,

- Implementing noise reduction algorithms in cochlear implant devices is an effective strategy to restore better hearing in the pediatric and adult population. The conferring benefits in terms of sound quality, localization, and speech perception in both quiet and noisy environments and, therefore, an improvement in quality of life can be observed.
- The implementation of pre-processing strategy in a cochlear implant does not degrade the performance in quiet conditions. Rather supports the speech recognition in noisy environments

- The pre-processing strategies also help to maintain appropriate SNR levels in degraded listening environments.

The most beneficial strategy can vary according to the listening environment, study population, sample size, population age type of CI device, and CI experience.However, there is considerable variability among individuals for each of the strategies. The choice of the most appropriate strategy would have to be decided on an individual's personal preference.

5.1 Clinical implications

- Based on the findings from the review, it can be inferred that an appropriate pre-processing strategy needs to be provided based on the listening preference, personal choice, and age of the recipient.
- This review provides information regarding the similarities and dissimilarities in the performance of adults and children using various cochlear implants and pre-processing strategies
- The information from this review can be used for selecting an appropriate cochlear implant device or pre-processing strategy for an individual. Also, the information can be used for counseling the implantee regarding the choice made.
- This review can update the clinical audiologist with recent advances in cochlear implant technology in terms of noise reduction strategies.

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APPENDIX A

QUALITY ASSESSMENT TOOL FOR OBSERVATIONAL COHORT AND CROSS-SECTIONAL STUDIES

SL NO	Studies	Q no 1	Q no 2	Q no 3	Q no 4	Q no 5	Q no 6	Q no 7	Q no 8	Q no 9	Q no 10	Q no 11	Q no 12	Q no 13	Q no 14
1	Wolfe et al. (2011)	YES	YES	YES	YES	NR	YES	NO	NA	YES	NO	YES	YES	NO	YES
2	Goffi-Gomez et al., (2020)	YES	YES	YES	YES	NR	YES	NO	YES	YES	NO	YES	YES	NA	YES
3	Guevara et al. (2016)	YES	YES	YES	YES	NR	YES	YES	NO	YES	NO	YES	YES	NO	YES
4	Bergeron &Hotton, (2016)	YES	NO	YES	YES	NO	NO	YES	NO	YES	NO	YES	YES	NO	YES
5	Yathiraj & Rao, (2013)	YES	YES	YES	CD	NR	NO	NO	YES	YES	NO	YES	YES	NA	YES
6	Spriet et al.,(2007)	YES	YES	YES	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES
7	Hersbach et al. (2012)	YES	YES	YES	YES	NO	YES	YES	NO	YES	NO	YES	YES	NO	YES
8	Ali et al.,(2014)	YES	YES	YES	YES	NR	NO	NO	NO	YES	NO	YES	YES	NA	YES

9	Wolfe et al., (2015)	YES	YES	YES	NO	NO	NO	NO	NO	YES	NO	YES	YES	NA	YES
10	Kordus et al.,(2015)	YES	YES	YES	YES	NO	NO	YES	NO	YES	NO	YES	YES	NO	YES
11	Di Berardino et al., (2021)	YES	YES	YES	NO	NO	YES	NO	NO	YES	NO	YES	YES	NA	YES
12	Honeder et al.,(2018)	YES	YES	YES	YES	YES	YES	YES	NO	YES	NO	YES	YES	NO	YES
13	Mauger et al., (2014)	YES	YES	YES	YES	NO	NO	NO	YES	YES	NO	YES	YES	NO	YES
14	Kam et al., (2012)	YES	YES	YES	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES
15	Holden et al. (2013)	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	NO	YES
16	Rakszawski et al. (2016)	YES	YES	YES	YES	NO	NO	NO	YES	YES	NO	YES	YES	NO	YES
17	Dawson et al. (2004)	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	NO	YES
18	Runge et al. (2016)	YES	YES	YES	YES	YES	NO	YES	YES	YES	NO	YES	YES	NO	YES
19	Razza et al.	YE	YE	YE	N	N	N	N	YE	YE	N	YE	YE	N	YE

	(2013)	S	S	S	O	O	O	O	S	S	O	S	S	O	S
20	Dillier and Laiv (2015)	YES	YES	YES	YES	NO	NO	YES	YES	YES	NO	YES	YES	NO	YES
21	James et al. (2002)	YES	YES	YES	YES	NO	YES	CD	YES	YES	NO	YES	YES	NO	YES
22	Mauger et al. (2012)	YES	NO	YES	NO	NO	NO	NO	YES	YES	YES	YES	YES	NO	YES
23	Iwaki et al. (2008)	YES	YES	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	NO	YES
24	Sivonen et al. (2020)	YES	YES	YES	YES	NO	NO	NO	YES	YES	NO	YES	YES	NO	YES
25	Noël-Petroff et al. (2013)	YES	YES	YES	YES	NO	NO	YES	YES	YES	YES	YES	YES	NO	YES
26	Buechner et al. (2010)	YES	YES	YES	YES	NO	NO	NO	YES	YES	YES	YES	YES	NO	YES

CD, cannot determine; NA, not applicable; NR, not reported

*(Questions: 1. Was the research question or objective in this paper clearly stated?, 2. Was the study population clearly specified and defined?, 3. Was the participation rate of eligible persons at least 50%?, 4. Were all the subjects selected or recruited from the same or similar populations (including the same time period)? Were inclusion and exclusion criteria for being in the study prespecified and applied uniformly to all participants?, 5. Was a sample size justification, power description, or variance and effect estimates provided?, 6. For the analyses in this paper, were the exposure(s) of interest measured prior to the outcome(s) being measured?, 7. Was the timeframe sufficient so that one could reasonably expect to see an association between exposure and outcome if it existed?, 8. For exposures that can vary in amount or level, did the study examine different levels of the exposure as related to the outcome (e.g., categories of exposure, or

exposure measured as continuous variable)?, 9. Were the exposure measures (independent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?, 10. Was the exposure(s) assessed more than once over time?, 11. Were the outcome measures (dependent variables) clearly defined, valid, reliable, and implemented consistently across all study participants?, 12. Were the outcome assessors blinded to the exposure status of participants?, 13. Was loss to follow-up after baseline 20% or less?, 14. Were key potential confounding variables measured and adjusted statistically for their impact on the relationship between exposure(s) and outcome(s)?)

QUALITY ASSESSMENT OF CONTROLLED INTERVENTION STUDIES

SL. NO	Studies	Q no .1	Q no .2	Q no .3	Q no .4	Q no .5	Q no .6	Q no .7	Q .8	Q no .9	Q no. 10	Q no. 11	Q no. 12	Q no. 13	Q no. 14
1	Dingemanse&Goedegebure, 2015	YES	YES	CD	YES	CD	YES	YES	YES	YES	YES	YES	NO	CD	YES
2	Koch et al., 2014	YES	YES	NO	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	YES
3	Potts and Kolb (2014)	NO	NA	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
4	Wolfe et al. (2012)	NO	NA	NO	NO	YES	YES	YES	YES	YES	YES	YES	YES	NO	YES
CD, cannot determine; NA, not applicable; NR, not reported															

*(Questions: 1. Was the study described as randomized, a randomized trial, a randomized clinical trial, or an RCT?, 2. Was the method of randomization adequate (i.e., use of randomly generated assignment)?, 3. Was the treatment allocation concealed (so that assignments could not be predicted)?, 4. Were study participants and providers blinded to treatment group assignment?, 5. Were the people assessing the outcomes blinded to the participants' group assignments?, 6. Were the groups similar at baseline on important characteristics that could affect outcomes (e.g., demographics, risk factors, co-morbid conditions)?, 7. Was the overall drop-out rate from the study at endpoint 20% or lower of the number allocated to treatment?, 8. Was the differential drop-out rate (between treatment groups) at endpoint 15 percentage points or lower?, 9. Was there high adherence to the intervention protocols for each treatment group?, 10. Were other interventions avoided or similar in the groups (e.g., similar background treatments)?, 11. Were outcomes assessed using valid and reliable measures, implemented consistently across all study participants?, 12. Did the authors report that the sample size was sufficiently large to be able to detect a difference in the main outcome between groups with at least 80% power?, 13. Were outcomes reported or subgroups analyzed prespecified (i.e., identified before analyses were conducted)?, 14. Were all randomized participants analyzed in the group to which they were originally assigned, i.e., did they use an intention-to-treat analysis?)

QUALITY ASSESSMENT OF CASE-CONTROL STUDIES

SL NO	Studies	Q no.1	Q no.2	Q no.3	Q no.4	Q no.5	Q no.6	Q no.7	Q no.8	Q no.9	Q no.10	Q no.11	Q no.12
1	Gifford et al. (2011)	YES	YES	NO	NO	YES	YES	YES	YES	NO	YES	YES	YES
2	Büchner et al. (2019)	YES	YES	NO	NO	YES	YES	YES	YES	NO	YES	YES	YES
CD, cannot determine; NA, not applicable; NR, not reported													

***(**Questions: 1. Was the research question or objective in this paper clearly stated and appropriate?, 2. Was the study population clearly specified and defined?, 3. Did the authors include a sample size justification?, 4. Were controls selected or recruited from the same or similar population that gave rise to the cases (including the same timeframe)?, 5. Were the definitions, inclusion and exclusion criteria, algorithms or processes used to identify or select cases and controls valid, reliable, and implemented consistently across all study participants?, 6. Were the cases clearly defined and differentiated from controls?, 7. If less than 100 percent of eligible cases and/or controls were selected for the study, were the cases and/or controls randomly selected from those eligible?, 8. Was there use of concurrent controls?, 9. Were the investigators able to confirm that the exposure/risk occurred prior to the development of the condition or event that defined a participant as a case?, 10. Were the measures of exposure/risk clearly defined, valid, reliable, and implemented consistently (including the same time period) across all study participants?, 11. Were the assessors of exposure/risk blinded to the case or control status of participants?, 12. Were key potential confounding variables measured and adjusted statistically in the analyses? If matching was used, did the investigators account for matching during study analysis?).