An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid

Submitted in total fulfilment of the requirements of the degree of Master of Audiology (by research)

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ABSTRACT

Speech perception outcomes obtainable with cochlear implants have improved over time, so cochlear implantation is now routinely offered to adults with residual hearing who gain benefit from using a hearing aid in their contralateral ear. To maximize the overall sound perception abilities for these patients, we need to consider optimizing the fittings of both the cochlear implant and the hearing aid. One means of optimizing a person's speech perception is to allow them to trial sound processing schemes and evaluate their effects on speech recognition. Adaptive Dynamic Range Optimization (ADRO) is one such scheme that is available in Cochlear Limited's speech processors and has been shown to offer speech perception benefits for adult and paediatric cochlear implant recipients. More recently, ADRO has been implemented in hearing aids and shown to offer some speech perception benefits over other hearing aid amplification algorithms.

The aim of this study is to evaluate the ADRO sound processing scheme when implemented in both a cochlear implant speech processor and a hearing aid in a group of adults who would normally wear both (bimodal) devices. Following a period of take-home experience with all device combinations, speech perception measures using words presented at 50dB SPL and 60dB SPL and sentences presented with competing noise were evaluated for the participants using their devices with and without ADRO activated, and the results compared. Participant preferences for the bimodal device combinations were also obtained using a take-home questionnaire.

The results from this study show that adults can obtain significant improvement in speech perception when listening in quiet environments when ADRO is activated in both their hearing aid and cochlear implant. The greatest benefit is seen when listening to softer levels of speech. There is no detrimental effect on speech perception when using ADRO in the bimodal device condition in noisy environments. Whist statistically significant differences in speech perception scores were observed between the bimodal-ADRO and no-ADRO device combinations, the differences were not large. This is reflected in the participants indicating no overall preference for either device combination.
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The outcomes of this study suggest that adults who routinely use a cochlear implant in one ear and a hearing aid in the other could benefit from having ADRO implemented in both devices.
DECLARATION

This is to certify that:

(i) the thesis comprises only my original work towards the Master of Audiology (by research),
(ii) due acknowledgement has been made in the text to all other material used,
(iii) the thesis is less than 32,000 words in length, inclusive of footnotes, but exclusive of tables, maps, bibliographies and appendices.

Signature:

Date:
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1. INTRODUCTION

A large proportion of the population experience significant hearing loss and the resultant difficulties this presents in communicating with other people. Technologies such as hearing aids and cochlear implants now exist to help enhance hearing and in turn communication, but these technologies have their limitations and are still not able to restore levels of sound awareness and ease of communication that can be achieved with normally functioning ears and hearing. Even with the help of hearing aids and/or cochlear implants, hearing impaired people struggle to follow conversations more than people with normal hearing when in difficult listening situations; such as when interfering background noises are present, or listening to someone from a distance or over a telephone, when voices are soft. Developers of both hearing aid and cochlear implant technologies are, in turn, presented with the challenge of finding ways to maximize the usefulness of the sounds they deliver to the hearing impaired listener in these situations.

1.1. Difficulties experienced by hearing impaired people

A recent investigation into the incidence of hearing loss in the Australian population (Access Economics 2006) revealed that one in six Australians were affected significantly by some degree of hearing loss. Furthermore, 10% of people aged between 15 and 60 years were diagnosed with a hearing loss, along with 56% of people aged 60 years or older. This means that a significant number of teenagers and adults experience difficulties listening and communicating in educational, work, social and family environments. For older people, their hearing loss may limit their opportunities to experience a fulfilling retirement and, importantly, limit their ability to live independently.

The investigation also found that of the group diagnosed with a hearing loss, 66% had a mild loss, 23% had a moderate loss and 11% had a severe loss of hearing or worse. Even with a minimal degree of hearing loss in the mild region, it can become difficult for a person to perceive many sounds in their environment and communicate effectively with other people. The challenges faced by a hearing impaired person can be related to a number of specific causes: a reduction in the audibility of sounds; a
narrowing of the range of hearing from where sounds are just audible to where they become too loud (the dynamic range of hearing); a reduction in the resolution of frequency and/or temporal cues; or a combination of any or all of these aspects of impaired hearing (Dillon 2001).

1.1.1. Reduced audibility

The normal range of acoustic frequencies for which hearing thresholds are measured corresponds to the frequency spectrum of speech sounds (approximately 125Hz to 8,000Hz). It is also relevant to note that for average human speakers, the softest components of the speech spectrum occur at around 45dB SPL for the lower frequencies, dropping down to about 25dB SPL for the higher frequencies, as illustrated by the Long Term Speech Spectrum (LTSS) in Figure 1 below (Byrne, Dillon et al. 1994).

![Figure 1. An example of an audiogram showing the Long Term Speech Spectrum (LTSS).](image)

For a person to be able to hear all speech components, they would require hearing thresholds that were better than 25dBHL; this would be classified as normal hearing. By definition, a mild hearing loss is diagnosed when a person is unable to hear some of the speech frequencies at levels of 20 to 40dBHL (Margolis and Saly 2007) (see Figure 2 below). In practical terms, this means that some of the softer high frequency components of speech (mostly consonants) would not be heard, even when the speaker is within close proximity to the listener.
As the distance between the hearing impaired listener and the speaker increases, the level of sound reaching the listener decreases and so the range of speech components audible to the person would also decrease. As the number of audible speech components decreases, so too will a person’s ability to recognize and understand what is being said. Similarly, if there is background noise in the listening environment that has amplitude and frequency components overlapping with the speech spectrum, the background noise has the potential to interfere with, or mask, the remaining speech components. In addition to affecting a person’s ability to hear speech sounds (or phonemes), a hearing loss would also mean some environmental sounds would be inaudible. In the case of a mild hearing loss, these might include sounds like a car approaching from a distance, birds singing or the turn indicators on a car.

For someone with a moderate hearing loss, the challenges relating to understanding speech and detecting environmental sounds are even greater than for someone with a mild hearing loss. A moderate hearing loss is diagnosed when a person is unable to hear some of the speech frequencies until the sounds get to levels of 45 to 60dBHL (Margolis and Saly 2007). With this degree of hearing loss, most of the speech spectrum and many environmental sounds would be inaudible without the use of an acoustic amplification device such as a hearing aid. Without amplification, speech recognition would be difficult, even in ideal listening environments and sounds like a door bell, telephone ring and footsteps may go unnoticed, however, with amplification, most of these sounds would be audible.
When the degree of hearing loss is even greater again (with hearing levels at 65dBHL or worse), as is the case for people who have a severe through to profound hearing loss, many sounds remain inaudible even with the use of acoustic amplification devices. Following a conversation in a small group of people or when in a noisy environment such as a restaurant would usually be very difficult, as would holding a fluent conversation over the phone. People with a severe or greater hearing loss often rely on combining whatever limited acoustic information they may detect with visual information to maximize their speech recognition and comprehension. ‘Speech reading’ (Woodhouse, Hickson et al. 2009) incorporates visual cues such as lip and mouth movements along with acoustic cues such as voicing and segmental information to maximize phoneme recognition. In addition, facial expressions and body language combine with prosodic cues to give clues to the speaker’s intent in what they are saying. So, even being able to hear minimal acoustic cues is an advantage to a hearing impaired person’s speech reading ability.

1.1.2. Reduced dynamic range

A reduction in audibility also impacts on the range of sounds that a person perceives as comfortably loud. People with normal hearing usually have a dynamic range of about 100dB; that is, sounds of about 10dB would be perceived as being very soft, sounds in the 50dB to 70dB range would be comfortable, while sounds with an intensity of about 110dB would be uncomfortably loud (Sherlock and Formby 2005). The point at which a sound becomes uncomfortably loud is often referred to as the Loudness Discomfort Level (LDL). For a person with a sensorineural hearing loss, their LDLs are unlikely to increase even as their hearing thresholds increase, meaning that the range between what is just audible and what is too loud reduces as the degree of hearing loss worsens (Kamm, Dirks et al. 1978). This squashing of the dynamic range, in effect, can distort the loudness or amplitude information that the person hears. For some people who have a severe or profound hearing loss, LDLs can even occur at lower than normal sound pressure levels, so that for some frequencies their dynamic range may only be a few decibels (Pascoe 1988). A reduced tolerance to sound like this makes finding an appropriate level of amplification a challenge; if insufficient gain is provided then frequencies remain inaudible, but if too much gain is used, the person experiences
discomfort. For most people with a sensorineural hearing loss, their need to have a large dynamic range of sounds in their environment reduced to a more narrow range that will be audible and yet comfortable can be achieved fairly successfully with the variety of compression algorithms offered in modern day hearing aids (Boike and Souza 2000; Blamey and Martin 2009).

1.1.3. Decreased frequency resolution

Another difficulty faced by people with a sensorineural hearing loss is the inability to separate or differentiate sounds that are of similar frequencies. This arises because damage to the outer hair cells within the cochlea reduces their tuning properties; as demonstrated by flatter tuning curves in psychophysical studies (Evans 1992; Scheidt, Kale et al. 2010). So instead of two sounds that have similar frequencies causing neural activity in two marginally separated regions within the cochlea (or critical bands), the sounds generate activity in one broad region only. The brain then receives information that there is just one broad frequency range of sound rather than two distinct sounds in the environment. This can have significant impact on speech recognition in noisy environments. If the speech components are characterized by the same or similar frequencies as components of the background noise, then as described above, the brain will be receiving the message that there is only one sound to process and not two. It will not be able to separate the speech from the noise.

If a person’s frequency resolution is very badly affected, understanding speech in quiet environments can be difficult too. Studies that have demonstrated the phenomenon of upward spread of masking have shown that it is possible for the naturally louder, low frequency components (e.g. vowel formants) of a speech phoneme to blend with (or mask out) a slightly higher frequency formant, hence, reducing the available high frequency information for the listener (Danaher and Pickett 1975; Moore 2008).

It is known also that frequency resolution is reduced at higher levels of sound, even for people with normal hearing (Dubno and Schaefer 1991). For people with a severe or profound hearing loss, who rely on high levels of amplification to make sound audible, their difficulty in separating sounds can, therefore, be caused by both the damage to the hair cells in the cochlea as well as the need to listen to high levels of sound.
1.1.4. **Decreased temporal resolution**

Understanding speech in the presence of background noise is influenced by temporal resolution as well as frequency resolution. Although more intense sounds can mask softer sounds that occur just before or after the masker, normal hearing listeners are generally able to pick out weaker acoustic cues from amongst stronger sounds if there are sufficient gaps. For example, a normal hearing listener can usually identify segments of speech within brief gaps and fluctuations that occur in real-time background noise such as speech babble in a restaurant. Unfortunately, hearing impaired people partially lose this ability to gain useful speech cues from amongst background noise (Hygge and Ronnberg 1992). This ability seems to decrease as hearing loss worsens and as age increases (Duquesnoy 1983; Ching, Dillon et al. 1998; Peters, Moore et al. 1998).

1.1.5. **Combined effects of reduced audibility, dynamic range, frequency & temporal resolution**

In isolation, any of the above-mentioned deficits can reduce speech understanding. For a person with a sensorineural hearing loss, it is most likely that they will experience these deficits in combination, and so their ability to understand speech will be considerably less than that of a normally hearing person in the same situation. This can be demonstrated by studies that have shown that hearing impaired people need a greater signal-to-noise (SNR) ratio than normally hearing people in order to achieve the same level of speech understanding (Plomp 1988). The required signal-to-noise ratio has also been shown to increase as the degree of hearing loss increases. For example, people with a mild hearing loss, on average, need 4dB greater SNR than normal hearing people, while those with a severe loss require about 10dB greater SNR than normal (Killion 1988).

No matter what the degree of hearing loss, hearing impaired people report that understanding what another person is saying is made more difficult when the speaker has a soft voice, if they are speaking from some distance away, or if there is a background noise in the environment that is at a level that is competing with the voice of the person speaking.
1.2. Social effects of hearing loss

The effects of having a hearing loss are more far-reaching than just being unable to easily follow a conversation or hear some environmental sounds. When conversing with others becomes difficult and people start to regularly experience embarrassment due to their misunderstandings, their confidence in their ability to communicate successfully suffers and they begin to avoid communication situations. This in turn can make the person withdraw from social contact and feel isolated (Lutman, Brown et al. 1987; Bess, Lichtenstein et al. 1991). Their self esteem and self worth may come into doubt, with the possibility of depression developing (Trychin 1991; Metselaar, Maat et al. 2009).

The inability to hear some environmental sounds, such as cars or people approaching, the door bell or phone ringing, the kettle or a pot on the stove boiling, can leave a person feeling less safe and, therefore, anxious about moving out of their familiar surroundings. This might affect their ability to remain in the workforce and/or their willingness to participate in family or social activities (Hawthorne and Hogan 2002).

So, maximizing a person’s ability to hear speech cues and environmental sounds has many benefits. Being able to recognize and comprehend speech in most, if not all, of a person’s usual listening environments, gives that person the confidence to participate in conversations and a sense of worth that they can successfully contribute to their family and community. Being able to detect and recognize sounds in their environment gives a person a sense of safety and confidence to move more freely and widely beyond their home. For many, it is also a necessity for remaining in the workforce.

Maximizing hearing thresholds and, therefore, sound awareness and speech recognition, can be achieved for most hearing impaired people through the use of technologies such as hearing aids and cochlear implants.

1.3. Hearing device technologies for assisting hearing impaired people

Hearing aids and cochlear implants are devices that aim to restore access to acoustic information for hearing impaired listeners that they would otherwise miss.
1.3.1. Hearing aids

Hearing aids are essentially personal amplification devices that deliver amplified sound directly into the wearer’s ear canal. The premise behind this technology is that if sounds which would normally be inaudible to the hearing impaired person can be amplified sufficiently, those sounds would become audible.

The first known personal amplification devices were acoustical horns and trumpets that were used in the 17th century (Lybarger 1988; Dillon 2001). Amplification of sound was achieved by collecting as much sound as possible in the wide opening of the horn or trumpet and having it pass down a gradually tapering, long tube. The sound pressure coming out the narrow ear piece and entering the ear canal of the listener was greater than that entering the wide opening of the trumpet. An improvement on the horn or trumpet was the speaking tube. The speaking tube made use of a long flexible tube with a wide horn on one end and a narrow ear piece on the other to allow the speaker to talk directly into the device. This increased the intensity of the sound entering the horn as well as improving the speech-to-noise ratio.

The end of the 19th century and the beginning of the 20th century saw the invention of carbon hearing aids. These hearing aids made use of a carbon microphone that was attached to a magnetic receiver and a carbon amplifier and powered by a battery. In these devices, sound pressure caused carbon granules to move, which in turn would alter the resistance of the microphone. These fluctuations in resistance produced fluctuations in electrical current and the magnetic field in the receiver and so synchronized the movement of the receiver’s diaphragm with the input of the microphone. The resultant amplification was in the order of 20–40dB and so enough to assist people with a mild to moderate hearing loss.

The capabilities of amplifiers in hearing aids took a leap forward in the 1920s following the invention of the first vacuum tube amplifier. Vacuum tubes allowed small electrical currents (as would come from a microphone) to control larger currents and, if connected together in an amplifier, could produce considerable levels of amplification. Such amplifiers allowed hearing aids to produce up to about 70dB of gain and, therefore, be of help to people with more severe degrees of hearing loss.
Other advances in electronics at this time also meant that the gain and frequency response could be shaped more effectively than could be achieved with carbon hearing aids. Vacuum tube hearing aids were, however, quite large in size. It wasn’t until 1944 that this technology had advanced to the stage that a one-piece hearing aid could be produced, with the microphone, amplifier and batteries all housed in a body-worn unit that connected to the ear-level receiver via a cable.

The decades that followed saw a significant miniaturization of hearing aid components with the advent of transistors and integrated circuits and the reduction in the size of batteries. By the late 1980s, all of the necessary components of a hearing aid could fit into a package small enough to fit totally within an ear canal. These technologies also allowed for more refined filtering of sound and more complex shaping of the gain and frequency response and user-controls could be fitted to even very small hearing aids. Other acoustical benefits came from having the hearing aid microphone more protected from wind noise and the extra amplification that came from having the pinna deflect sound into the microphone with hearing aids that were placed in the ear canal.

The late 1980s also saw the first application of digital processing circuits and digital memories in hearing aids. Occupying a lot less space than the previously used potentiometers (variable resistors that permitted adjustment to electrical current and in turn, the gain of the signal), these circuits allowed for more options for controlling the acoustic signal, both by the person programming the hearing aid and the user. The use of digital technologies in hearing aids advanced even further in the 1990s when digitization of the acoustic waveform commenced. This meant that the sound waveform could be deconstructed into a set of numbers, manipulated very precisely by acoustic control circuits and then reconstructed in a new form that would better meet the hearing needs of the hearing aid wearer. Practical benefits of having such a high level of control of the output of the hearing aid included: more precise tailoring of the gain and frequency response to the wearer’s hearing thresholds and comfort levels; improved speech recognition in the presence of background noise due to automatic manipulation of the response in different frequency bands based upon an analysis of the incoming sound wave-form and automatic manipulation of gains from
sounds coming from different directions; greater ability to control feedback oscillations and therefore maintain the required gain levels; and the ability to perform complex functions with minimal use of power. These are the advancements that form the basis of our current hearing aid technology.

While virtually all current-day hearing aids utilize digital technology to analyse input sound waveforms and determine the gain and frequency output responses, the fundamental components in the design of hearing aids have remained essentially the same throughout the past two decades (see Figure 3 below).

![Schematic representation of components in a digital hearing aid](image)

**Figure 3. Schematic block diagram of the components in a modern hearing aid.**

As illustrated, microphones (typically of the electret type) are used to convert the sound pressure input into an electrical output. The analog electrical output from the microphone is then passed through an analog-to-digital converter, sampled at an appropriate rate and converted into a digitized code. The code is then passed through a programmable multi-channel filter bank where information about the energy levels in the different frequency bands (or channels) is analysed. Digital signal processing algorithms are then applied and decisions made about the need for amplification or compression in the different channels based upon the wearer’s hearing thresholds and comfort levels. Many modern-day hearing aids also incorporate advanced forms of signal processing for speech enhancement, noise reduction, self-adapting directional microphone inputs and feedback cancellation. Once the signal has been manipulated, it is then passed through a digital-to-analog converter and a transducer and delivered into the ear canal of the wearer by the receiver.

Digital signal processors may vary amongst hearing aid manufacturers but they are generally considered to be either “hard-wired” or “general arithmetic/open platform” or a hybrid of the two. Hearing aids containing hard-wired digital signal processors can
be thought of as containing a series of blocks, where each block is responsible for performing one function only (e.g. filtering, compression). The way sounds are processed is dictated by that series of blocks and only varies to the extent that the parameters of each block can be adjusted. Hearing aids containing general arithmetic processors can be likened to computers in that software can be loaded into the hearing aid’s hardware. If desired, different versions of an arithmetic processor (software) could be loaded into the hearing aid, hence this type of technology is sometimes termed “open platform” digital signal processing.

The need to amplify soft sounds so that they can be audible to the hearing impaired listener is one of the most important requirements of a hearing aid. The amplification schemes commonly used in digital hearing aids are based upon the linear and non-linear schemes that had been developed for analog technologies. Compression amplification schemes are used predominantly; they aim to sufficiently amplify soft sounds as well as avoid loud sounds from being over-amplified (Dillon 2001). Research by Buus and Florentine (1983) has suggested that people with a sensorineural hearing loss have normal loudness growth at higher levels, even though their dynamic range is less than that of people with normal hearing. Compression amplification schemes aim to compensate for this reduction in dynamic range by applying less gain to louder sounds than to softer sounds. This helps limit the output levels of loud sounds to within the hearing impaired person’s comfort range.

There are three main compression strategies for limiting the output dynamic range of a hearing aid (see Figure 4 below). A low level compression strategy applies most of the gain reduction to low level (soft) input sounds, allowing for more linear amplification of the moderate and higher level (loud) inputs. A high level or compression limiting strategy provides linear amplification for low level sounds and then starts reducing the gain for moderate and/or high level sounds. A wide dynamic range compression (WDRC) strategy applies compression gradually over a wide range of input levels, so with this strategy, there are no input levels for which the corresponding output levels need to be highly compressed. The WDRC strategy is commonly used in modern digital hearing aids.
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

Figure 4. Diagrammatic representation of input-output functions for 3 compression strategies: Low level compression, High level compression and wide dynamic range compression (WDRC).

In modern-day multi-channel hearing aids, each channel will typically have its own compressor. This helps normalize sounds across the different channels and, therefore, across the frequency spectrum. Over the last century, hearing aid technology has become more effective and efficient at delivering controlled amplification of sounds to hearing impaired people. Current digital hearing aids can analyse sounds in multiple frequency channels and, for each channel, continually control the amount of gain so that the maximum number of soft speech sounds will be audible while the more intense sounds remain comfortable. In addition to fitting the dynamic range of a person’s acoustic environment into their reduced perceptual hearing range, digital hearing aids are also more capable of enhancing speech recognition in noise environments as well as limiting the occurrence of the feedback ‘whistle’. Feedback has long been an annoying side-effect of hearing aids, which occurs when sound escapes from the ear canal past the ear mould and re-enters the hearing aid to be amplified again and again, ultimately resulting in an unwanted oscillation.

Self-report questionnaires designed to assess the benefits of hearing aid fittings have demonstrated that most people perceive that their hearing aid has helped reduce their level of communication disability and their perception of being handicapped in social, occupational and recreational situations (Cox and Alexander 1995; Dillon, James et al. 1997; Kochkin and Rogin 2000). However, when a person’s hearing loss is more severe, and so their dynamic range of hearing and frequency resolution is greatly reduced, restoring effective hearing through amplification is less successful.
1.3.2. **Cochlear implants**

Cochlear implant devices, like hearing aids, aim to make the maximum amount of sounds audible to the hearing impaired person. The difference is that cochlear implants take the acoustic input from the environment and represent those sounds as series of electrical pulses that are delivered into the cochlea of the recipient. The electrical pulses sent into the cochlea stimulate auditory neurons, which in turn send information in the form of action potentials to the central auditory system. The brain then interprets the messages from the cochlea as sound.

The first recorded event of electrical stimulation of the ear producing hearing was in 1800 at the Royal Society of London, when Count Alessandro Volta recounted an experiment he had performed not long after he invented the first battery (Clark 2003). He described hearing “crackling or bubbling” sounds having inserted metal rods into each ear and connected them to a battery. Volta also experienced “the disagreeable sensation of a jolt in the head” and so no significant attempts to reproduce his experiment took place for many years.

It was then in 1868 that Brenner published his results from investigating the effects of varying electrode placement, rate, intensity and polarity of the electrical current. Like Volta, Brenner also reported producing crackling and whistling noises of varying pitch.

The discovery of the electronic vacuum tube amplifier and its usefulness in hearing aid technology in the 1930s sparked renewed interest in investigating the effects of electrically stimulating the auditory nerve. Studies throughout the 1930s to 1950s investigated the effects of indirect stimulation of the auditory nerve but still led to discoveries such as the rate of stimulation having an effect on pitch (Gersuni and Volokhov 1936) and that different body tissues could act as transducers, passing electrical current into the inner ear, and in turn producing hearing sensations (Flottorp 1953).

It was reported in 1950 that direct stimulation of the auditory nerve was attempted in a neurosurgery operation by Lundberg that resulted in the patient hearing a noise. Then in 1957 Eyries used a telecoil to stimulate the auditory nerve of a hearing
impaired patient for whom he was performing a facial nerve graft. It was reported that intensity discrimination was possible and that some crude pitch differences could be detected for different pulse rates (cited by Simmons, 1966). Studies throughout the 1960s experimented with different designs of single electrode stimulators and animal studies sought to further explore if insertion of an electrode and electrical stimulation of the inner ear was possible without damaging the nerve fibres (Simmons 1967). Investigations also demonstrated how electrical pulse rates could influence pitch and possibly convey speech cues (Clark 1969). A number of these studies indicated that the reliance of varying electrical pulse rates on a single channel electrode would be insufficient to effectively code frequency information as would be needed for recognition of speech (Clark 1973a; Clark 1973b). The quest then began to develop a multi-channel electrode array that: 1. could localize the electrical stimulation to separate groups of nerve fibres, 2. could be positioned within the cochlea such that it would lie close to the nerve fibres that would be appropriate for the place coding of speech frequencies, 3. would produce safe electrical charge densities for long-term neural stimulation and 4. could be safely inserted into the cochlea without damaging the inner ear or neural structures. Researchers also faced the challenge of developing a safe and effective receiver-stimulator that would need to be attached to the electrode array. The receiver-stimulator needed to be capable of receiving information about the acoustic environment as well as delivering controlled current charge outputs from chosen pairs of electrodes, all in real time.

Throughout the 1970s, much work on the development of electrode arrays and receiver-stimulators was carried out in research centres in Austria, France, England, the United States of America and Australia (Clark 2003). During this time a number of human volunteers were implanted with research devices across the centres allowing psychophysical and speech recognition studies to be performed. Preliminary findings were positive, showing volunteers could obtain auditory perception, discriminate pitch changes for different stimulation rates and discriminate intensity differences for different stimulation amplitudes. The first recipient of the University of Melbourne’s prototype multi-channel receiver-stimulator and electrode array also described stimulation on basal electrodes as being “sharp” and stimulation on apical electrodes
as being “dull” (Tong, Black et al. 1979). These studies set the scene for the development and investigation of speech coding strategies that would enhance the implanted volunteers’ recognition of speech sounds.

1.3.3. Development of contemporary Nucleus® cochlear implants

The University of Melbourne team developed one of the first effective speech coding strategies in 1978. The strategy coded voicing information (fundamental frequency: F0) using the rate of stimulation, the second formant frequency energy (F2) that occurs in speech sounds from the site of stimulation (electrode position) and sound intensity as the amount of charge delivered (roughly the amplitude multiplied by the pulse width of the biphasic square-wave electrical pulses – see Figure 5 below).

![Figure 5. Intensity information could be controlled by varying the amplitude or width of the biphasic pulses produced by The University of Melbourne’s prototype implant.](image)

This F0/F2 coding strategy was trialled with the first recipients of the University of Melbourne team’s 10-channel cochlear implant and resulted in scores on speech perception tests being 3 to 4 times greater than when the recipients were speech reading only. Some subjects were also able to obtain minimal open-set speech recognition with electrical stimulation alone (Tong, Black et al. 1979). The same strategy was implemented in the University of Melbourne group’s first wearable speech processor which was trialled in 1980.

Commercial interest in cochlear implants was sparked in the early 1980s and a number of research groups in Europe, the USA and Australia partnered with commercial biomedical companies. Refinements to electrode array and receiver-stimulator
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

designs and manufacturing processes followed. The most significant example of such a partnership (and the one relevant to this research) was between The University of Melbourne and Cochlear Pty Ltd, a subsidiary of the Australian pacemaker company, Telectronics. Beginning their partnership in 1980, it took just 2 years for Cochlear Pty Ltd to industrially develop The University of Melbourne’s prototype 10-channel receiver-stimulator and electrode array and the F0/F2 speech coding strategy into a 22-channel cochlear implant and a wearable F0/F2 speech processor for clinical trial. In the years that followed up to the time of writing this paper, Cochlear Pty Ltd (now called Cochlear Limited) and The University of Melbourne researchers (now extended to research partners in the HEARing Cooperative Research Centre) produced 5 generations of Nucleus® cochlear implant systems.

The more recent generations of Cochlear Limited’s electrode arrays come in different forms, to optimize positioning of the electrodes near nerve fibres in different shaped cochleae: a pre-curved 22-electrode array for normally formed cochleae; a 22-electrode straight array for malformed or ossified cochleae or a Double Array consisting of twin 11-electrode arrays (again for ossified cochleae), or shorter, slimmer 16 or 22-electrode arrays for when preservation of low frequency hearing is important. In addition to the electrode arrays that are inserted into the cochlea, two extra-cochlear electrodes have been added, that allow for more power efficient monopolar stimulation modes as well as the historical bipolar and common ground stimulation modes.

Figure 6. The early University of Melbourne and Cochlear Limited implants could use either bipolar or common ground stimulation modes, while more recent implants also offer monopolar modes.
Frequency information can be reproduced by controlling the place of stimulation within the cochlea. This has been achieved by directing electrical current between pairs of electrodes (paired electrodes being labelled as a “channel”). The different arrangements of the electrode pairings are termed ‘stimulation modes’ (see Figure 6 on the previous page). Monopolar stimulation modes enable auditory sensations to be elicited using considerably lower electrical current levels without significant loss of electrode discrimination.

Advances in the design of the receiver-stimulators have meant that they are now capable of stimulating with a range of different pulse rates and to much higher rates, they are considerably slimmer and so less drilling of the temporal bone is required to position the receiver-stimulator and the casings are more resistant to impact. The speech processor (more recently called a sound processor) has benefited from miniaturization of components and improved battery technologies and so current devices can now be worn completely behind the ear instead of on the body as they were initially.

Speech coding strategies, too, have been refined over time. The early coding strategies developed by The University of Melbourne researchers were known as feature extraction strategies. With the earliest F0/F2 strategy, recipients could identify male versus female speakers through the coding of voice pitch, as well as differentiate vowels using second formant information and, hence, obtain improved speech recognition. While the F0/F2 coding strategy offered many recipients good improvement in their face-to-face communication, average sentence recognition test scores were less than 20% when listening without the aid of visual cues (Dowell, Mecklenburg et al. 1986). In 1986, this strategy was modified to include information about the first formant energy peak (F1) in vowel sounds and so the F0/F1/F2 coding strategy was incorporated into the speech processor. The additional F1 place pitch information was enough to increase the average sentence recognition test scores to just under 40% with recipients listening alone (Dowell, Seligman et al. 1987). The final feature extraction coding strategy was introduced in 1989. Known as Multipeak, this strategy extracted high frequency information from the incoming waveform and added it to the F0/F1/F2 strategy. Specifically, the new speech processor incorporated 3 high
frequency filters to examine energy levels in frequency bands centred around 2000, 3000 and 4000Hz, which would then produce stimulation on the corresponding 3 fixed basal electrodes, allowing **Multipeak** to present additional information about consonants as well as vowels. Once again, the additional information led to an increase in the average speech recognition for recipients, with average audition alone sentence recognition test scores rising to just under 60% (Dowell, Whiford et al. 1990).

In 1991, The University of Melbourne researchers reported on a spectral maxima processing scheme (McKay, McDermott et al. 1991). Incorporated into Cochlear Limited’s **Spectra** speech processor as the **SPEAK** coding strategy (Seligman and McDermott 1995), this scheme passed the incoming acoustic waveform through a bank of 20 filters, then selected 6 to 10 filters that had the highest outputs (spectral maxima). Each filter was linked to an active electrode in a tonotopic order (the lowest frequency filter associated with the most apical electrode and the highest frequency filter associated with the most basal electrode) and so the spectral maxima frequency information could be represented by the site of stimulation within the cochlea and the amplitude information as electrical current amplitude. The stimulation rate for each channel was kept constant at around 250 pulses per second (pps), but could vary adaptively between 180 pps and 300 pps depending upon stimulation parameter limitations. Results from a multi-centre study (Skinner, Clark et al. 1994) showed that the **SPEAK** coding strategy enabled another significant increase in speech recognition, with mean sentence recognition test scores being measured at 77% when presented with sound alone.

The introduction of the **Nucleus® 24** implant and speech processor system in 1997, brought with it further refinements to the **SPEAK** strategy. The **Nucleus 24** implant incorporated two extra-cochlear electrodes in addition to the 22 electrode array with the purpose of providing monopolar stimulation modes. With the extra-cochlear electrodes acting as the indifferent electrodes, auditory sensations could be elicited at much lower electric current levels. This then allowed for pulse widths to be much narrower and hence allowing higher stimulation pulse rates (up to 14,400 pps) and more spectral maxima. This new coding strategy with programmable pulse rates and number of maxima was called the **Advanced Combination Encoder (ACE)** strategy.
(Vandali, Whitford et al. 2000). While clinical studies indicated only a slight improvement in mean scores on sentence tests from those obtained with SPEAK, measures of recipient preferences showed different people had a preference for different stimulation rates and different numbers of spectral maxima (Arndt, Staller et al. 1999; Grayden and Clark 2000; Vandali, Whitford et al. 2000; Skinner, Holden et al. 2002). Having the option to trial and have a recipient choose their preferred rate and maxima could improve their satisfaction of the sound quality from their cochlear implant. It has also been reported that, on average, recipients would choose a stimulation rate between 500pps or 900pps per channel and 8 maxima, which are higher than the 250pps and 6 maxima offered by the SPEAK coding strategy (Plant, Whitford et al. 2002; Arora, Dawson et al. 2009).

The next (and current) generations of Nucleus cochlear implant systems (Freedom and System 5 – see Figure 7 below) also utilized the ACE speech coding strategy as the default coding strategy, however, advancements in both the speech processors and implants meant that even higher stimulation rates (up to 32,000pps) were possible.

**Figure 7.** Left frame: the Nucleus® Freedom™ cochlear implant system consisting of (a) the Freedom implant with Contour Advance electrode array, (b) the Freedom implant with Straight electrode array and (c) the Freedom speech processor. Right frame: the Nucleus® System 5 cochlear implant system consisting of (d) the CI512 implant with Contour Advance electrode array (e) and CP810 sound processor. The CI512 implant is illustrated with the stylet in place to straighten the pre-curved 22-electrode array in readiness for insertion into the cochlea. (Photos courtesy of Cochlear Limited.)
The newer speech processors have also been able to offer an input dynamic range of 40dB compared to the 30dB input range of previous processors. This means that both the Freedom speech processor and CP810 sound processor start coding acoustic inputs with intensities of around 25dB through to about 65dB, after which higher intensity inputs are compressed, whereas previous speech processors only commenced coding sounds that were around 35dB in intensity. The wider input dynamic range available in the newer processors has meant that recipients are able to hear softer sounds than previously possible, the main advantage being that they can hear the softer components of the speech spectrum.

Recipients of modern day cochlear implant systems are also able to make use of a range pre-processing algorithms that aim to further enhance speech recognition in challenging listening situations, such as in noisy environments. Acting upon the speech processor’s input prior to the implementation of the speech coding strategy, these Smart Sound™ (Cochlear Ltd trademark name) options include an automatic sensitivity control, fixed and adaptive directional microphone settings, an increased compression ratio setting and “Adaptive Dynamic Range Optimization” (which will be discussed in detail in later paragraphs). These pre-processing options can be applied individually or in combination, with the aim of giving the recipient the option of selecting programmes that can enhance the signal-to-noise ratio or the audibility of soft sounds and speech, depending upon their requirement for a particular listening situation.

So, over time, cochlear implants have become an effective means of providing severely and profoundly hearing impaired adults and children with the frequency and intensity cues that they would otherwise miss out on, even with the use of hearing aids. In turn, cochlear implant recipients have been able to obtain significant improvements in awareness of environmental sounds (Shafiro, Gygi et al. 2011) and speech recognition, both face-to-face and audition alone (Dowell, Mecklenburg et al. 1986; Dowell 1994; Blamey, Arndt et al. 1996; Gomaa, Rubinstein et al. 2003; Brough, Walker et al. 2010). These benefits have also been reflected in the results of self-report and quality-of-life questionnaires (Hinderink, Krabbe et al. 2000; Hogan, Hawthorne et al. 2001; Vermeire, Brokx et al. 2005; Hirschfelder, Gräbel et al. 2008).
While the benefits of cochlear implantation can be significant for many recipients, they do not restore normal auditory function. Studies have shown that the average speech recognition abilities for present-day cochlear implant recipients are still only equivalent to the speech recognition abilities of people who have a moderate hearing loss and use hearing aids (Dowell, Hollow et al. 2003; Dowell, Hollow et al. 2004; Leigh, Dettman et al. 2011). So, as with hearing aids, improvements in sound awareness and speech recognition continue to be sought through ongoing research and development of new cochlear implant technologies, speech coding strategies and sound processing algorithms.

1.4. Adaptive Dynamic Range Optimization (ADRO®)

Adaptive Dynamic Range Optimization (ADRO®) is a digital sound processing algorithm that has been specifically designed for use in both cochlear implant systems and hearing aids (Blamey, James et al. 1999; James, Blamey et al. 2002; Blamey 2005). The aim of the ADRO processor is to provide and maintain audibility and comfort for the maximum range of sounds, in effect to continuously optimize the output dynamic range across the useable frequency spectrum.

There are three main stages to ADRO’s processing of sound:

1. ADRO Frequency Decomposition:

The input sound signal is firstly split into frequency bands. When ADRO is implemented in hearing aids, 64 or 32 bands are typically used, with bandwidths of 125Hz and 250Hz, respectively. In the case of cochlear implants, the number of bands is equal to the number of active electrodes (or channels) being used by the implant to electrically stimulate the cochlea. A maximum of 22 active electrodes, and hence frequency bands, are available with the current Nucleus cochlear implant systems that use ADRO. The bandwidths are in turn determined by the cochlear implant sound processor frequency filter-bank set-up, which is based upon the number of active electrodes and/or the fitting clinician’s discretion.

There are theoretical advantages for using a large number of narrow frequency bands, especially in hearing aids. The main advantage is the greater flexibility in shaping the
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

maximum gain and output levels at a number of frequency points, enabling more accurate fitting of the hearing aid to a greater range of hearing losses, including steeply sloping losses. In addition, speech recognition in background noise is more likely to be improved when the background noise has a narrow frequency distribution. In these instances, the gain in the frequency bands containing the noise can be reduced. The component of the speech signal that falls into the same frequency bands will also be reduced, but as the speech components in the many other frequency bands will be unaffected, the overall signal will be improved. If a hearing device with only a small number of frequency bands was exposed to a similar noise environment, a reduction in gain in order to reduce the noise could also reduce so much of the speech signal that there may be no overall improvement in the effective signal-to-noise ratio.

2. ADRO Percentile Estimation:

Next, the output of each frequency band is analysed using two statistical measures. Rather than take an average of the input signal to determine the output level of a frequency band, as is done in conventional signal processors, ADRO uses the 30th and 90th percentiles of the output signal to determine the output level. These statistical calculations are performed by two ‘percentile estimators’ allocated to each frequency band. The percentile estimators measure signal intensities in each band at regular time intervals and calculate the percentiles. Each successive measurement is compared to the current estimate. If the new measurement is higher than the current estimate, then the estimate is increased by a small amount. Likewise, if the new measurement is lower than the current estimate, then the estimate will be decreased slightly.

Measurement of the 30th percentile (the level that is exceeded 70% of the time) and the 90th percentile (the level that is exceeded 10% of the time) gives information about the troughs and peaks (and effectively the dynamic range) of the output signal. Having information about the troughs is important in ensuring the full dynamic range of the signal is audible, while information about the peaks helps determine if the signal will be at a comfortable level. This can be seen in Figure 8 on the following page, which gives a hypothetical intensity distribution in one frequency band, typical of speech in a
relatively quiet environment. The lower intensity peak may represent low level background noise and the higher intensity peak may represent speech.

![Intensity Distribution](image)

Figure 8. Hypothetical distribution of intensity measurements in one frequency band, typical of speech presented in a relatively quiet environment. The 30\textsuperscript{th} and 90\textsuperscript{th} percentiles are also indicated, illustrating how these measures can provide information about the troughs and peaks in the signal. (Reproduced from Blamey 2005.)

It should be noted that when ADRO is implemented in Nucleus cochlear implant systems, the percentile estimators calculate the 40\textsuperscript{th}, 70\textsuperscript{th} and 98\textsuperscript{th} percentiles (James, Blamey et al. 2002). In addition, percentile estimates are updated at an analysis rate of around 250Hz, while a hearing aid using 64 bands uses an analysis rate of 62.5Hz.

3. ADRO Gain Rules:

The output of each frequency band is directly controlled by the application of four “fuzzy logic” rules. Fuzzy logic rules deal with situations that have “degrees of truth” – ranging from completely true to completely false – and are often expressed in the form: IF variable IS property THEN action. The ADRO rules are:

- **Comfort rule**: If the 90\textsuperscript{th} percentile level (98\textsuperscript{th} percentile in the case of a Nucleus cochlear implant) exceeds the comfort target, the gain is reduced slightly.
- **Audibility rule**: If the 30\textsuperscript{th} percentile level (70\textsuperscript{th} percentile in the case of a Nucleus cochlear implant) falls below the audibility target, the gain is increased slightly.
• **Hearing protection rule**: The amplitude of the output is limited so that it never exceeds a set maximum output level and avoids overstimulation for the listener.

• **Background noise rule**: In the case of hearing aids, the maximum gain is limited to avoid over-amplification of environmental background noise or internal noise from the hearing aid. In the case of Nucleus cochlear implant systems, the gain is reduced if the 40th percentile level exceeds the background noise target.

The targets used in the gain rules are determined by obtaining measures of ‘audibility’ and ‘comfort’ in each frequency band for the listener. Audibility measures for a hearing aid user can be obtained from their audiogram – measures of the person’s hearing thresholds using pure-tone stimuli presented at octave band frequencies, typically between 250Hz and 8,000Hz. For a cochlear implant recipient, the same measurement technique for finding a hearing threshold can be used, but in this instance, the stimuli are electrical rather than acoustic. Current levels that produce hearing thresholds (“T-levels”) can be measured for a selection of the cochlear implant electrodes (usually a set of 5 to 7 electrodes) and then interpolated for the remaining electrodes across the electrode array. The process for obtaining comfort measures for ADRO is similar for both hearing aids and cochlear implants. A hearing aid user is presented with narrow band noises (⅙ octave) of increasing volume at 7 audiometric frequencies between 500Hz and 4000Hz and asked to judge when each gets to a comfortably loud level. These stimuli can be generated by the hearing aid. For a cochlear implant recipient, current levels are raised up from the “T-levels” and the person indicates when the sound is comfortably loud (“C-level”). Again, C-levels can be interpolated for the remaining electrodes. “Loudness balancing” is then used for both hearing aids and cochlear implants to attempt to match or equalize the comfort measures across the frequency range (or electrode array). The listeners are presented with comfort levels from 2 or 3 frequencies or channels and asked to comment on their relative loudness. If need be, the comfort levels are then adjusted up or down to equalize the loudness. The process is repeated across the range of frequencies or channels. The final stage in determining the audibility and comfort levels is to activate the programme or Map in the hearing aid or cochlear implant and ask the person to listen to different sounds in the room (e.g. speech and incidental noises like air-
conditioning) and comment on the loudness of the sounds. Adjustments to the audibility and comfort levels can then be made until the listener is happy with the programme or Map.

Figure 9. Schematic diagrams for the implementation of ADRO in hearing aids (top) and cochlear implants (bottom).

In real time operation, the gain in an ADRO device is constant most of the time, as it is only altered when the output signal is at its extremes and the ‘comfort’, ‘audibility’ or ‘background noise’ rules come into effect. Most of the time, therefore, the hearing aid or cochlear implant is operating with a linear gain function. When these rules are applied, the gain increments or decrements are in the order of 3dB per second in hearing aids and equivalent to about 6dB per second in the Nucleus cochlear implant systems, which equate to fairly slow changes in gain. It has been reported that less variance in gain and slower time constants (such as attack and release times) are associated with better sound quality (Neuman, Bakke et al. 1998; Hansen 2002). The ‘hearing protection’ rule, however, operates almost instantaneously in both types of devices to protect the listener from loud sounds with a rapid onset.
ADRO incorporates a number of features that differentiates it from other sound processing approaches currently in use. Firstly, ADRO offers many more (and narrower) frequency bands than most conventional amplification systems (32 or 64 bands compared to 6 or less bands in standard hearing aids and 20 or less bands in a top of the range models). With its ‘audibility’, ‘comfort’, ‘back-ground noise’ and ‘hearing protection’ rules operating on the output of each band independently, ADRO should provide more specificity and flexibility in optimizing the hearing dynamic range across frequencies. The second and most distinctive feature is the use of percentile estimators to measure the output amplitudes and, hence, the dynamic range of each band. Most compression sound processors measure the average level of the input and then make the presumption that the dynamic range is in the order of 30dB; the average dynamic range of speech (Byrne, Dillon et al. 1994). ADRO, however, will determining the dynamic range of each band based on measures of the peaks and troughs in a signal.

1.5. Clinical studies evaluating ADRO

A number of studies have been published that have compared the performance of hearing aids and cochlear implant systems with and without ADRO. More specifically, the studies have aimed to evaluate if the novel approach to sound processing offered by ADRO provides hearing benefits to listeners familiar with the more traditional approaches of wide dynamic range compression (WDRC) in hearing aids or fixed gain in cochlear implant speech processors.

Martin et al. (2001) first looked at the effectiveness of ADRO when implemented in a hearing aid. The hypothesis of this study was that ADRO would produce higher speech perception scores than a fixed-gain hearing aid, especially for moderately low presentation levels. The researchers aimed to validate the ADRO processing scheme and fitting procedure in a laboratory-based hearing aid for listeners with a range of hearing losses.

The hearing aid used in the study was a bench-top digital signal processor fitted with a microphone, preamplifier, output amplifier and a hearing aid receiver. The receiver was attached to an individually fitted ear mould for each listener. The digital signal
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

A processor was interfaced with a personal computer and custom fitting software (called AUDY) so that the processing scheme parameters and stimuli could be controlled during the fitting procedure. With this arrangement, both ADRO and fixed-gain amplification schemes could be produced.

The researchers recruited 15 hearing impaired adults. Audiometric testing revealed the group had hearing losses ranging from moderate to profound (44 – 98dB HL pure tone average hearing loss). Although not specifically defined in this paper, a pure tone average is usually defined as the mean of the hearing thresholds measured using 500, 1,000 and 2,000 Hz pure tones. The fixed gain hearing aid was programmed for each individual using their audiometric results and the NAL-RP prescription (Byrne, Parkinson et al. 1990; Byrne, Parkinson et al. 1991). The targets for the ADRO hearing aid were determined using ⅓ octave band noises produced by the signal processor and controlled by the AUDY software. The ‘minimum audibility’ levels for each frequency band were determined using the standard audiometric technique for determining hearing thresholds. A loudness scale was then used to determine the ‘comfort levels’ and the ‘maximum comfort’ levels for each frequency band. The volume of each hearing aid option was adjusted to match the loudness of speech at a normal conversational level. Speech perception testing was then conducted using the ADRO and fixed-gain schemes with open-set CUNY Sentences (Boothroyd, Hanin et al. 1985) presented free-field at intensities of 55, 65 and 75dB SPL.

Analysis of the results showed that the presentation level and hearing aid had a significant effect (p<0.001 on a two-way ANOVA) on the scores. The difference in the mean scores for the fixed-gain and ADRO hearing aids was not significant at 75dB SPL (83.6% and 81.7% respectively; p=0.99 using post hoc Tukey t-test), however, the differences were significant at 65dB SPL (63.7% and 79.6% respectively; p=0.014) and 55dB SPL (18.6% and 55.0% respectively; p<0.001). Comparison of the mean scores at the different presentation levels showed that for ADRO, there was no significant drop in scores for the 75 and 65dB SPL presentation levels (difference=6.1%; p=0.80) but the difference between the 65 and 55dB SPL levels was significant (difference=27.1%; p<0.001). For the fixed-gain scheme, the difference between the 75 and 65dB SPL
presentation level scores was significant (difference=20.2%; p=0.001) as was the difference between the 65 and 55dB SPL levels (difference=47.6%; p<0.001).

The researchers concluded from these results that the ADRO processing scheme was able to maintain speech recognition at lower intensities better than a fixed-gain amplification scheme. They acknowledged that the scores obtained at 75dB SPL were greater than 80% and therefore any difference may have been limited by a ceiling effect. It was suggested that the use of more difficult speech materials could identify if this was the case. The authors also suggested that ADRO be evaluated in more challenging listening situations such as in background noise and be compared against other commonly used amplification schemes such as compression schemes.

James et al. in 2002 reported on speech perception results for a group of adult cochlear implant recipients using ADRO. This study had a number of aims, including: 1. to determine which of 2 ‘audibility targets’ in the ADRO scheme would be most beneficial, 2. to determine whether the use of ADRO in addition to the listener’s usual speech coding strategy would improve speech recognition at a number of different presentation levels, 3. to determine if speech recognition in background noise would be affected by the use of ADRO and 4. to assess the perceived benefit and acceptability of ADRO for the group.

Two versions of the ADRO scheme were created for this study (‘LowA’ and ‘HighA’); the difference being the settings for the audibility target. For the LowA programme, the audibility target was set midway into the cochlear implant speech processor’s 30dB instantaneous input dynamic range (i.e. -15dB), while the audibility target was set to -5dB for the HighA programme. The background noise and comfort targets were the same for both the LowA and HighA programmes.

Nine post-linguistically deafened adults, who had a minimum of 1 year experience using a cochlear implant, participated in the study. The subjects were given a Nucleus 24® Sprint™ speech processor (Vandali, Whitford et al. 2000) loaded with the LowA and HighA ADRO programmes as well as their standard programme that did not incorporate ADRO. The subjects were informed which programme number related to their standard programme and which related to the two ADRO programmes and asked
to take the processor home and try out the different programmes in different listening environments.

Closed-set spondees, open-set monosyllable words (Henry, McDermott et al. 1998) and open-set CUNY sentences (Boothroyd, Hanin et al. 1985) were administered at different sound levels to evaluate speech perception in quiet listening situations. CUNY sentences were also presented with 8-talker babble as the background noise to evaluate the performance of the different programmes in noise. For testing in quiet, it appears that some subjects were tested using the standard and LowA programmes while others were tested with their standard and HighA programmes, meaning the sample sizes could be as small as N=4. For the CUNY sentences presented in noise, all subjects were tested using the standard, LowA and HighA programmes at the 2 signal-to-noise ratios (SNRs). The three subjects who wore a hearing aid in the contralateral ear were asked to remove the aid during the test sessions but could wear it at home. Subjects were asked to document their take-home experience and rate the effectiveness of the different programmes using a questionnaire.

For the materials presented in quiet, the researchers sought only to compare the standard programme with either the LowA or HighA ADRO programmes at the different presentation levels. For the spondee test, there were no significant differences in mean scores for the standard and ADRO programmes for the 60dB SPL and 50dB SPL presentation levels (97.7% versus 96.9% and 78.1% versus 87.2% respectively). At the 40db SPL presentation level, the mean score with the ADRO programme (35.6%) was significantly higher (p<0.02) than the score with the standard programme (14.9%). A 2-way ANOVA was performed on the monosyllabic word data which revealed a significant effect (p<0.01) of programme and presentation level for both the word and phoneme scores. For both words and phonemes, the ADRO scores were higher than the standard programme scores and a 70dB SPL presentation level produced higher scores than a 60dB SPL presentation level. For CUNY sentences presented in quiet, 7 subjects were tested with both the LowA and HighA programmes. There was no significant difference between mean scores for the two ADRO programmes at the 70dB SPL (LowA 92.6%, HighA 92.3%), 60dB SPL (LowA 76.6%, HighA 80.4%) or 50dB SPL (LowA 24.4%, HighA 24.2%) presentation levels. When the
LowA and HighA scores were averaged and compared to the standard programme scores, there were significant differences between the ADRO and standard scores at the 60dB SPL (p<0.05) and 50dB SPL (p<0.01) presentation levels but not at 70dB SPL. There were also significant presentation level effects for both the ADRO and standard programmes.

All subjects were presented with CUNY sentences presented in 8-talker babble at signal-to-noise ratios of +10dB and +15dB. This testing was performed with both the LowA and HighA programmes as well as the standard programme. There was no significant difference between any of the programmes. Scores obtained with a +15dB SNR were significantly higher than those obtained with a +10dB SNR as expected.

Following their take-home experience, subjects were asked to judge the loudness of 13 different environmental sounds and rate their preference for the ADRO or standard programmes in 16 listening situations. Loudness judgements for LowA and HighA programmes were equivalent and there was no difference between the ADRO and standard programmes for 67% of the sounds. The group rated 25% of sounds louder with the ADRO programme and 8% louder with the standard programme. Subjects reported a preference for the ADRO programmes in 59% of situations, had no preference in 31% of situations and preferred the standard programme in 10% of situations. When asked to compare the LowA and HighA programmes, 3 subjects preferred LowA, 5 preferred HighA and 1 had no preference.

The researchers concluded that the benefits of ADRO were more noticeable at softer presentation levels due to the improved audibility it offered over standard programmes. It was stated that ADRO effectively offered up to 5dB extra gain based on the observation that the ADRO phoneme and sentence scores at 60dB were equivalent to the averaged 60dB and 70dB scores with the standard programme. While an increase in audibility could also be achieved by increasing the sensitivity of the speech processor, the authors reported that subjects tended to choose sensitivity settings that gave a balance between maximizing audibility while retaining comfort for loud sounds. In addition, the subjects in this study with higher sensitivity settings did not score more highly on the tests than those using lower sensitivities. No
recommendation was given about the optimal audibility target setting (i.e. -15dB or -5dB) when implementing ADRO in cochlear implant speech processors.

A further evaluation of ADRO in a take-home SPrint speech processor was conducted by Dawson et al (2004), but this time with a group of children. While the authors hypothesized that the benefits of using ADRO described in studies with adult participants would be similar for children, verification was needed as children who receive cochlear implants were typically congenitally deafened and implanted at young ages and so not able to report if a programme is not ideal (for example, too loud). With this study, the researchers aimed to determine if when using ADRO: 1. speech perception benefits could be measured for speech materials presented at 50dB SPL in quiet, 2. speech perception in the presence of multi-talker babble would be equivalent to a standard programme, 3. speech perception performance would improve with increased experience, 4. the loudness of environmental sounds would be acceptable and 5. children would have a preference for an ADRO programme over their standard speech processor programme.

Fifteen children who used a SPrint speech processor with a Nucleus 24 cochlear implant participated in the study. The children had at least 6 months experience with their cochlear implant and had adequate speech and language skills to be able to complete a sentence recognition test. The version of ADRO used in this study was already incorporated into Cochlear Ltd’s commercially available WIN 124 programming software, with the target levels being: 0dB for the Comfort rule (98% percentile rank), -15dB for the Audibility rule (70% percentile rank) and -5dB for the Background noise rule (10% percentile rank). As with the study with adults, all children used a 30dB instantaneous input dynamic range in the SPrint speech processor and maintained the same speech coding strategy and sensitivity setting for both the ADRO and standard programmes. Once again, the parents of the participants were informed how to select the ADRO and standard programmes and so were aware which programme was being used at any one time.

The study used a repeated-measures single-subject design. The children were given 4 weeks take-home experience with the ADRO programme, with speech perception
measures performed after 1 week of using ADRO and again after the 4th week of using ADRO. At the end of the 1st week, children were asked to complete an environmental sounds questionnaire and in the 4th week they were asked to compare the ADRO and standard programmes in 12 different everyday listening situations. The children's speech perception with each programme was measured using BKB sentences adapted for Australian conditions (Bench, Kowal et al. 1979; Bench, Doyle et al. 1987) presented at 50dB SPL in quiet and 65dB SPL in the presence of 8-talker babble. The signal-to-noise ratio was individually selected for each child to avoid floor and ceiling effects. The order of testing the 2 programmes was balanced across the 2 test sessions. If a child wore a hearing aid in the contralateral ear, it was removed during the speech perception testing.

The researchers were able to show using 2-way repeated measures analysis of variance that there were significant effects of programme and session for the BKB sentences presented both in quiet and in noise. For BKB sentences presented at 50dB in quiet, the mean score with the ADRO programme was 8.60% higher than with the standard programme (significance level p<0.001), while the mean score with the ADRO programme was 6.87% higher than with the standard programme (significance level p<0.01) for sentences presented in 8-talker babble. The mean scores obtained in session 2 were found to be significantly higher than those obtained in session 1 for both the ADRO and standard programmes when tested with the sentences in quiet (8.90% and 6.90% respectively, p<0.05) and in noise (13.47% and 12.27% respectively, p<0.05). A forward stepwise regression analysis of a number of variables indicated that the microphone sensitivity setting was the only significant predictor of average difference in sentence scores in noise only. Specifically, a microphone setting of ‘12’ was associated with higher mean scores in noise when using ADRO, compared to scores obtained with lower microphone settings. For the questionnaire that asked children to indicate if they had a preference for the ADRO or standard programmes in 12 different listening situations, ADRO was the preferred programme in 46% of the situations, the standard programme was preferred in 26% of the situations and for the remaining 28% of situations there was no difference reported. The group’s median loudness ratings of 8 environmental sounds rated 6 of the 8 sounds as being louder
with the standard programme. No sounds were rated as too loud when using the ADRO programme.

In their discussion about the findings, the authors made comparisons between the results they obtained with the children and the results from the group of adults in James et al. (2002). It was noted that while ADRO offered improved speech perception with sentences presented at 50dB in quiet for both groups, the mean group improvement was only 8.6% for the children compared to 11.5% for the adults. They acknowledged that the test materials and conditions were not the same in the 2 studies, but also proposed that the microphone sensitivity settings may have had an effect. The majority of adults used a sensitivity setting of 8 whereas the majority of children used a setting of ‘12’. The implication of this difference was that the audibility rule could have raised the gain an extra 6dB higher for the adults compared to the children. The difference in the average sensitivity settings was also proposed as a reason for ADRO offering improved speech perception in noise for the children but not for the adults. For the sentences presented at the higher level of 65dB SPL, it was proposed that the comfort rule would be activated more frequently with a sensitivity of ‘12’ than it would with a sensitivity of ‘8’. This in turn would mean that ADRO would be using the top end of the dynamic range less frequently than the standard programme for the higher sensitivity setting. This effect of the different sensitivity settings was also given as a possible explanation for why the children tended to rate environmental sounds softer with ADRO whereas the adults tended to rate sounds as being louder with ADRO. The authors reported no other significant variables that were related to speech perception differences.

Blamey et al. (2004) followed on from the work of Martin et al. (2001) by comparing the effectiveness of ADRO against a 9-channel compression scheme for a group of adults who had mild to moderate hearing impairments. Their hypothesis was that the speech perception benefits offered by ADRO to adults with moderate to profound hearing impairments would also be possible for people with lesser degrees of hearing loss.
The study involved 22 adults who each trialled ADRO and a 9-channel Wide Dynamic Range Compression (WDRC) scheme in a commercial in-the-ear (ITE) hearing aid. The ADRO scheme was fitted using the custom ADRO fitting method described earlier and the WDRC scheme was fitted based upon the NAL-NL1 (Dillon 1999) prescription and the ITE manufacturer’s recommendations. Each scheme was trialled at home for a period of 7 weeks. Half of the group commenced with the ADRO scheme before changing to the WDRC scheme and the other half of the group did vice versa. The study participants were not told which scheme they were using in either phase of the trial to avoid potential bias. Subjects were fitted with monaural or binaural trial hearing aid(s), as per their usual fitting condition. The first 4 weeks of each phase allowed the subjects to acclimatize to the amplification scheme before speech perception testing was conducted in the final 3 weeks. CNC words (Peterson and Lehiste 1962; Henry, McDermott et al. 1998) were used to evaluate speech perception at soft presentation levels and CUNY sentences (Boothroyd, Hanin et al. 1985) with competing 8-talker babble were used to evaluation speech perception in noise. The presentation level of the CNC words and the signal-to-noise ratio for the CUNY sentences were individually set for each subject to avoid floor and ceiling effects. At the start of each trial phase, the materials were presented to each subject in the unaided condition to obtain a baseline measure. Once determined, the same presentation levels and signal-to-noise ratios were used for all test sessions and both the ADRO and WDRC schemes. Subjects were tested monaurally or binaurally, depending upon their hearing aid fitting.

As hypothesised, the mean CNC word score using ADRO was significantly higher (difference=7.85%, p=0.002) than the WDRC score. Similarly, the CNC phoneme score using ADRO was significantly higher (difference=6.41%, p=0.006) than the WDRC score. The unaided scores obtained at the start of each test phase were not significantly different (difference=0.2%, p=0.82). In addition, the mean scores obtained with CUNY sentences presented in 8-talker babble were also significantly higher with ADRO than with WDRC (difference=7.25%, p=0.01). Once again, the unaided scores obtained at the start of each test phase were not significantly different (difference=0.7%, p=0.77).
The authors again related the magnitude of the differences in mean scores to previous studies that have compared ADRO to other amplification schemes. While the effect of ADRO on sentence recognition in babble was similar to previous studies, the authors commented that the difference in scores using speech perception materials presented at soft levels with this group was less than had been reported earlier. Reasons suggested for this were: this study used CNC words rather than CUNY sentences which had been used before; the 9-channel WDRC compression scheme may have been more effective than the linear gain scheme used by Martin et al. (2001) and the subjects in this trial had more residual hearing (mild and moderate hearing losses) than the groups in previous studies (moderate to profound losses as in Martin et al. (2001).

Blamey et al (2005) also reported on a similar comparative study using a commercial behind-the-ear (BTE) hearing aid that could be programmed with both ADRO and a 3-channel WDRC scheme. In this trial, the subjects were able to switch between the two amplification schemes but they were not informed as to which programme used ADRO and which used WDRC. The 19 adults who participated in this study had hearing impairments that ranged from mild to profound.

The subjects were given 6 weeks to acclimatize to the hearing aid and the two amplification schemes before speech perception testing was performed. As with the above-mentioned study, the speech perception battery was designed to highlight differences between the two amplification schemes with soft presentation levels and with competing noise. CUNY sentences were chosen as the test material for both the quiet and competing noise test conditions. To accommodate the wide range of hearing losses in the subject group, the presentation level of the CUNY sentences was individually determined (between 45 and 65dB SPL) such that it would be “soft” but would avoid floor and ceiling effects. The signal-to-noise ratio for CUNY sentences presented with 8-talker babble was also individually determined to produce scores of around 50%, again aiming to avoid floor and ceiling effects.

The results from this study, as with previous studies, showed the mean scores using ADRO to be significantly higher than the WDRC scores. For CUNY sentences presented
in quiet at soft levels, the difference was 14.2% (p<0.001). For CUNY sentences presented at 65dB SPL with 8-talkers babble, the difference was 7.3% (p<0.001).

As subjects could switch between the ADRO and WDRC schemes in the hearing aid, they were asked to complete the Hearing Aid Measure of Contrast questionnaire; a modified version of the SHAPIE questionnaire (Dillon 1994; Dillon, James et al. 1997). This gave a preference comparison for the two schemes across 25 listening situations. A total of 74% of preferences went to ADRO (31% ‘slightly better’, 31% ‘better’ and 12% ‘much better’) and 26% went to WDRC (16% ‘slightly better’, 10% ‘better’ and 0% ‘much better’).

Summarizing the results from this study as well as from Martin et al. (2001) and Blamey et al. (2004), the authors stated that these comparisons of ADRO to linear gain and compression amplification schemes “show that clinically and statistically significant improvements to intelligibility of speech at moderately soft levels are possible without compromising comfort, sound quality, or intelligibility in noise” (Blamey et al 2005: 3031).

Some recent studies have reported on the effectiveness of ADRO when implemented as a part of Cochlear Limited’s SmartSound™ input processing options that were introduced in the Freedom speech processor. Cochlear Limited’s Implantable Hearing Solutions publication (Cochlear Ltd 2007) summarized a study using a group of 39 adults who were tested with CUNY Sentences in noise to compare the Smart Sound options of ADRO and Autosensitivity™ control (ASC) and a standard Map with no input processing. The participants were also tested with CNC Words at 50dB SPL and 60dB SPL to compare ADRO, Whisper™ and a standard Map. The group mean scores for the sentences in noise indicated a significant improvement when the pre-processing options of ADRO (mean=51%) and ASC (mean=52%) were used compared to the standard Map without pre-processing (mean=47%). Similarly with the CNC Words, the ADRO and Whisper Maps produced significantly higher mean scores than the standard Map, but only for words presented at 50dB SPL. Participants reported on a comparative questionnaire that they preferred to use a SmartSound option 83% of the time in noisy situations and 63% of the time in quiet situations. ADRO was the
preferred *SmartSound* option for about half the group in both noisy and quiet situations. As ADRO was the only pre-processing option that could be used effectively in both noisy and quiet environments, it was the option recommended for general use with children who wouldn’t be able to select their own *SmartSound* options. It has also been reported by Müller-Deile et al. (2008) and Müller-Deile (2009) that ADRO implemented in *Sprint* and *Freedom* speech processors offered significant improvement in speech reception thresholds in quiet and equivalent performance in noise when using German speech perception materials and preference surveys.

The studies described above produced quite consistent findings. First, recognition of speech spoken at softer levels was enhanced by the use of ADRO. Secondly, it could also be concluded that speech recognition performance in noisy environments when using ADRO, was at least equivalent to other standard processing options in either hearing aids or speech processors. These findings have been demonstrated when ADRO has been used as an amplification scheme in hearing aids and as a pre-processing algorithm in cochlear implant speech processors. It is also of interest to establish whether the benefits of ADRO for people using a single device type (i.e. either a cochlear implant speech processor or hearing aid(s)) would also be available to people who use bimodal devices (both a cochlear implant in one ear and a hearing aid in the other).

### 1.6. Bimodal fitting of cochlear implants and hearing aids

Being able to hear with both ears (binaural hearing) has been shown to be especially important for understanding speech in noisy environments as well as having the ability to localize sounds (Hirsh 1950; Pollack and Pickett 1958). Acoustic phenomena such as the head shadow effect, binaural summation and binaural squelch are thought to assist in understanding speech in noise, while being able to detect timing and sound level differences between ears (resulting from the head shadow effect) helps in the localization of sounds (Durlach and Colburn 1978; Blauert 1997; Moore 2003). It has been shown that if these acoustic cues can be detected and processed by the binaural hearing pathway, then hearing impaired people can also gain some benefit from binaural hearing if appropriate amplification is provided in both ears (Durlach and
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

Thompson 1981; Feston and Plomp 1996; Noble, Byrne et al. 1997; Noble and Gatehouse 2006). It has now become standard clinical practice to fit hearing aids bilaterally whenever possible.

Historically, cochlear implantation was only recommended for people who had a bilateral profound hearing loss and unilateral implantation was considered sufficient. Binaural hearing was, therefore, not an option that was given much thought for that group. In the past decade however, cochlear implantation has become a suitable option for many people with lesser degrees of hearing loss (Cullen, Higgins et al. 2004; Adunka, Buss et al. 2008) and their non-implanted ear will have residual hearing that can benefit from amplification. This now very common group of people, who use a cochlear implant in one ear and a hearing aid in the other ear, are said to have ‘bimodal’ hearing. The potential benefits of bimodal hearing are that the electrical stimulation from the implant will provide good high frequency hearing, which is important for speech recognition, while amplification in the other ear will enhance the person’s low frequency hearing, giving better tonal and music perception. The main challenge, however, is that some people may not be able to effectively integrate the two different inputs; the electrical and the acoustic (Blamey, Dooley et al. 2000; Tyler, Parkinson et al. 2002; Mok, Grayden et al. 2006).

A number of studies have reported on the limitations and benefits of bimodal hearing in adults. A systematic review of 52 such studies and the findings of 11 studies that met the authors’ criteria for research merit has been published by Olson and Shinn (2008). The studies reviewed employed a variety of methodologies, outcomes measures and subjects, so the reviewers found it difficult to arrive at any clear conclusions. It was, however, possible to observe trends in the studies’ outcomes:

1. The majority of studies demonstrated that most participants performed better on speech perception tasks in the bimodal condition compared to either the cochlear implant alone or hearing aid alone conditions (Armstrong, Pegg et al. 1997; Tyler, Parkinson et al. 2002; Ching, Incerti et al. 2004; Ching, van Wanrooy et al. 2005; Dunn, Tyler et al. 2005; Luntz, Shpak et al. 2005; Morera, Manrique et al. 2005). There were, however, a few subjects for whom the bimodal condition was not as
good as the monaural conditions and others that appeared to take longer to integrate the acoustic and electrical signals (Luntz, Shpak et al. 2005), suggesting that neural plasticity might affect the rate at which adults can integrate the two signals.

2. The improvements in speech perception were most significant on word and sentence recognition tasks presented in noise (Hamzavi, Pok et al. 2004; Ching, van Wanrooy et al. 2005; Dunn, Tyler et al. 2005; Luntz, Shpak et al. 2005; Morera, Manrique et al. 2005) which, as mentioned earlier, is similar to findings from investigations into binaural hearing with acoustic input only.


4. Most subjects indicated that their functional listening performance was enhanced by bimodal hearing over just the use of their cochlear implant (Tyler, Parkinson et al. 2002; Ching, Incerti et al. 2004), suggesting unfavourable interactions between the acoustic and electrical inputs is not common.

These trends have been seen in more recent studies, too. Potts and colleagues (2009) fitted a group of 29 adult cochlear implant recipients with the same model of digital hearing aid and then measured sound field thresholds, loudness growth, speech recognition with roaming speech and localization abilities. A repeated-measures study design was used and the researchers obtained results from subjects listening with just their cochlear implant, the hearing aid alone and both devices together (bimodal condition). The sound field thresholds and loudness growth results indicated 1-3dB binaural loudness summation. The roaming speech recognition task was performed using monosyllabic words presented from one of an array of speakers positioned in front of the subject with a radius of 140°, to try and better replicate the real-life environment. Recognition was significantly better in the bimodal condition compared to either cochlear implant alone or hearing aid alone. The localization task also utilized
the monosyllabic words as stimuli and, again, significantly better localization was achieved in the bimodal condition. The authors noted that while the mean bimodal localization RMS error (39°) was similar to other bimodal studies (Ching, Incerti et al. 2004; Dunn, Tyler et al. 2005) it was poorer than that found in normally hearing people or hearing impaired people using hearing aids (Butler, Humanski et al. 1990; Byrne, Sinclair et al. 1998; Noble, Sinclair et al. 1998), suggesting that the inter-aural cues provided by the two forms of input (electrical and acoustic) are limited. For both the speech recognition and localization tasks, it was observed that for both monaural conditions (cochlear implant alone or hearing aid alone) significantly fewer errors were made when the stimuli were presented on the side of the working device. There was no effect of side of presentation in the bimodal condition, demonstrating that binaural processing can effectively assimilate different degrees of sound and speech perception; in this case from a cochlear implant in one ear and a hearing aid in the other severely-to-profoundly deafened ear. This was also borne out in the questionnaires, to which 15 out of the 19 subjects reported hearing sounds “in the centre of their head” when listening in the bimodal condition but to the side they were wearing a device in the monaural conditions. For this group of adults, unaided and aided hearing thresholds and the Speech Intelligibility Index were significant factors affecting the speech recognition and localization results.

Similar findings have also been reported for children. Dettman et al (2004) found that for 14 children the group mean speech recognition scores were significantly higher in the bimodal condition using word tests (phoneme scores) and sentence tests in quiet. Ching and colleagues (2006) compared binaural/bimodal hearing abilities in 29 children with those of 21 adults. To examine the effects of binaural redundancy, subjects were asked to listen to sentences and babble coming from the same speaker. To examine the effects of binaural redundancy and head shadow effect, subjects were tested with sentences and babble coming from different speakers (±60° from the azimuth with speech coming from the speaker closest to the hearing aid). In both test conditions, adults and children performed significantly better with bimodal hearing compared to just using their cochlear implant. Localization abilities in the horizontal plane were tested using an array of 11 speakers. Better localization was seen for both
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

adults and children in the bimodal condition compared to the cochlear implant alone condition. It was also noted that localization ability was correlated to speech perception when the speech and noise were spatially separated.

All of the bimodal investigations outlined above have been conducted with subjects using conventional hearing aids, in most cases the subject’s own hearing aid. Iwaki et al. (2008) conducted a bimodal study with adult subjects using a cochlear implant speech processor and a hearing aid that could both utilize the ADRO sound processing strategy. The aim of their study was to demonstrate the clinical benefits of ADRO in bimodal devices for people with severe and profound hearing impairments. In particular, the researchers hypothesised that the bimodal ADRO combination would result in improved audibility in quiet environments and improved comfort and speech intelligibility in a variety of listening situations, compared with bimodal device combinations that did not utilize ADRO.

The study participants were 6 post-linguistically deafened adults who had been implanted with Nucleus 24 cochlear implants and who had continued to use hearing aids in their non-implanted ears. Five of the six participants had a profound hearing loss in the non-implanted ear and one participant had a moderate-to-severe hearing loss. It was reported that aided speech perception scores pre-implantation were at chance levels.

The study design consisted of 1-3 device fitting and optimization sessions, an acclimatization period and an evaluation session. At the first session, the subject’s own hearing aid and SPrint speech processor fittings were reviewed to “ensure that each participant was reasonably satisfied with their devices” (Iwaki et al. 2008: 312). If their ear-mould was more than 6 months old, a new ear-mould was arranged before fitting the ‘ADRO hearing aid’ at the second session. The ‘ADRO hearing aid’ was a high-powered aid from Interton GmbH and was fitted using the custom fitting software, ADROfit. The volume was balanced between the hearing aid and cochlear implant. At the completion of the fitting session, subjects were given a questionnaire to take home that asked questions about fitting related issues, such as: the loudness of environmental sounds, the quality of their own voice and the presence of feedback in
the hearing aid. The participants’ answers on the questionnaires guided the researchers in the fine-tuning of the ‘ADRO hearing aid’ fitting at the following session. If required, a second ‘fine-tuning’ session was conducted with some participants.

A 3 week acclimatization period followed, during which the subjects were asked to trial and compare the bimodal ADRO and no-ADRO device combinations by completing the Hearing Aid Measure of Contrast (HAMOC) questionnaire. The HAMOC questionnaire, which is a modified version of the SHAPIE (Dillon 1994) comprises 25 items (or listening situations), and asks for a preferred device combination to be noted for each item. This meant subjects were required to swap between hearing aids and select the matching ADRO or no-ADRO program on their speech processor as they encountered each listening environment listed in the HAMOC.

When the subjects returned for the evaluation session, free-field aided thresholds were measured to compare audibility with each hearing aid and the Japanese version of the Hearing in Noise Test (JHINT) (Nilsson, Soli et al. 1994) was administered to compare speech reception thresholds (SRT) for the bimodal ADRO and no-ADRO device combinations. The JHINT was administered in 4 conditions: in quiet, noise from the front, noise from the same side as the cochlear implant and noise from the same side as the hearing aid. The tests were administered twice in each condition and the test order balanced across the subjects.

The aided threshold testing revealed more variation in thresholds when subjects were using their own hearing aid compared to the ‘ADRO hearing aid’. When the thresholds were averaged across the group, it was found that the ‘ADRO hearing aid’ produced thresholds in the 500 to 2000Hz range that were 8 to 15dB lower than with the subjects own hearing aids. This improved audibility could be a direct effect of using ADRO, however, it is possible that the variation in thresholds seen with the ‘no-ADRO hearing aids’ may be a result of different fitting techniques being used by the subjects’ hearing aid providers. In comparison, the ‘ADRO hearing aids’ were all fitted by the researchers so the fitting method would be more uniform. The authors do not state if the subjects’ own hearing aids were optimized at the beginning of the study, only that
they were fitted by their hearing aid providers and that the subjects were satisfied with the fitting.

The JHINT speech reception threshold results were averaged across the group and the results for the bimodal ADRO device combination compared to the no-ADRO combination. For testing in quiet the average SRT (dB SPL) for the ADRO condition was 42.88 and for the no-ADRO condition the SRT (dB SPL) was 48.09. With noise coming from the front, the average SRT (dB SNR) was 7.86 for the ADRO condition and 10.81 for the no-ADRO condition. With the noise coming from the side of the implanted ear, the average SRT (dB SNR) was 5.62 for the ADRO condition and 8.33 for the no-ADRO condition. Finally, with the noise on the side of the hearing aid, the average SRT (dB SNR) was 2.37 for the ADRO condition and -0.29 for the no-ADRO condition. Two sample t-tests using the non-parametric Wilcoxon signed rank test showed that bimodal ADRO offered significant improvement in the SRTs for all test conditions except for when noise was presented on the side of the hearing aid. It was noted that standard deviations were quite high for the condition with noise coming from the hearing aid side, hence the difference in results not reaching significance.

The results from the HAMOC questionnaire indicated that the study’s participants rarely responded with “much better” for either the ADRO or no-ADRO combinations. They also indicated that they did not encounter 21% of the situations described in the questionnaire. Even so, participants had a preference for the bimodal ADRO combination in 77% of listening situations.

The authors concluded that, as with unimodal studies, the use of ADRO in bimodal devices could improve audibility and speech recognition and provide comfortable hearing.

1.7. Summary

Through the use of hearing aids and/or cochlear implants, people with impaired hearing are able to gain greater access to acoustic cues that assist in the recognition of speech and identification of environmental sounds. Moreover, it has been shown that it is possible for people to use a cochlear implant in one ear and a hearing aid in the
other ear and for the bimodal inputs to be successfully integrated, producing binaural listening benefits such as limited sound localization and improved speech recognition, especially in some noisy environments.

While historically hearing aids and cochlear implant sound processors have used different amplification and sound processing schemes, there is now a processing scheme that can be employed in both modern-day digital hearing aids and cochlear implant sound processors. That scheme is called Adaptive Dynamic Range Optimization (ADRO). Based around the use of fuzzy-logic rules that act independently on the outputs of multiple channels, ADRO aims to maximize the audibility and comfort of sounds for the listener, while reducing background noise and protecting against sudden loud noises.

Previous studies have shown ADRO to offer speech perception benefits for hearing aid users and cochlear implant users alike. There is limited literature to date, however, showing the effects of ADRO for people with who use both a cochlear implant in one ear and a hearing aid in the other.

The objective of the study described in the following pages is to evaluate the effects on speech perception when ADRO is implemented in both a cochlear implant speech processor and a contralaterally worn hearing aid for a group of hearing impaired adults who routinely use both devices. The more specific hypotheses of the study being:

- the implementation of ADRO in both a hearing aid and speech processor fitting would enhance speech perception compared to a bimodal fitting without ADRO;
- ADRO would have a positive effect on speech perception when only implemented unilaterally in one device; and
- adults who use both a cochlear implant and a hearing aid would perceive improvements in their hearing when using ADRO in their normal listening environments.
2. METHOD

2.1. Introduction

A prospective study was designed to examine the effects of implementing ADRO in both a cochlear implant speech processor and a hearing aid for recipients of these bimodal devices. This allowed for a number of variables such as appropriateness of speech processor Maps and hearing aid fittings, learning effects when using a new hearing aid, order effects when testing and comparing different listening conditions and acoustic parameters when conducting speech perception testing, to be controlled as much as practicable. Over the course of the study, subjects gained take-home experience using a trial ‘ADRO hearing aid’ plus ‘ADRO’ and ‘no-ADRO’ speech processor Maps (or programmes), as well as using their own ‘no-ADRO’ hearing aid plus the two different Maps. They also attended the clinic weekly so that speech perception measures could be made with the different hearing aid and speech processor combinations. Information about subjects’ preferences for using bimodal ADRO devices versus bimodal no-ADRO devices was obtained with a take-home questionnaire that the subjects completed.

2.2. Study design

The practical part of the study consisted of two phases: a device fitting and optimization phase and a speech perception testing phase. The device optimization phase consisted of 3 to 4 sessions and the testing phase consisted of 8 sessions. Sessions were typically spaced 1 week apart. The number of sessions in the device optimization phase varied slightly as some subjects needed more familiarization time and more adjustments with the ‘ADRO hearing aid’ before feeling comfortable using it for the duration of the study.

For the 8 test sessions, an ABBA test protocol was used, with order balanced across subjects. The evaluation order used for each subject was selected to be either ABBA or BAAB where:

\[
A = \text{Hearing aid without ADRO (HA-ADRO) and cochlear implant speech processor with both an ADRO Map (CI+ADRO) and no-ADRO Map (CI-ADRO).}
\]
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

B = Hearing aid with ADRO (HA+ADRO) and cochlear implant speech processor with both an ADRO Map (CI+ADRO) and no-ADRO Map (CI-ADRO).

Half the subjects followed an ABBA protocol and half followed the BAAB protocol. Each (A or B) phase consisted of two test sessions.

2.3. Test battery

The speech perception test battery consisted of CVC Words (Henry, McDermott et al. 1998) presented in quiet and Australian CUNY-like Sentences (Boothroyd, Hanin et al. 1985) presented with competing noise\(^1\). A rating questionnaire was also administered to gauge each subject’s preferred device configuration (cochlear implant with or without ADRO plus hearing aid with or without ADRO). The CVC Word test was chosen as it allowed an evaluation of whether ADRO in the different devices would have an effect on subjects’ recognition of complete words as well as the more fundamental speech elements of vowels, consonants and phonemes. The CVC Words were presented at two presentation levels, 60dB SPL(RMS) and 50dB SPL(RMS), to simulate a normal speaking level and a softer speaking level, for which ADRO was anticipated to have different effects. CUNY-like Sentences presented at a level equivalent to a strong speaking voice with competing noise were included in the battery, as listening to someone speaking in the presence of substantial background noise is a very common listening environment for most people and knowing the effect ADRO would have in this situation was, therefore, highly relevant. Also of relevance was the subjects’ feedback about the usefulness of ADRO in the hearing aid and/or the cochlear implant speech processor, hence the inclusion of a questionnaire in the study.

The study used 32 CVC Word lists; each list consisting of 50 monosyllabic words spoken by a female speaker. The word lists could be scored for the number of correct vowels, consonants, phonemes and words. All lists were phonemically balanced. The presentation order of the lists was randomized for each subject. Subjects were

\(^1\) CVC Words and Australian CUNY-like Sentence were used rather than the original CNC Words and CUNY Sentences to avoid repetition of lists for subjects. Most subjects would have been tested with CNC Words and CUNY Sentences during their clinical evaluations at the Cochlear Implant Clinic and the number of available lists was quite limited.
presented with 2 lists of CVC Words for each of the 2 listening conditions (either HA with CI+ADRO and the same HA with CI-ADRO) in each session – 1 list at 60dB SPL(RMS) and 1 list at 50dB SPL(RMS) – giving 4 lists at each presentation level for each listening condition over the course of the study. The order of administering the word lists at the two presentation levels was alternated in each session e.g. if the order in the first session was 50dB then 60dB, then in the next session a list at 60dB would be presented first then a list at 50dB. The test items were presented in the sound field from a speaker positioned directly in front of the subject and the tester transcribed the subjects’ verbal responses for later scoring. Scores were calculated by dividing the number of items repeated correctly by the total number of items presented (each list contained a total of 50 vowels, 100 consonants, 150 phonemes and 50 words).

The Australian CUNY-like Sentence lists consisted of 12 sentences spoken by a female speaker (a different speaker to that used with the CVC Words). There were 170 CUNY-like Sentence lists in total. From here on in the text, the Australian CUNY-like Sentences will be referred to as CUNY Sentences for simplicity. For this study, 30 sentence lists that had previously been identified as contributing the most variability in speech recognition scores across the lists were removed (Gorrie and Dawson 2006). A randomized selection of the remaining 140 sentence lists and competing noise were presented at an individual signal-to-noise ratio (SNR) for each subject. A SNR was sought such that each subject’s CUNY Sentence scores would not be consistently low (a floor effect) nor too high (a ceiling effect). If either of these situations occurred, we would be less likely to see changes in scores as a result of changing the hearing aid or speech processor Map. To set each subject’s SNR, the BKB-SIN Test (Etymotic Research 1993) was administered with the subject using their usual hearing aid and speech processor Map configuration. The BKB-SIN Test determined the SNR at which the subject’s recognition of BKB Sentences was 50%. As CUNY Sentences vary in length and complexity to BKB Sentences, 2 lists of CUNY Sentences were then administered at the BKB-SIN SNR to confirm that the SNR was also valid for CUNY Sentences. Depending on the CUNY Sentences scores, the SNR was adjusted and further lists administered until the CUNY Sentence score with competing noise was approximately 50%. The resultant SNR was used with the CUNY Sentences for that subject for all
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

Further test sessions. The presentation level used with both the BKB-SIN Test and CUNY Sentences was 65dB SPL(RMS) and the competing noise was four-talker babble (Auditec of St. Louis 1971). For each subject, 2 lists of CUNY Sentences were presented with four-talker babble set at the pre-determined SNR for each of the 2 listening conditions (HA±ADRO with CI+ADRO and HA±ADRO with CI-ADRO) in all further test sessions – giving 8 lists for each listening condition over the course of the study. Both the sentences and competing noise were presented from the same speaker positioned directly in front of the subject and the tester transcribed the subjects’ verbal responses for later scoring. Scores were calculated by dividing the number of words repeated correctly by the total number of words presented (2 lists each containing 102 words were presented, giving 204 words in total).

In addition to the more objective speech perception measures, subjects were asked to provide subjective feedback about the effectiveness of the hearing aid and cochlear implant Map combinations via a questionnaire, which they completed at home. The questionnaire asked subjects to compare the effectiveness of two bimodal device combinations: 1. hearing aid and cochlear implant both without ADRO and 2. hearing aid and cochlear implant both with ADRO, in 10 listening environments:

1. conversing in a quiet room,
2. conversing while travelling in a car,
3. conversing in a shopping centre,
4. conversing with 3-4 people in a restaurant,
5. watching TV,
6. group discussion in a quiet room,
7. conversation with continuous background noise,
8. listening to music,
9. clarity and naturalness of voices and
10. recognizing environmental sounds.

The questions were formulated such that the subject indicated the effectiveness of the bimodal device combinations on a rating scale between 1 and 10, where 1 = “can’t understand” and 10 = “understand completely” (see Appendix 1) for an example of the
questionnaire). The questionnaire also contained four questions that asked the subject to nominate:

1. their preferred Map when using each hearing aid,
2. their preferred hearing aid when listening in quiet environments,
3. their preferred hearing aid when listening in noisy environments and
4. their preferred hearing aid when listening to music.

Two versions of the patient questionnaire were produced – one for subjects who had the ADRO Map written into the first memory location of their speech processor (P1) and another for subjects who had the ADRO Map written into P2. The questionnaire was given to subjects at the half-way point in the testing phase of the trial. Subjects were asked to take the questionnaire home and consider the listening situations and questions posed in the questionnaire during the final 4 weeks in the trial, during which time they had 2 more weeks of experience with the hearing aid with ADRO and 2 weeks with the hearing aid without ADRO. If they did not experience any of the listening situations listed in the questionnaire, they had the option of indicating “not applicable”. Subjects were asked to return the questionnaire at the end of the trial.

To avoid possibly biasing the subjects’ responses on the questionnaires, no feedback about their relative performance on the speech recognition tests with the different hearing aid and Map combinations was provided in the test sessions.

2.4. Test set-up

All speech perception testing was performed inside a sound treated booth. The speech perception materials (CVC Words, CUNY Sentences and competing noise) had previously been recorded and saved as WAV files on a personal computer situated in the booth. A custom designed software program (written by William Kentler) was used to access and present the WAV files via an external sound card and an active speaker (Genelec 8020B) which was positioned directly in front of the subjects (0° azimuth). The custom software allowed the tester to choose the desired speech perception material list as well as control the presentation level in 1dB steps. Speech materials and competing noise materials could be presented at the same time from
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

the speaker with the tester being able to independently control the materials’ presentation levels. The sound field environment was calibrated using a third-octave noise centred at 1kHz with an RMS level set to 10 dB above that of the speech materials, to ensure the subjects would be listening to the speech perception materials at the appropriate sound levels.

2.5. Session outline

2.5.1. Device fitting and optimization - Session 1

At the initial session, the benefits and risks of the study were explained to the subjects and their consent to participate in the trial of a different hearing aid, different speech processor Maps and subsequent test sessions, was obtained. If subjects did not have an audiogram on file that was more recent than 6 months old, then a pure-tone audiogram was obtained under sound treated conditions. Next, the ‘ADRO hearing aid’, an Interton Bionic BigNano prototype hearing aid was fitted using custom built ADROfit (Dynamic Hearing 2006) fitting software. The ‘ADRO hearing aid’ was attached to the subject’s own ear mould to eliminate ear-mould acoustics as a variable. Once the subjects’ hearing aid settings were comfortable for normal speech input and the volumes of the ‘ADRO hearing aid’ and their cochlear implant were equivalent, they were asked to take the ‘ADRO hearing aid’ home to try for a week.

2.5.2. Device fitting and optimization - Sessions 2 - 3

Over the course of the next 1 to 2 device optimization sessions, all subjects requested at least minor adjustments to the gain or frequency response of the ‘ADRO hearing aid’ before agreeing that the hearing aid provided acceptable audibility and comfort for sounds encountered in their regular environments.

In addition to optimizing the fitting of the ‘ADRO hearing aid’, the fitting sessions were also used to verify the subjects’ own hearing aid (and ear-mould) was fitted appropriately for their current hearing thresholds and to set up the ‘ADRO’ and ‘no-ADRO’ Maps for their cochlear implant speech processor. Verification of each subject’s own hearing aid function and fitting was done by obtaining coupler gain and real-ear gain measures (using Noah audiometric software and Aurical hearing aid analyser) and
comparing to the NAL-NL1 (Dillon 1999) prescribed target gains that were based upon the recently obtained hearing thresholds. If the real-ear gain curve deviated from the NAL-NL1 target by more than 5dB or if the subject reported there had been a deterioration in hearing clarity since they last had their hearing aid adjusted, then it was suggested that they have their hearing aid fitting reviewed by their hearing aid provider before continuing in the study. Similarly, each subject’s speech processor Map was reviewed (using Nucleus® Custom Sound programming software) if it was more than 6 months since their cochlear implant Map had been checked or if the subject felt they weren’t hearing as well as usual with their cochlear implant. Having established the subject had an appropriate Map, one Map (or programme\textsuperscript{2}) was created without activating ADRO and another Map was created with ADRO activated. All other Custom Sound “SmartSound” pre-processing options, e.g. auto-sensitivity control (ASC), super directional microphone option (Beam) and non-linear compression (Whisper), were disabled for the two test Maps. The subject was asked to rate the loudness of both Maps and, if need be, global modifications to one of the Map’s “C-levels” (the maximum current levels output by the cochlear implant and, therefore, the main determinant of overall volume of the cochlear implant) were applied such that both Maps were comfortable and of equal volume. Both Maps were written into the subject’s speech processor for them to take home and try for one week. Subjects were not told which memory location in their speech processor (P1 or P2) contained the ‘ADRO Map’. At the next session, subjects were asked if they needed further adjustment to their Maps but no subject required any further modifications.

The final device optimization procedure was the balancing of loudness between the two hearing aids that each subject would be using throughout the study. Subjects were asked to remove their cochlear implant speech processor and initially just wear

\textsuperscript{2} During the course of the study, an up-dated version of Custom Sound was installed on the programming computers, resulting in the application of “Smart Sound” options (including ADRO) creating a “programme” and not a “Map” as was previously the case. This meant that some subjects were using different “Maps” for the ADRO and no-ADRO options while more recently recruited subjects were using different “programmes”. For consistency, the term “Map” will be used from here on.
their own hearing aid with the volume set to its usual level. They were then asked to judge the volume of multi-talker babble presented at 55dB SPL (a sound level easily audible but which should not activate any form of gain limiting in the hearing aids) from a speaker positioned directly in front of them. Their hearing aid was then swapped with the ‘ADRO hearing aid’ and a judgement again made about the volume of the multi-talker babble. The subjects could swap between hearing aids a number of times until they could make a judgement about the relative volume of the two hearing aids. The tester would then make small adjustments to the manual volume control on the ‘ADRO hearing aid’ until the subject could not perceive any difference in volume with the two hearing aids. In the case of two subjects, the difference in volume between the hearing aids was so great that the ‘ADRO hearing aid’ needed to be reprogrammed before returning to the loudness balancing procedure. The tester noted the final volume setting of the ‘ADRO hearing aid’ and that setting was used in the following test sessions.

Once the settings of both hearing aids had been optimized and the ADRO and no-ADRO Maps written into the cochlear implant speech processor, subjects were taken to the speech perception test booth to determine the signal-to-noise ratio that would be used in the test sessions. As described earlier, this was done using the BKB-SIN Test and confirmed with some test lists of CUNY Sentences.

At the end of the final device optimization session, each subject took home both Maps (CI-ADRO and CI+ADRO) in their speech processor and either the hearing aid without ADRO (HA-ADRO) if they were following the ABBA test protocol, or the hearing aid with ADRO (HA+ADRO) if they were following the BAAB test protocol.

2.5.3. **Speech perception testing - Sessions 1 - 2**

Each test session commenced by checking that the subjects felt both the hearing aid and cochlear implant were functioning properly and a visual check that the volume settings were appropriate for both devices. The CVC Words and CUNY Sentence tests were then administered as described previously, first with one Map then the other:

- If a subject was following the ABBA protocol then in the first session, the HA-ADRO with CI-ADRO condition would be tested first, followed by the HA-ADRO
with CI+ADRO condition. In the second session, the order that the Maps were tested was reversed: HA-ADRO with CI+ADRO would be tested first, followed by the HA-ADRO with CI-ADRO condition.

- If a subject was following the BAAB protocol then the HA+ADRO with CI+ADRO condition would be tested first, followed by the HA+ADRO with CI-ADRO condition. In the second session, the order that the Maps were tested was reversed: HA+ADRO with CI-ADRO would be tested first, followed by the HA+ADRO with CI+ADRO condition.

The presentation level of the CVC Words was alternated between sessions, such that if the words were initially administered at 50dB SPL in the first session, they would be administered at 60dB SPL initially in the second session.

Subjects continued to use the same hearing aid after the first session. At the end of the second session the hearing aid was swapped and subjects took the different hearing aid home to get accustomed to using it in different listening environments for a period of 1 week.

2.5.4. Speech perception testing - Sessions 3 - 6

Each test session commenced by checking that subjects felt both the hearing aid and cochlear implant were functioning properly and a visual check that the volume settings were appropriate for both devices. The CVC Words and CUNY Sentence tests were then administered, first with one Map then the other:

- If a subject was following the ABBA protocol then they would now be using the HA+ADRO and would alternate between the CI+ADRO and CI-ADRO Maps in sessions 3 through 6.

- If a subject was following the BAAB protocol then they would now be using the HA-ADRO and would alternate between the CI-ADRO and CI+ADRO Maps in sessions 3 through 6.

The presentation level of the CVC Words was still alternated between sessions, such that if the words were initially administered at 50dB SPL in one session, they would be administered at 60dB SPL for the first list in the next session.
Subjects continued to use the same hearing aid for sessions 3 to 5. At the end of the 6th session, the hearing aid was again swapped and subjects took the different hearing aid home to use in different listening environments for a period of 1 week.

Subjects were presented with the questionnaire at the end of session 4 and took it home after being given some guidance on how to interpret the questions. It was suggested that subjects consider rating their hearing abilities for all listening situations outlined in the questionnaire before Session 6 and then repeat the exercise once they had changed to the other hearing aid at the end of Session 6. That way, they would have 2 weeks in which to listen with and rate the bimodal ADRO device combination and another 2 weeks to rate the bimodal no-ADRO device combination.

### 2.5.5. Speech perception testing - Sessions 7 - 8

Once again, each test session commenced by checking that subjects felt both the hearing aid and cochlear implant were functioning properly and a visual check that the volume settings were appropriate for both devices. The CVC Words and CUNY Sentence tests were then administered, first with one Map then the other:

- If a subject was following the ABBA protocol then they would now be using the HA-ADRO and would alternate between the CI+ADRO and CI-ADRO Maps in sessions 7 and 8.
- If a subject was following the BAAB protocol then they would now be using the HA+ADRO and would alternate between the CI-ADRO and CI+ADRO Maps in sessions 7 and 8.

The presentation level of the CVC Words was again alternated between sessions.

Subjects returned their completed questionnaire at the end of session 8 along with the ‘ADRO hearing aid’.

An outline of each session’s structure and activities is presented in the form of a flow chart in Figure 10 on the following pages.
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

**FITTING & OPTIMIZATION SESSION 1** (Week 1)
- Obtain audiogram if required
- Fit HA+ADRO
- Subject takes home HA+ADRO to trial for 1 week with current CI Map

↓

**FITTING & OPTIMIZATION SESSION 2-3** (Week 2-3)
- Adjust HA+ADRO if necessary
- Evaluate/optimize HA-ADRO
- Create Maps with and without ADRO
- Establish S/N for CUNYs
- Subject takes home HA-ADRO or HA+ADRO and both CI Maps

↓

**TEST SESSION 1** (Week 4)
- Evaluate either HA-ADRO or HA+ADRO with both CI Maps
- Subject again takes home HA-ADRO or HA+ADRO and both CI Maps

↓

**TEST SESSION 2** (Week 5)
- Evaluate same HA with both CI Maps
- Subject changes to HA+ADRO or HA-ADRO

↓

**TEST SESSION 3** (Week 6)
- Evaluate either HA+ADRO or HA-ADRO with both CI Maps
- Subject takes home same HA and both CI Maps

↓

**TEST SESSION 4** (Week 7)
- Evaluate same HA with both Maps
- Subject takes home same HA and both CI Maps
- Give subject questionnaire to take home
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

### TEST SESSION 5
**(Week 8)**
- Evaluate same HA with both CI Maps
- Subject takes home same HA and both CI Maps

### TEST SESSION 6
**(Week 9)**
- Evaluate either HA+ADRO or HA-ADRO with both CI Maps
- Subject changes to HA-ADRO or HA+ADRO

### TEST SESSION 7
**(Week 10)**
- Evaluate either HA-ADRO or HA+ADRO with both CI Maps
- Subject takes home same HA and both CI Maps

### TEST SESSION 8
**(Week 11)**
- Evaluate same HA with both CI Maps
- Subject returns questionnaire
- Subject returns HA+ADRO

Figure 10. Outline of session goals for this study.

### 2.6. Subject selection criteria

Subjects were recruited from the Cochlear Implant Clinic at the Royal Victorian Eye & Ear Hospital. The criteria for considering the subjects suitable for the study were:

- They were adults of 18 years of age or older.
- They had a minimum of 3 months experience using the *Nucleus Freedom* cochlear implant system, comprising of the *Nucleus CI24RE(CA)* implant and *Freedom* speech processor.
- They routinely wore a hearing aid in the ear contralateral to the cochlear implant.
- They had a sensorineural hearing loss with the onset being post-lingual.
- They were willing to participate in and comply with all investigational requirements of the study.
English was their primary language.

A total of 17 subjects who met the above criteria commenced the study, however, 3 were unable to complete the study due to personal or medical reasons. Subjects were reimbursed for their travel expenses to and from the test sessions.

2.7. Subject demographics

As can be seen in Table 1 below, the 14 adult subjects who completed the study had experienced a severe hearing loss or worse in the ear implanted for an average of 18 years, with the range being from 2 to 60 years. For 7 subjects, the cause of their hearing loss was unknown, while 2 had been diagnosed with otosclerosis, 2 had a family history of hearing loss (familial), 1 subject had a long history of chronic otitis media (COM), 1 reported both a history of familial hearing loss and chronic otitis media and 1 subject’s hearing loss was related to excessive noise exposure and ototoxicity. The group had on average 14 months experience using a cochlear implant, ranging from 6 to 28 months.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Aetiology</th>
<th>Duration of severe hg. loss (yrs)</th>
<th>4FPTA (dBHL)</th>
<th>Age at implant (yrs)</th>
<th>Ear implanted</th>
<th>Experience with CI (mths)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>unknown</td>
<td>5</td>
<td>79</td>
<td>67</td>
<td>right</td>
<td>12</td>
</tr>
<tr>
<td>S2</td>
<td>unknown</td>
<td>6</td>
<td>98</td>
<td>81</td>
<td>left</td>
<td>13</td>
</tr>
<tr>
<td>S3</td>
<td>familial</td>
<td>20</td>
<td>93</td>
<td>66</td>
<td>right</td>
<td>21</td>
</tr>
<tr>
<td>S4</td>
<td>otosclerosis</td>
<td>20</td>
<td>64</td>
<td>70</td>
<td>left</td>
<td>28</td>
</tr>
<tr>
<td>S5</td>
<td>familial</td>
<td>5</td>
<td>69</td>
<td>64</td>
<td>right</td>
<td>8</td>
</tr>
<tr>
<td>S6</td>
<td>unknown</td>
<td>3</td>
<td>96</td>
<td>82</td>
<td>right</td>
<td>14</td>
</tr>
<tr>
<td>S7</td>
<td>noise/ototox.</td>
<td>20</td>
<td>80</td>
<td>75</td>
<td>right</td>
<td>22</td>
</tr>
<tr>
<td>S8</td>
<td>otosclerosis</td>
<td>15</td>
<td>88</td>
<td>56</td>
<td>left</td>
<td>12</td>
</tr>
<tr>
<td>S9</td>
<td>COM/familial</td>
<td>2</td>
<td>88</td>
<td>76</td>
<td>right</td>
<td>6</td>
</tr>
<tr>
<td>S10</td>
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<td>20</td>
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<td>62</td>
<td>right</td>
<td>15</td>
</tr>
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<td>S11</td>
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<td>7</td>
</tr>
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<td>93</td>
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<td>left</td>
<td>10</td>
</tr>
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<td>60</td>
<td>80</td>
<td>68</td>
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<td>47</td>
<td>89</td>
<td>73</td>
<td>right</td>
<td>20</td>
</tr>
</tbody>
</table>

Note: COM = chronic otitis media; ototox. = ototoxicity

*Table 1. Demographic & audiometric data for subjects.*
The audiometric data for the ears in which the subjects used a hearing aid showed the 4 frequency pure tone averages (4FPTA) to range from 64 to 98dB HL, with the mean being 84dB HL. The hearing thresholds for the subjects are illustrated on the combined audiogram in Figure 11 below.

![Figure 11. Subject audiograms for ears in which hearing aids were used.](image-url)

All 14 subjects had been implanted with a Nucleus Freedom CI24RE(CA) implant and were using a Freedom speech processor. The ACE speech processing strategy, which is the default processing strategy in the Freedom cochlear implant system, was used by 12 of the subjects. The remaining 2 subjects used a research processing strategy called MP3\(^{000}\) (Noguiera, Büchner et al. 2005). These subjects had previously been a part of a trial which had investigated the usefulness of the MP3\(^{000}\) strategy in its different forms. At the end of that trial, these 2 subjects had chosen to continue using MP3\(^{000}\) rather than return to the ACE processing strategy. The use of a different processing strategy in this study was not deemed to be of concern as MP3\(^{000}\) was the strategy with which the 2 subjects were familiar and as ADRO is a pre-processing algorithm it would be applied to the acoustic input of the speech processor prior to either ACE or MP3\(^{000}\) taking effect. The subjects all used the same amplitude mapping functions, such that they had an instantaneous input dynamic range of 40dB (T-SPL = 25dB and C-SPL =...
65dB), their loudness growth function was set to ‘20’ and they all used their sound processors on sensitivity ‘12’.

All of the group were using up-to-date digital hearing aids in the ears contralateral to their cochlear implants. These hearing aids utilized wide dynamic range compression (WDRC) algorithms in order to control the gain applied to the acoustic input and therefore the resultant output. The number of channels offered by the hearing aids ranged from 2 to 20 channels, with 6 channels being the most commonly used; by 5 out of the 14 subjects.

The signal-to-noise (S/N) ratios used to mix the CUNY Sentences and competing noise ranged from +5 to +18dB, with the average being +10dB. These individual signal-to-noise ratios were determined to ensure the CUNY Sentence scores would neither be too low nor too high; the aim being to maximize the test sensitivity.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Processing strategy</th>
<th>Rate/channel (pps)</th>
<th>Processor sensitivity</th>
<th>Location of ADRO Map</th>
<th>Own hearing aid model</th>
<th>No. of chan.</th>
<th>Test order</th>
<th>S/N (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>ACE</td>
<td>720</td>
<td>12</td>
<td>P1</td>
<td>Siemens Music Pro</td>
<td>2</td>
<td>ABBA</td>
<td>+9</td>
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<tr>
<td>S2</td>
<td>ACE</td>
<td>720</td>
<td>12</td>
<td>P1</td>
<td>Siemens Music Pro</td>
<td>2</td>
<td>BAAB</td>
<td>+13</td>
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<td>ACE</td>
<td>900</td>
<td>12</td>
<td>P2</td>
<td>GN Resound Canta</td>
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<td>BAAB</td>
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<td>P1</td>
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<td>ABBA</td>
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<tr>
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<td>Phonak Eliva</td>
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<td>12</td>
<td>P2</td>
<td>Siemens Cielo</td>
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<td>BAAB</td>
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<td>P1</td>
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<td>P1</td>
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<td>900</td>
<td>12</td>
<td>P2</td>
<td>Phonak Savia</td>
<td>20</td>
<td>ABBA</td>
<td>+12</td>
</tr>
<tr>
<td>S11</td>
<td>ACE</td>
<td>900</td>
<td>12</td>
<td>P1</td>
<td>Siemens Artis</td>
<td>12</td>
<td>BAAB</td>
<td>+10</td>
</tr>
<tr>
<td>S12</td>
<td>ACE</td>
<td>900</td>
<td>12</td>
<td>P1</td>
<td>Siemens Motion</td>
<td>6</td>
<td>ABBA</td>
<td>+18</td>
</tr>
<tr>
<td>S13</td>
<td>ACE</td>
<td>900</td>
<td>12</td>
<td>P1</td>
<td>Siemens Intuis</td>
<td>4</td>
<td>BAAB</td>
<td>+8</td>
</tr>
<tr>
<td>S14</td>
<td>ACE</td>
<td>900</td>
<td>12</td>
<td>P2</td>
<td>Unitron Unison</td>
<td>6</td>
<td>ABBA</td>
<td>+11</td>
</tr>
</tbody>
</table>

Table 2. Cochlear implant and hearing aid data for subjects. All subjects used the Nucleus Freedom cochlear implant and speech processor system.
2.8. Summary

A group of 14 adult subjects who used a cochlear implant in one ear and a hearing aid in the other (bimodal devices) completed this study. After having the adjustment of their cochlear implant, own hearing aid and an ‘ADRO hearing aid’ optimized for their current hearing needs, the subjects participated in 8 speech perception testing sessions. In each test session, speech perception measures were performed with the subject using either their own hearing aid or the ‘ADRO hearing aid’ in conjunction with their cochlear implant. There were 2 bimodal listening conditions tested in each session; one involved the use of an ‘ADRO Map’ in the cochlear implant and the other was with a ‘no-ADRO Map’. The speech perception materials that were administered were CVC Words (presented at both 50dB SPL and 60dB SPL) and CUNY Sentences (presented at 65dB SPL in competing noise at an individual signal-to-noise ratio). Subjects were tested with both hearing aids in the course of the study, using a balanced order protocol for each subject and across the group; half the group commenced with their own hearing aid (ABBA protocol) and half commenced with the ‘ADRO hearing aid’ (BAAB protocol). In addition to collecting speech perception data with the different ADRO combinations in the devices, data about subjects’ preferences for the device combinations was sought through the administration of a questionnaire.
3. RESULTS
3.1. Introduction

Sentence and word recognition scores were obtained for 14 subjects in each of the following 4 hearing aid and cochlear implant combinations: 1. “no ADRO” (HA-ADRO with CI-ADRO), 2. “HA ADRO” (HA+ADRO with CI-ADRO), 3. “CI ADRO” (HA-ADRO with CI+ADRO), and 4. “both ADRO” (HA+ADRO with CI+ADRO). During the course of the study, each subject was tested with each of these 4 device combinations on 4 separate occasions. Scores from the CVC Word lists (vowel, consonant, phoneme and word scores) and CUNY Sentence lists administered in the 4 separate sessions were collated and mean scores calculated for each device combination for each subject as well as for the group. Comparisons of means were examined for the effects of implementing ADRO in the hearing aid and/or the cochlear implant speech processor.

The subjects’ preference data from the questionnaires was tabulated and examined for any relationship with the speech perception scores.

3.2. Speech perception test results
3.2.1. CVC Words

The group mean percentage scores for CVC Word lists presented at 50dB SPL are illustrated in Figure 12 and tabulated in Table 3. Balanced, repeated measures, analyses of variance were performed to account for the effects of different subjects’ speech perception ability, the type of hearing aid (HA+ADRO vs. HA-ADRO) and cochlear implant Map (CI+ADRO vs. CI-ADRO) on the vowel, consonant, phoneme and words scores obtained from presenting CVC Words at 50dB SPL. There was a significant effect of subject across all measures (for vowels (F=23.66, p<0.001), consonants (F=41.68, p<0.001), phonemes (F=38.39, p<0.001) and words (F=40.23, p<0.001)). Of more interest were the effects of the hearing aid and Map. For all measures, there was a significant effect of Map (for vowels (F=19.85, p<0.001), consonants (F=53.31, p<0.001), phonemes (F=52.66, p<0.001) and words (F=43.52, p<0.001)). There was a significant effect of hearing aid on the phoneme scores (F=4.31, p=0.039), but not on the other measures (for vowels (F=2.55, p=0.112), consonants (F=3.73, p=0.055) and words (F=3.14, p=0.078)). There was no significant interaction
between the variables for any of the measures. More detailed data relating to the analysis of variance for speech perception scores can be found in Appendix 3.

Comparisons of each device combination (and therefore, listening condition) were made using a one way ANOVA with Tukey post-hoc comparisons. The means and standard deviations for the ‘no ADRO’, ‘HA ADRO’, ‘CI ADRO’ and ‘both ADRO’ combinations are set out in Table 3.

All pairwise comparisons were made using Tukey 95% simultaneous confidence intervals which resulted in individual confidence levels of 98.97%. At these confidence levels, there were significant differences between listening conditions observed for all measures. For vowels, the mean scores obtained in the ‘both ADRO’ condition were significantly higher (F=3.23, p=0.023) than the mean scores for the ‘no ADRO’ condition. For consonants (F=5.59, p=0.001) and phonemes (F=5.94, p=0.001), the mean scores obtained in the ‘both ADRO’ condition were significantly higher than the

![Figure 12. Group mean percentage scores for CVC Words presented at 50dB SPL. The interval plots represent the 95% confidence intervals for the mean scores. The p-values represent the probability that mean scores are not significantly different. In this analysis, differences in mean scores with \( p < 0.05 \) are considered to be significantly different.]
mean scores for the ‘HA ADRO’ and ‘no ADRO’ conditions and the mean scores obtained in the ‘CI ADRO’ condition were significantly higher than the mean scores for the ‘no ADRO’ condition. In the case of the word scores, the mean score obtained in the ‘both ADRO’ condition was significantly higher ($F=4.70$, $p=0.003$) than the means for the ‘HA ADRO’ and ‘no ADRO’ conditions.

<table>
<thead>
<tr>
<th>CVC Words at 50dB</th>
<th>no-ADRO</th>
<th>HA ADRO</th>
<th>CI ADRO</th>
<th>both ADRO</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Mean</td>
<td>StDev</td>
<td>Mean</td>
<td>StDev</td>
</tr>
<tr>
<td>Vowels</td>
<td>56</td>
<td>67.04</td>
<td>67.79</td>
<td>70.79</td>
</tr>
<tr>
<td>Consonants</td>
<td>56</td>
<td>53.38</td>
<td>13.94</td>
<td>55.00</td>
</tr>
<tr>
<td>Phonemes</td>
<td>56</td>
<td>57.71</td>
<td>12.75</td>
<td>59.19</td>
</tr>
<tr>
<td>Words</td>
<td>56</td>
<td>31.75</td>
<td>14.76</td>
<td>33.36</td>
</tr>
</tbody>
</table>

Table 3. Group mean percentage scores and standard deviations for CVC Words presented at 50dB SPL.

The scores from the CVC Word lists presented at 60dB SPL were examined in the same way. The group mean percentage scores for this test are illustrated in Figure 13 and tabulated in Table 4. An analysis of variance using the Balanced ANOVA once again showed a significant effect of subject across all measures (for vowels ($F=54.98$, $p<0.001$), consonants ($F=54.44$, $p<0.001$), phonemes ($F=65.04$, $p<0.001$) and words ($F=60.45$, $p<0.001$)). More importantly, for all measures there was a significant effect of Map (for vowels ($F=14.55$, $p<0.001$), consonants ($F=11.51$, $p<0.005$), phonemes ($F=16.54$, $p<0.001$) and words ($F=25.00$, $p<0.001$)). With the words presented at the higher volume, there was also a significant effect of hearing aid on the consonant ($F=14.13$, $p<0.001$), phoneme ($F=11.93$, $p<0.005$) and word ($F=13.48$, $p<0.001$) scores but not on the vowel scores ($F=2.41$, $p=0.122$). There was no significant interaction between the variables for any of the measures. Again, refer to Appendix 3 for more detailed data relating to the analysis of variance for speech perception scores.

Comparisons of each device combination (and therefore, listening condition) were again made using Tukey post-hoc comparisons. The means and standard deviations for the ‘no ADRO’, ‘HA ADRO’, ‘CI ADRO’ and ‘both ADRO’ combinations are set out in Table 4.
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

**Figure 13.** Group mean percentage scores for CVC Words presented at 60dB SPL. The interval plots represent the 95% confidence intervals for the mean scores. The p-values represent the probability that mean scores are not significantly different. In this analysis, differences in mean scores with p<0.05 are considered to be significantly different.

**Table 4.** Group mean percentage scores and standard deviations for CVC Words presented at 60dB SPL.

All pairwise comparisons were made using Tukey 95% simultaneous confidence intervals which resulted in individual confidence levels of 98.97%. At these confidence levels, the only significant difference between any of the means was for the word scores (F=2.84, p=0.039), with the mean score obtained in the ‘both ADRO’ condition being significantly higher than the mean score for the ‘no ADRO’ condition.
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

### 3.2.2. CUNY Sentences

The group mean percentage scores for CUNY Sentences in competing noise are illustrated in Figure 14 and tabulated in Table 5. An analysis of variance using the Balanced ANOVA indicated a significant effect of subject (F=28.63, p<0.001) but not of the Map (F=0.06, p=0.807) nor hearing aid (F=1.95, p=0.164). Again, there was no significant interaction between the variables for any of the measures. More detailed data relating to the analysis of variance for speech perception scores is tabulated in Appendix 3.

![CUNY Sentences](image)

**Figure 14.** Group mean percentage scores for CUNY Sentences presented at 65dB SPL with competing 4-talker babble. Interval plot indicating 95% confidence intervals for mean scores.

Comparisons of each device combination (and therefore, listening condition) were once again made using Tukey post-hoc comparisons. The means and standard deviations for the ‘no ADRO’, ‘HA ADRO’, CI ADRO’ and ‘both ADRO’ combinations are set out in Table 5.

<table>
<thead>
<tr>
<th>CUNY Sentences</th>
<th>no-ADRO</th>
<th>HA ADRO</th>
<th>CI ADRO</th>
<th>both ADRO</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Mean</td>
<td>StDev</td>
<td>Mean</td>
<td>StDev</td>
</tr>
<tr>
<td>Sentences</td>
<td>56</td>
<td>53.69</td>
<td>13.40</td>
<td>52.63</td>
</tr>
</tbody>
</table>

**Table 5.** Group mean percentage scores and standard deviations for CUNY Sentences presented at 65dB SPL with competing 4-talker babble.
All pairwise comparisons were made using Tukey 95% simultaneous confidence intervals which resulted in individual confidence levels of 98.97%. At these confidence levels, there were no significant differences between any of the means for any of the device combinations.

3.2.3. **Speech perception for individual subjects**

It is worth noting that if we consider the speech perception scores for each individual subject (see Appendix 2 for a graphical representation of each subject’s results), that the ‘both ADRO’ device combination gave a significantly higher mean score than the other device combinations (no ADRO, HA ADRO or CI ADRO) on at least one speech perception measure for 4 (29%) of the subjects (S8, S9, S10 and S12). There were 3 (21%) subjects (S6, S7 and S11) who obtained their greatest advantage in the ‘CI ADRO’ condition, 2 (14%) subjects (S3 and S5) who showed an advantage in both the ‘CI ADRO’ and ‘both ADRO’ conditions, 1 (7%) subject (S13) who showed an advantage in both the ‘HA ADRO’ and ‘both ADRO’ conditions while the remaining 4 (29%) subjects (S1, S2, S4 and S14) obtained no significant differences in scores with any of the device combinations. No subject performed best in the no-ADRO condition.

One subject, S13, performed considerably better on the CNC Word tests when using the ADRO hearing aid compared to her own hearing aid. The sentence scores were not influenced by the ADRO hearing aid in the same way as the word scores. To establish, however, if this subject had skewed the results, one-way ANOVA pairwise comparisons were made with this subject’s data removed from the data set. This analysis of the data indicated the remaining group of 13 subjects still performed significantly better in the ‘both ADRO’ condition with CNC Words presented at 50dB based upon the word (p=0.002), phoneme (p<0.001) and consonant (p=0.001) scores, however, the difference in the vowel scores was no longer significant. For the CNC Words presented at 60dB, the group mean word scores that had previously been higher in the ‘both ADRO’ condition, was not statistically significant (p=0.072) from the ‘no ADRO’ condition once S13’s scores were removed.
3.2.4. **Predictive factors for differences between test conditions**

A stepwise regression analysis was performed to determine if the variables of duration of severe-profound deafness (duration of HL), age at implantation (age), length of experience with cochlear implant (CI experience), degree of hearing loss in non-implanted ear (pure tone average (PTA)), or cochlear implant stimulation pulse rate (pulse rate), accounted for any of the variance in the differences between the ‘both ADRO’ and ‘no ADRO’ scores on the CVC word and CUNY sentence tests.

A longer duration of severe-to-profound deafness was a significant predictor of greater differences between the ‘both ADRO’ and ‘no ADRO’ conditions for the CVC words presented at 50dB for the phoneme ($r^2(\text{adj})=37.03$, $p=0.012$), vowel ($r^2(\text{adj})=29.60$, $p=0.026$) and consonant scores ($r^2(\text{adj})=40.60$, $p=0.008$), but not the word scores ($r^2(\text{adj})=11.73$, $p=0.124$). For the CVC words presented at 60dB, duration of deafness was again a significant predictor of differences in scores, this time for the word ($r^2(\text{adj})=69.65$, $p<0.001$), phoneme ($r^2(\text{adj})=39.01$, $p=0.010$) and consonant scores ($r^2(\text{adj})=38.41$, $p=0.011$). Variance in the differences in phoneme scores was also influenced by the subjects’ length of experience with their cochlear implant ($r^2(\text{adj})=54.63$, $p=0.045$), with less experience leading to greater differences. The cochlear implant stimulation rate appeared to be a predictor of differences in the 60dB vowel scores ($r^2(\text{adj})=55.84$, $p=0.001$), with higher rates relating to greater differences. Subjects’ age at implantation or degree of hearing loss in their non-implanted ear, did not account for any significant variance in differences in any of the speech perception scores.

3.2.5. **Subject preference questionnaire**

The subjects’ responses to the questionnaire are tabulated in Table 6 and Table 7. For each of the 10 listening environments described in the questionnaire, the 14 subjects were asked to rate their speech recognition ability on a scale of 1 to 10 for 2 device combinations: 1. when using the ‘ADRO hearing aid’ combined with an ‘ADRO Map’ in their speech processor (the ‘both ADRO’ combination) and 2. when using their own hearing aid combined with a ‘no-ADRO Map’ (the ‘no ADRO’ combination). The ratings for each listening environment were totalled for the group, giving a group rating out of
a possible 130 for each device combination. The mean rating for each listening situation was also calculated for comparison. Subject S10 was the only person who did not give ratings for all listening environments. The ratings that S10 did offer were still included in the final tally.

In 5 (50%) of the 10 environments the total ratings were very similar for both the ‘both ADRO’ and ‘no ADRO’ conditions: speaking to a familiar person in a shopping centre (both ADRO = 78, no ADRO = 82), speaking with 3 – 4 friends in a restaurant (both ADRO = 67, no ADRO = 70), watching TV (both ADRO = 79, no ADRO = 80), conversing with a small group in a quiet room (both ADRO = 87, no ADRO = 90) and recognizing environmental sounds (both ADRO = 102, no ADRO = 104). In the other 5 (50%) listening environments, the group rated the ‘no ADRO’ condition higher than the ‘both ADRO’ condition: speaking with a familiar person in a quiet room (both ADRO = 111, no ADRO = 120), while driving in a car (both ADRO = 82, no ADRO = 97), listening with a continuous background noise present (both ADRO = 70, no ADRO = 76), music clarity (both ADRO = 69, no ADRO = 75), and clarity and naturalness of people’s voices (both ADRO = 95, no ADRO = 104). Parametric statistical analyses are not usually appropriate for establishing the significance of questionnaire results, however, in this case the rating responses were from a continuous scale (between 1 and 10) and each subject was making the same comparison of ‘both ADRO’ and ‘no ADRO’ device combinations in the same 10 listening conditions, so a paired t-test was used to determine if the speech recognition ratings for each device combination were significantly different. The results from the t-test analysis indicated that it was only when listening to a familiar person in a car (p=0.01) and rating the clarity and naturalness of people’s voices (p=0.01) that the ratings for ‘both ADRO’ and ‘no ADRO’ devices were significantly different. In both of these situations, the ‘no ADRO’ device combination was rated more highly.

Four (29%) of the subjects (S5, S9, S12 and S14) rated ease of listening significantly higher (p=0.04, p<0.001, p<0.001 and p=0.001 respectively) across the listening environments with ‘no ADRO’. The ratings given by the remaining 10 subjects (71%) did not indicate a significant difference between the ‘both ADRO’ and ‘no ADRO’ device combinations according to a paired t-test analysis. The mean ratings for the
group across all listening environments were 6.7 for ‘no ADRO’ and 6.2 for ‘both ADRO’, with the difference being 7% between the 2 device combinations. This difference was interpreted to not be statistically significant (p=0.051).

It is interesting to note that of the 9 subjects who obtained some measured speech perception benefit from the ‘both ADRO’ combination (S3, S5, S7, S8, S9, S10, S11, S12 and S13), 3 subjects (S5, S9 and S12) rated their listening performance in the 10 listening environments to be lower in the ‘both ADRO’ condition, while 6 subjects (S3, S7, S8, S10, S11 and S13) gave equivalent ratings for the ‘both ADRO’ and ‘no ADRO’ conditions. A correlation analysis was performed to see if there was any association between the subjects’ preferences on the questionnaire and the differences in their speech perception scores for the ‘both ADRO’ and ‘no ADRO’ conditions. The subjects’ preference difference was taken to be their total rating for ‘both ADRO’ across the listening conditions minus their total rating for ‘no ADRO’. Similarly, their speech perception differences were taken to be the difference in ‘both ADRO’ and ‘no ADRO’ scores on the different tests. There were no significant correlations for any of the word or sentence scores (Pearson correlations r<0.2 and p>0.4), confirming there was no association between the subjects’ preferences for a device combination and any of the speech perception measures.

When asked for their device combination preferences, the group did not have a strong preference for any particular combination. In terms of their preferred hearing aid when listening in quiet environments, 2 subjects (14%) favoured the ‘ADRO hearing aid’, 7 (50%) favoured their own hearing aid and 5 (36%) had no preference. When listening in noisy environments, 2 subjects (14%) favoured the ‘ADRO hearing aid’, 6 (43%) favoured their own hearing aid and 6 (43%) had no preference. For appreciation of music, 3 subjects (21%) favoured the ‘ADRO hearing aid’, 4 (29%) favoured their own hearing aid and 7 (50%) had no preference. In terms of their preferred speech processor Map to use in conjunction with the ‘ADRO hearing aid’, 7 subjects (50%) favoured the ‘ADRO Map’, 2 (14%) favoured the ‘no-ADRO Map’ and 5 (36%) had no preference. Similarly, 6 subjects (43%) favoured the ‘ADRO Map’ when using their own hearing aid, 3 (21%) favoured the ‘no-ADRO Map’ and 5 (36%) had no preference. The subjects’ device preferences are tabulated in Table 7.
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

Table 6. Questionnaire results: ease of listening ratings for both-ADRO versus no-ADRO in 10 listening environments.

<table>
<thead>
<tr>
<th>LISTENING SITUATION</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>S5</th>
<th>S6</th>
<th>S7</th>
<th>S8</th>
<th>S9</th>
<th>S10</th>
<th>S11</th>
<th>S12</th>
<th>S13</th>
<th>S14</th>
<th>Total</th>
<th>mean</th>
<th>t-test p value</th>
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<tbody>
<tr>
<td>familiar person in quiet room</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>both ADRO</td>
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<td>7</td>
<td>9</td>
<td>9</td>
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<td>10</td>
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<td></td>
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<tr>
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Table 7. Questionnaire results: ADRO versus no-ADRO cochlear implant Map and hearing aid preferences.

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3.3. **Summary**

Speech perception testing performed by the 14 subjects demonstrated some significant differences in mean scores for the 4 device combinations tested: 1. own hearing aid used with no-ADRO Map (no ADRO), 2. ‘ADRO hearing aid’ used with no-ADRO Map (HA ADRO), 3. own hearing aid used with ADRO Map (CI ADRO) and 4. ‘ADRO hearing aid’ used with ADRO Map (both ADRO). The greatest effects were seen with the CVC Words presented at 50dB SPL, where the vowel, consonant, phoneme and word scores in the ‘both ADRO’ condition were significantly higher than those obtained in the ‘no ADRO’ condition. When the CVC Words were presented at 60dB SPL, the only significant difference in group means was between word scores, where the ‘both ADRO’ condition again produced a higher score than the ‘no ADRO’ condition. There were no significant differences between the scores obtained with the 4 device combinations on the CUNY Sentences test with competing noise.

Individual subject results revealed that 10 of the 14 subjects obtained a significant benefit from using ADRO in at least one device on at least one test measure. The remaining 4 subjects had no significant differences between their mean scores for the different device combinations. No subject performed better when tested in the ‘no ADRO’ condition.

After having had 4 weeks of take-home experience, subjects rated the effectiveness of the ‘no ADRO’ and ‘both ADRO’ device combinations in 10 different listening conditions. In 8 of the listening environments the subject’s ratings for ‘no ADRO’ and ‘both ADRO’ were not statistically different. In the other 2 environments they rated ‘no ADRO’ more highly. The mean ratings for the group across all listening environments were 6.7 for ‘no ADRO’ and 6.2 for ‘both ADRO’; a difference of 7% but which did not reach statistical significance. There was no correlation between the subjects’ preferences for a device combination and any of the speech perception measures.

Subjects had a tendency to favour their own hearing aid over the ADRO hearing aid and a tendency to favour the ADRO Map over the no ADRO Map. They were just as likely, however, to rate the device combinations as having “no difference”.
Relating these findings to the original hypotheses, it can be said that: 1. the implementation of ADRO in both a hearing aid and speech processor fitting did enhance speech perception compared to a bimodal fitting without ADRO, 2. ADRO enhanced speech perception when implemented unilaterally in a speech processor for some subjects but not to a significant degree when implemented unilaterally in the hearing aid and 3. the adults in this group did not perceive significant differences in their ease of listening when using ADRO in their normal listening environments.
4. DISCUSSION

4.1. Introduction

This study set out to investigate if adults who had received a cochlear implant and who routinely wore a hearing aid in their contralateral ear could obtain any improvement in speech understanding if the sound processing scheme, Adaptive Dynamic Range Optimization (ADRO), was utilized in both their cochlear implant speech processor and their hearing aid. More specifically, the hypotheses were that 1. the implementation of ADRO in both a hearing aid and speech processor fitting would enhance speech perception compared to a bimodal fitting without ADRO, 2. ADRO could improve speech perception when only implemented unilaterally in either the hearing aid or speech processor and 3. adults would perceive improvements in their ease of listening when using ADRO in their normal listening environments.

Results from other studies, as described in earlier chapters, have shown that adults who use a cochlear implant in one ear and a hearing aid in the other ear, are able to effectively integrate the bimodal input and gain improvements in speech recognition. It has also been demonstrated that the implementation of ADRO in either hearing aids or cochlear implants has speech perception benefits for both adults and children.

The speech recognition test results described in this present study, indicated that the use of ADRO in bimodal devices offered improved speech recognition in quiet environments, especially for soft voice levels. In addition, bimodal ADRO offered equivalent speech recognition to that provided by standard speech processing and amplification strategies in noisy environments.

4.2. Implications of current findings

The first hypothesis of this study was that the implementation of ADRO in both a hearing aid and speech processor fitting would enhance speech perception compared to a bimodal fitting without ADRO. For the group of subjects who participated in this study, the use of bimodal ADRO produced equivalent if not better speech recognition scores on all tests in both the quiet and noisy test situations. No subject performed more poorly in the ‘both ADRO’ condition than they did in the ‘no ADRO’ condition.
The second hypothesis was that ADRO could improve speech perception when only implemented unilaterally in either the hearing aid or speech processor. The results obtained when CVC Words were presented at 50dB SPL, indicated significantly higher mean scores for consonants and phonemes when ADRO was only implemented in the cochlear implant speech processor. Implementation of ADRO in the hearing aid alone, did not produce any improvements in speech perception for the group. There was, however, one subject (S13) for whom the ‘HA ADRO’ scores were significantly higher than the ‘no ADRO’ scores. This subject had reported that she relied more on her hearing aid than her cochlear implant for speech recognition. Although subjects were not specifically asked, it can be assumed, based upon clinical experience, that most, if not all, of the other subjects gained greater speech recognition from their cochlear implant than their hearing aid. From this, it could then be predicted that in bimodal device fittings, ADRO is more likely to offer the greatest advantage when implemented in the device (or perhaps ear) which is the dominant one for speech recognition. These findings suggest that it would be optimal to recommend bimodal ADRO fittings to all adults who use a cochlear implant in one ear and a hearing aid in the contralateral ear. If it is not practical for a person to obtain a new hearing aid in which ADRO was implemented, it would at least be reasonable to recommend the use of ADRO in their cochlear implant speech processor.

The findings from the group feedback obtained with the participant questionnaires, however, indicated that not all adults will perceive a benefit from using bimodal ADRO in their everyday environments. This finding did not support the third hypothesis that adults would perceive improvements in their ease of listening when using ADRO in their normal listening environments. It should also be noted that there may not be any correlation between a person’s speech recognition scores in the ‘both ADRO’ or ‘no ADRO’ conditions and their preference rating for either device combination.

In the current study, a stepwise regression analysis was performed to determine if the variables of duration of severe-profound deafness, age at implantation, length of experience with cochlear implant, degree of hearing loss in non-implanted ear, or cochlear implant stimulation pulse rate, accounted for any of the variance in the differences between the ‘both ADRO’ and ‘no ADRO’ scores on the speech recognition
tests. The results of such an analysis may be able to guide clinicians as to which cochlear implant recipients would be expected to gain the most benefit from a bimodal ADRO fitting.

The duration of severe-to-profound deafness was a significant predictor of differences between the ‘both ADRO’ and ‘no ADRO’ conditions for the CVC words presented at 50dB for the phoneme, vowel and consonant scores, but not the word scores. This result suggests that adults with a longer duration of deafness may obtain the greatest benefit from using ADRO in bimodal devices. For the CVC words presented at 60dB, the duration of deafness was again a significant predictor of differences for the phoneme, consonant and word scores, but not the vowel scores.

It is not immediately obvious as to why duration of deafness might be a predictor of differences between the ‘both ADRO’ and ‘no ADRO’ scores, especially that longer durations of deafness would be associated with greater differences. Longer durations of deafness are usually associated with poorer speech perception outcomes for cochlear implant recipients (Dowell, Hollow et al. 2004). The explanation for this finding is that the longer the auditory pathway is deprived of auditory stimulation, the less it is able to process complex auditory input (Shepherd, Hartmann et al. 1997). If this was the case for the group of subjects in this study then we would expect that those who had a longer duration of deafness would have been less likely to make use of the added acoustic information provided by ADRO, at least in the ear with the cochlear implant. The duration of deafness discussed here, however, more specifically relates to the implanted ear. As all of the subjects had been using hearing aids in their other ear prior to and after implantation, the duration of severe-to-profound hearing loss in their non-implanted ear may not be have been as long as for their implanted ear. So the data listed for duration of deafness may be slightly misleading in the context of binaural duration of deafness and, therefore, the statistical analysis.

Furthermore, there was one subject in the group (S13) who had a considerably longer duration of deafness (60 years) compared to the rest of the subjects (3 – 47 years). When this subject was omitted from the stepwise regression analysis, the duration of deafness only accounted for a significant proportion of variance in the differences in
the 60dB SPL CVC word scores. If this is more indicative of the demographics of a larger population, then the duration of deafness may not be a highly relevant clinical predictor of bimodal ADRO benefit.

The difference in the 60dB phoneme scores was also influenced by the subjects’ length of experience with their cochlear implant, with less experience leading to greater differences between the ‘both ADRO’ and ‘no ADRO’ scores. As this finding only related to the phoneme scores but not the vowel or consonant scores, it is possible that an aberration in the data and, hence, the statistical analysis, gave rise to this result. On the other hand, the acoustic cues provided by ADRO may have made it easier for the less experienced cochlear implant recipients to correctly perceive phonemes. The use of bimodal ADRO from the time of the initial switch-on of a cochlear implant could, therefore, be beneficial for developing useful speech perception skills more quickly.

The cochlear implant stimulation rate appeared to be a predictor of differences in the 60dB vowel scores only, with the use of higher rates leading to larger differences. It is possible that higher stimulation rates helped present the amplitude and frequency information generated by ADRO more effectively. If this was the case, it would be reasonable to expect the stimulation rate to be a predictor of differences for the softer 50dB CVC Word scores where larger differences between the ‘both ADRO’ and ‘no ADRO’ scores were seen. This was not observed though.

As stimulation rate only accounted for a significant proportion of variance in the differences in the 60dB vowel scores, its clinical relevance as a predictor of benefit with bimodal ADRO may not be high, especially when other factors are considered. In this group of subjects, 8 of the 14 subject were using 900Hz, 3 subjects were using 500Hz, 2 subjects were using 720Hz and one was using 1,200Hz. This spread of the use of different pulse rates is reasonably representative of the population of cochlear implant recipients at large, as 900Hz is the default pulse rate in the cochlear implant programming software (at the time of writing) and so the most commonly selected by clinicians. Cochlear Ltd’s choice of 900Hz as the default pulse rate was based upon recipient feedback in clinical trials such as reported by Skinner, Holden et al. (2002).
Higher pulse rates may be tried by some programming clinicians for some recipients, however, higher pulse rates can have a detrimental effect on battery life. A shortened battery life may be unsatisfactory for some recipients and so medium pulse rates (such as 720 or 900Hz) may be preferred over high pulse rates (such as 1,800 or 2,400Hz) by these people. For other recipients, low pulse rates (such as 250 or 500Hz) may be required to compensate for their need to use wide pulse widths in order to achieve appropriate current levels in their speech processor Maps. The pulse rate used in a recipient’s Map may, therefore, be dictated by factors other than clinician or recipient choice. This being the case, this potential predictor of benefit with bimodal ADRO may, again, not have much significance when counselling individuals about the potential benefits of bimodal ADRO in their situation.

The subjects’ age at implantation or degree of hearing loss in the non-implanted ear did not account for any significant variance in differences in any of the speech perception scores.

4.3. Comparisons with previous studies

It is valuable to establish how the outcomes from this trial of bimodal ADRO compare to the outcomes from previous trials of unimodal ADRO. Such information can help verify the repeatability and robustness of the findings, as well as give insight into the limitations of the study that will assist in the interpretation of the findings.

Beginning with the group mean scores on the CVC Word test, significantly different results were measured for a number of the test conditions. As had been found in other studies (Martin, Blamey et al. 2001; James, Blamey et al. 2002; Cochlear Ltd 2007), the most notable differences occurred when the words were presented at the softer 50dB SPL level.

For the CVC Words presented at 50dB, the mean scores were significantly higher with the ‘both ADRO’ combination compared to the ‘no ADRO’ combination on all measures. The mean differences between the ‘no ADRO’ and ‘both ADRO’ scores were 9.11% for words, 8.73% for phonemes, 7.04% for vowels and 8.75% for consonants. The magnitudes of these differences are in keeping with previous studies that have used
similar technology and speech recognition tests, such as when Blamey et al (2004) found a 7.9% difference between ADRO and 9-channel WDRC amplification schemes and the 7% benefit offered by ADRO when implemented in Freedom speech processors (Cochlear Ltd 2007; Müller-Deile, Kortmann et al. 2009).

For the CVC Words presented at 60dB SPL, the ‘both ADRO’ mean scores were once again higher than the ‘no ADRO’ scores (8.86% for words, 5.12% for phonemes, 4.32% for vowels and 5.59% for consonants), however, only the difference in word scores was statistically significant (p=0.039). This finding that at higher input levels, speech perception scores obtained with the use of ADRO become more similar to those obtained without ADRO, has also been observed in other studies (Martin, Blamey et al. 2001; James, Blamey et al. 2002; Cochlear Ltd 2007).

This result is not unexpected, as softer level inputs, such as the CVC Words heard at 50dB, are most likely to be enhanced by ADRO due to the activation of the Audibility Rule and the resultant increases in gain. Based on the findings of earlier studies (James, Blamey et al. 2002; Iwaki, Blamey et al. 2008), this could equate to an improvement in sensation level for softer inputs in the order of 5dB for both the cochlear implant and hearing aid, compared to devices not using ADRO. Even slight improvements in the audibility of speech sounds can lead to improved recognition of certain phonemes and, hence, words.

This was demonstrated in the analysis of the CVC Word results, where scores were obtained for vowels and consonants to see how ADRO might affect the different types of phonemes. At the 50dB presentation level, the differences between the ‘no ADRO’ and ‘both ADRO’ mean scores were 7.04% for vowels and 8.75% for consonants. At the 60dB presentation level, the differences between the ‘no ADRO’ and ‘both ADRO’ mean scores were 4.32% for vowels and 5.59% for consonants. While only the differences obtained at the 50dB presentation level are significant, the trend that the consonant score differences were greater than for vowels at both presentation levels, would suggest that consonants are enhanced by ADRO more than vowels. This finding is to be expected as consonants are generally the softer phonemes and so more likely to be enhanced when ADRO’s Audibility Rule comes into play.
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

Input levels of about 60-65dB, however, are typically considered as comfortable levels for listening in everyday life. This being the case, sound inputs in this range do not require enhancement or limiting, so speech processing or amplification strategies, be they ADRO or an alternative strategy, typically operate the same way and provide linear gain for these inputs. For example, it is a fundamental premise of the ADRO processing scheme that the gain should remain constant and only be changed if any of the Comfort, Audibility, Background noise or Hearing protection rules come into play. With there being no significant differences in the way alternative speech processing strategies manage sounds at comfortable levels in quiet environments, it is to be expected that there would be little difference in the speech recognition scores the strategies are capable of offering.

Results from speech perception testing in competing noise have shown some variation across the different ADRO studies. In this study, as well as James et al.’s (2002) evaluation of ADRO in the SPrint speech processor, no significant difference between any of the device conditions was measured using sentence materials. These results were not predicted, as theoretically, speech recognition in noise should be enhanced by ADRO, especially when implemented in the hearing aid. The reasoning behind this is that ADRO rules are applied to each channel independently, so variations in gain can be quite frequency specific; in this case, according to the amplitude – frequency spectrum of the background noise. The more channels there are in a hearing aid, the more narrow the frequency bandwidth of each channel and so the more selective the speech processing strategy can be about maximizing the signal-to-noise ratio across the total frequency range.

In the present study, the ‘ADRO hearing aid’ was a 32 channel hearing aid, while the subjects’ own ‘no ADRO’ hearing aids used 20 channels or less. In fact, 9 subjects used hearing aids that had 2 - 6 channels and the other 5 subjects used hearing aids that had 12 - 20 channels. Utilizing a larger number of channels, the ‘ADRO hearing aid’ should have offered more flexibility in reducing noise only in select channels where the Background noise rule was activated, while other channels presented salient information about the speech signal.
Dawson et al.’s (2004) comparison with children using the SPrint processor and Cochlear Ltd’s (2007) evaluation of SmartSound options in the Freedom speech processor showed ADRO offered improvements of 6.9% and 4% respectively on sentences in noise perception tests. Blamey et al.’s (2004 & 2005) comparative studies of ADRO and 9 and 3-channel WDRC amplification schemes in hearing aids, both found ADRO offered 7.3% improvement in speech recognition in noise. It was proposed by Dawson et al. (2004) that the lack of a difference in scores in the James et al (2002) study was due to most subjects using a speech processor sensitivity setting of ‘8’ compared to a setting of ‘12’ as used by the children in Dawson et al.’s study. With a lower sensitivity setting, the 40th and 98th percentile estimates of the output of the speech processor’s frequency filters would exceed the ADRO background noise and comfort targets less often than if a higher sensitivity setting was used, resulting in less reduction in gain in noisy environments. In the case of the present study, all subjects used a sensitivity setting of ‘12’ so an alternative explanation is needed.

The insignificant differences between sentence in noise results for the ADRO and no-ADRO listening conditions in this study may be due to the relatively small sample size of 14 subjects, compared to 39 subjects in Cochlear Ltd’s (2007) study with the Freedom processor or the 22 and 19 subjects in Blamey et al.’s (2004 & 2005) studies. The small sample size, plus considerable variation in scores for some subjects within this group would have made it more difficult for any differences in scores to reach statistical significance. Another variable that may have influenced this finding was the choice of background noise used with the CUNY Sentences. In the Cochlear Ltd and Blamey et al. studies, 8-talker babble was used, whereas 4-talker babble was used in the present study. There would be more gaps or troughs in the 4-talker babble so potentially the ADRO background noise target would be reached less often than with 8-talker babble, resulting in less compensation in the filter gains for the background noise. If this was the case, then ADRO may be performing more like the no-ADRO processing strategies.

The feedback from the study’s participants regarding their experiences with the bimodal ‘ADRO’ and ‘no-ADRO’ devices showed some individual preferences for one device combination or the other. As a group, however, there was no strong
preference for either the bimodal ‘ADRO’ or ‘no-ADRO’ combination. Four (29%) of
the subjects rated ease of listening significantly higher across the listening
environments with ‘no ADRO’, while the ratings given by the remaining 10 subjects
(71%) did not indicate a significant difference between the ‘both ADRO’ and ‘no ADRO’
device combinations. Similarly, there was a 7% trend towards the ‘no ADRO’ condition
being more highly rated by the group across all listening environments, however, the
difference did not reach statistical significance. In terms of the listening environments
themselves, there were only 2 (20%) environments for which ‘no ADRO’ was rated
significantly higher than ‘ADRO’, while in the remaining 8 (80%) of the listening
situations, there was no significant preference for either ‘ADRO’ or ‘no ADRO’.

This result was somewhat different to previous studies that have shown ADRO to be
the preferred sound processing strategy to use in most listening environments: 74% of
Blamey et al.’s (2005) subjects rated ADRO at least “slightly better” than a WDRC
scheme in hearing aids; the children using cochlear implants in Dawson et al.’s (2004)
study preferred to use ‘ADRO’ in 46% of listening situations, ‘no ADRO’ 26% of the time
and had no preference in the remaining 28% of listening situations; and in Iwaki et al.’s
(2008) bimodal study, participants had at least a slight preference to use bimodal
ADRO in 77% of listening situations. This variation in subjective responses may be due
to the small number of subjects in each of these studies or the influence that
variations in the design and wording of questions may have over respondents.

In the current study there was not a good correlation between subjective ratings and
speech perception results. Within this group of adults, 7 (50%) of the 14 subjects
achieved their highest speech perception scores in the ‘both ADRO’ condition - with 2
of these subjects also scoring equally high in the ‘CI ADRO’ condition and 1 subject
scoring equally high in the ‘HA ADRO’ condition. There were 3 (21%) subjects who
obtained their greatest advantage in the ‘CI ADRO’ condition, while the remaining 4
(29%) subjects obtained no significant differences in scores with any of the device
combinations. None of the subjects performed best in the ‘no-ADRO’ condition on any
speech perception measure and yet 4 (29%) subjects rated this as the condition in
which listening in their everyday environments was easiest and the other 10 (79%)
subjects showed no significant preference for any device combination. A statistical
analysis confirmed there was no correlation between speech perception scores obtained in the test sessions and preference ratings on the questionnaires. This would suggest that subjects based their ratings and preferences on factors other than just speech perception ability.

Possibly the 10 listening environments described in the questionnaire were a small subset of the listening environments encountered by the subjects in their daily lives and the subjects’ performance in the other environments influenced their ratings on questionnaires. It could also suggest that this group of adults encountered mostly noisy environments in their daily lives, for which, as the speech perception results showed, there was no difference in performance between the ‘ADRO’ and ‘no ADRO’ devices. These possibilities could be further investigated by asking subjects for more detail about why they chose the ratings that they did for each device. This could be achieved by modifying the questionnaire or through in-session discussions. It could also be of value to consider using competing noise samples that are more representative of real-life environments in order to improve the correlation between subject ratings in their own environments and speech perception measures in the laboratory.

Familiarity with a device or processing strategy may have influenced overall preferences for a device combination. When subjects were asked to indicate a preference (or no preference) for the ‘ADRO’ or ‘no-ADRO’ Map or the ‘ADRO’ or ‘no ADRO’ hearing aid, they tended to choose the ‘ADRO’ Map and the ‘no ADRO’ hearing aid, if they had any preference at all. These were the Map and hearing aid options that all subjects had been using prior to commencing this study. Perhaps if the acclimatization period for the ‘ADRO’ hearing aid was longer and if more opportunities were provided to fine-tune the hearing aid, these subjects, who were long-term users of compression hearing aids, may have offered a higher preference rating for the ‘ADRO’ hearing aid.

There is also a slim possibility that some of the subjects may have inadvertently used the wrong Map in some listening situations for the hearing aid they were asked to use at the time. As already stated, many of the subjects (50%) indicated a preference for
the ‘ADRO’ Map in their speech processor, so there was the slight chance that they may have been using this Map, the best sounding Map, a lot of the time, even though the questionnaire they were given indicated which Map (in P1 or P2) needed to be selected for use with each hearing aid. If this was the case, some ratings of speech clarity may have been made with the subject’s own hearing aid but with the ‘ADRO’ Map instead of the ‘no ADRO’ Map, resulting in a potentially higher rating being reported. The only way to minimize this possibility was to carefully instruct the subjects; asking them to be diligent in regularly noting their hearing aid and speech processor settings. Perhaps in the future, speech processors will have data logging capabilities allowing researchers to look back over a period of time and note the settings that have been selected in different noise environments.

4.4. Considerations when interpreting the results of this study

While the results from this study indicate that adults who use both a hearing aid and a cochlear implant can gain improved understanding of speech when ADRO is implemented in both devices, a number of issues need to be considered when interpreting the findings of this study. Aspects of the study, such as how the cochlear implant and hearing aids were fitted, the number of subjects in the study, the speech perception materials that were used and the way in which results were analysed, may have influenced the outcomes.

4.4.1. Device fittings

In the present study, care was taken to minimize variations in device fittings. Subjects were recruited that had at least 3 months experience using the Nucleus Freedom speech processor (the most up-to-date technology at the time of testing) and who had routinely worn a hearing aid in their non-implanted ear (at least) since implantation. All subjects had used an instantaneous input dynamic range of 40dB and sensitivity setting of ‘12’ since the fitting of their speech processor. As a part of the initial phase of the study, subjects’ cochlear implant Maps were checked (if not recently done so) to ensure the current levels were set accurately at hearing thresholds and maximum comfortable levels. The loudness growth of each subject’s cochlear implant should, therefore, have been equivalent. There may, however, have been variation in
perceived loudness growth across the group that could have resulted from differences in each subject’s perceptual judgments when setting the current levels in their Maps. In turn, this may have had an impact on the some subjects’ processing of inter-aural acoustic cues and unduly added to the variability in speech perception across the group.

The hearing aids that the subjects routinely wore were fitted by their usual hearing aid provider. This meant that a number of different (‘no ADRO’) hearing aids were used by the group and that fitting approaches may have been different for different subjects. All of the subjects’ hearing aids were up-to-date devices that used what were fundamentally Wide Dynamic Range Compression amplification schemes, but the amplification scheme parameters may have varied across the hearing aids. In this study, the adequacy of the fitting of each subject’s hearing aid was verified using real-ear gain measures that were compared against NAL-NL1 prescribed gain targets. Subjects would only commence the testing phase of the study once an acceptable match to the targets was achieved and they were happy with the fitting of the hearing aid. A more stringent approach would have been to fit all the subjects with the same ‘no ADRO’ hearing aid as well as the ‘ADRO hearing aid’.

The subjects all used the same model of ‘ADRO hearing aid’ and all of these hearing aids were fitted using the standard ADRO fitting technique and software. This reduced variability associated with the fitting of the ‘ADRO hearing aid’, however, as with all fittings of new devices the time needed for subjects to acclimatize to the new hearing aid became a variable that could influence hearing outcomes.

A useful feature of the Freedom speech processor was that the ‘no ADRO’ and ‘ADRO’ Maps could be loaded into “P1” or “P2” memory locations without giving any clue as to which one was the ‘ADRO’ Map and which was not. That meant that the subject could be blind to the type of Map they were using and, therefore, make judgements about the usefulness of a particular Map without bias. This was not the case for the hearing aids, however, so subject bias to one hearing aid was possible.

It is worth considering that the current speech perception and subject questionnaire feedback were obtained with subjects using a hearing aid and speech processor in
which ADRO was implemented slightly differently. These differences in the ADRO algorithms in the hearing aid and cochlear implant may have introduced an inherent limit to the binaural acoustic cues that could have been of benefit to the subjects.

All subjects used the *Interton Bionic BigNano* hearing aid and the *Nucleus Freedom* speech processor. In the *BigNano* hearing aid, the ADRO rules were applied to 32 frequency channels while in the *Freedom* speech processor the rules were applied to a maximum of 22 frequency channels. The percentage estimators that were applied in the *BigNano* hearing aid determined the 30th and 90th percentiles of each channel's output while in the *Freedom* speech processor, the 40th, 70th and 98th percentile output levels were measured. The ADRO rules were also applied somewhat differently in the two devices: the Comfort Rule was applied to the 90th percentile channel outputs in the hearing aid but the 98th percentile outputs in the speech processor. The Audibility Rule was applied to the 30th percentile outputs in the hearing aid but the 70th percentile outputs in the speech processor. In the case of the Background Noise Rule in the hearing aid, the maximum gain was limited to avoid over-amplification of environmental background noise or internal noise, while in the speech processor, the gain was reduced if the 40th percentile output exceeded the background noise target.

Although the current ADRO parameters were developed to work well with the fundamental technologies in the speech processor and hearing aid separately, perhaps further refinement to the parameters may be possible to maximize bimodal benefit. Future psychophysical investigations may be able to shed light on the more specific acoustic cues that can be enhanced by ADRO (or other sound processing strategies) and how timing and intensity differences in the acoustic signal arriving at each ear can be optimized to give the binaural listening benefits that assist in recognizing speech in competing noise. This information may then help guide technical refinements to optimize the implementation of ADRO when used concurrently in a hearing aid and a cochlear implant. This research may also lead to new sound processing strategies being developed that better represent the acoustic cues that enhance binaural listening in bimodal hearing devices.

Where the application of ADRO offered some similarity between the hearing aid and cochlear implant, was in the fitting of the devices. For both the hearing aid and the
An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.

cochlear implant, the targets for the Comfort Rule were determined by the same psychophysical tasks. First, the subject listened to bursts of sound (either narrow-band noise centred around a selection of frequencies between 500Hz and 4000Hz from the hearing aid, or electrical pulse-trains generated from a selection of electrodes in the cochlear implant) and reported when they were sufficiently loud. This determined their comfort level or ‘C-level’ for the different channels in the two devices. Second, the subject listened to a selection of adjacent ‘C-levels’ and judged their volume (or loudness) relative to each other. Based upon the subject’s comments about the relative volumes, the clinician could then make adjustments to the outputs of the channels in order to equalize the volume of the ‘C-levels’ across the different channels. A benefit of performing this ‘loudness balancing’ task was that it minimized the chance of sounds or frequencies generated by some channels from being masked by improperly louder sounds from other channels.

A secondary benefit that came from the very similar fitting techniques for the hearing aid and cochlear implant was that both the clinician and the subject perceived the fitting process to be a more truly bimodal fitting rather than the fitting of two unimodal devices as is the case when ADRO is not the common speech coding strategy. This enhanced the subject’s confidence that the fitting of the two different devices could produce a better match in hearing for their two ears.

4.4.2. Subject group size

There were only 14 subjects who participated in this clinical trial of bimodal ADRO. The speech perception and questionnaire results from this relatively small number of subjects may not be representative of what bimodal ADRO could offer the broader population of adults who use both a hearing aid and a cochlear implant. Extending this trial to include a larger number of subjects would be helpful in increasing the confidence levels of this study’s findings.

4.4.3. Choice of speech perception test materials

The CVC Word and CUNY-like Sentence tests were chosen as the speech perception test materials as essentially the same materials (CNC Words and CUNY Sentences) had
been used in a number of previous ADRO studies and so the outcomes of this study could be compared with previous studies’ outcomes. For the speech perception testing in noise, however, 4-talker babble was chosen instead of 8-talker babble as the competing noise to make the task more challenging. Having fewer talkers in the background resulted in more gaps and bursts of sound in the background noise. This greater variation in intensities in the background made the noise less of a steady-state noise. The amplification and sound coding schemes in the hearing aids and speech processors, and in turn the listener, were then more challenged to deal with the greater short-time variations in speech-to-noise ratios. This type of listening situation with competing background voices was more like the majority of situations that listeners would encounter in the real world, rather than the less frequently encountered steady-state background noises. There may possibly be more variation in speech recognition results obtained with 4-talker versus 8-talker babble, however, making it somewhat more difficult to achieve statistical significance when comparing results across subjects.

4.4.4. Possible outlying results

One subject, S13, performed considerably better on the CNC Word tests when using the ADRO hearing aid compared to her own hearing aid. This was evident no matter which Map (ADRO or no-ADRO) was being used. The magnitude of the difference in scores was initially suggestive that the subject’s own hearing aid was malfunctioning or offering insufficient amplification. This was not the case, however, as the subject’s hearing aid functionality and appropriateness of the fitting had been confirmed using Coupler Gain and Real Ear Gain measures at the commencement of the testing phase of their trial. Subjective checks of functionality were also performed during the trial. It was interesting to note that the large differences in scores observed on the CNC Word tests were not present for the CUNY Sentence test. This may relate to the subject being more sensitive to recognizing differences in short, isolated words compared to the greater amount of information contained in sentences. It could alternatively be related to the subject finding it easier to perceive differences in speech when heard in quiet rather than in competing noise.
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To determine if subject S13’s scores were biasing the CNC Word results, a one-way analysis of variance was conducted with the results from S13 removed from the data set. This analysis of the data showed the remaining group of subjects still performed better in the ‘both ADRO’ condition than in the ‘no ADRO’ condition, although not all differences reached significance once S13’s scores were removed. So, even with the outlying results from subject S13 excluded from the group’s CNC Word data, the finding that bimodal ADRO enhances speech recognition for softer speech inputs was still viable.

4.4.5. Limited unimodal results

One hypothesis of this study was that the implementation of ADRO in either the hearing aid or speech processor could enhance speech perception for someone who uses both devices. This hypothesis was examined by comparing group mean speech perception results obtained when subjects were using one device without ADRO and the other with ADRO against the ‘no ADRO’ condition, i.e. the ‘CI+ADRO’ and ‘HA-ADRO’ condition and the ‘HA+ADRO’ and ‘CI-ADRO’ condition compared with ‘HA-ADRO’ and ‘CI-ADRO’. Whilst this comparison indicated that ADRO implemented in the cochlear implant speech processor offered speech perception benefits over the ‘no ADRO’ condition for consonants and phonemes presented at 50dB, a more rigorous comparison of the effects of ADRO implemented uni-modally would involve testing subjects in the monaural conditions. Before such monaural testing could be performed, subjects fitted with bimodal devices would ideally require time to acclimatize to using each (unimodal) device, as this would not be their typical listening situation. The extra time for acclimatization to unimodal listening and the extra testing required to obtain unimodal as well as bimodal speech perception results was considered impractical for the subjects participating in this study. It is an area of investigation that could be pursued in the future.

4.4.6. Limited speech feature recognition results

This study did not examine in detail the effects ADRO had on the detection and recognition of vowel and consonant cues. Scores for the CVC Word tests were broken down and recorded for the number of vowels and consonants correctly recognized but
further detailed analyses, such as determination of information transfer (Summerfield 1987), were not performed. Such analyses could have provided information about which vowel or consonant features (e.g. consonant voicing and manner and place of articulation) were enhanced by the use of ADRO. As it was, this study’s analyses did indicate that the use of bimodal ADRO improved both vowel and consonant scores on the CVC Word test, although the improvement only reached significance when the CVC Words were presented at 50dB.

4.5. Future research

This study has shown that ADRO is a successful sound coding strategy when implemented in bimodal hearing devices. During the course of this research, however, further opportunities for the enhancement of our knowledge in this area have been identified. First, investigations to better understand of the effects different types of noise have on speech recognition when people are listening with bimodal devices are warranted. This may involve speech recognition testing with different types of common competing noises, roaming speech-in-noise tasks that better replicate the real-life environment as well as the use of information transfer analyses.

More rigorous speech recognition testing comparisons with unilateral as well as bimodal devices may also offer insight into which device (hearing aid or cochlear implant) is better able to transmit different acoustic cues to assist people who use bimodal devices. This information, along with psychophysical studies that enhance our understanding of how timing, intensity and frequency cues are being presented to users of bimodal technologies, may also help guide further refinements to bimodal speech processing schemes and even lead to new purpose-designed and built bimodal devices being developed. Such technologies should be able to offer more robust speech perception performance across the range of listening environments people encounter.

An extension of this study would be to recruit adults who were recipients of bilateral cochlear implants. The same study design could be used to investigate if the implementation of ADRO in bilateral cochlear implants would lead to the same speech
perception benefits demonstrated when ADRO is implemented in hearing aids, cochlear implants and now bimodal devices.

4.6. Conclusion

Past studies have shown that Adaptive Dynamic Range Optimization (ADRO) can be successfully implemented to enhance sound processing in cochlear implants and as an amplification scheme in hearing aids. Results from these single device clinical trials have indicated that ADRO can offer superior recognition of soft speech inputs for both adults and children when compared to commonly used sound processing or amplification strategies. It has also been shown that ADRO offers equivalent, if not better, speech recognition in the presence of competing noise compared to the alternative strategies and that recipients often rate ADRO as their preferred strategy to use in different listening situations.

This study set out to establish if the benefits reported from these unimodal studies would be observed when ADRO was implemented in both a cochlear implant and a hearing aid for adults who routinely wore both devices.

From the results of this study it was concluded that:

1. The implementation of ADRO in a bimodal hearing aid and speech processor fitting enhanced word recognition by about 5 - 10% in quiet environments, compared to a bimodal fitting without ADRO. These speech recognition effects were greater for soft speech. Speech recognition in the presence of competing noise was equivalent for both ‘ADRO’ and ‘no-ADRO’ bimodal fittings.

2. ADRO enhanced bimodal speech perception when implemented unilaterally in a speech processor for some subjects but not to a significant degree when implemented unilaterally in a hearing aid.

3. Despite the outcomes of tests in a controlled environment, adults may not report significant differences in their ease of listening when using bimodal ADRO in their normal listening environments.

ADRO was designed with the intention that it could be implemented in both cochlear implant speech processors as well as in hearing aids; the goal being to provide optimal
hearing and speech recognition for people who use both a cochlear implant and a hearing aid in opposite ears. This study has demonstrated that this goal has been achieved; with the use of ADRO in bimodal devices offering significant improvement in speech recognition for adults.

These findings should be considered when counselling hearing impaired adults about their cochlear implant speech processor and hearing aid fitting options and potential speech perception outcomes.
REFERENCE LIST


An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid.


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APPENDIX 1: Subject preference questionnaire

As an example, below is a copy of the questionnaire that was given to subjects who had the ADRO Map written into P1 of their speech processor:

QUESTIONNAIRE FOR BIMODAL ADRO PROJECT

Name:

Date questionnaire given:

Date questionnaire returned:

We are interested in knowing which of the speech processor - hearing aid combinations that you have been comparing perform best in your daily life. In this questionnaire, you are asked to judge the helpfulness of each speech processor - hearing aid combination in a variety of listening situations.

Please indicate the amount of help provided by each device combination by circling your choice on the rating scales that follow each question. If you do not encounter a situation like one that is described in the questions below, please tick the “Not applicable” box for that question.

Thank you for taking the time to complete the questionnaire.

1. You are having a conversation with a familiar person in a quiet room. How well are you able to understand the conversation?

Using THE LOAN hearing aid and the speech processor on P1:

Using YOUR OWN hearing aid and the speech processor on P2:
2. You are having a conversation with a familiar person whilst travelling in a car. How well are you able to understand the conversation?

Using THE LOAN hearing aid and the speech processor on P1:

Can’t understand

Using YOUR OWN hearing aid and the speech processor on P2:

Can’t understand

3. You are having a conversation with a familiar person in a busy shopping centre. How well are you able to understand the conversation?

Using THE LOAN hearing aid and the speech processor on P1:

Can’t understand

Using YOUR OWN hearing aid and the speech processor on P2:

Can’t understand

4. You are having a conversation with a group of 3-4 friends in a restaurant. How well are you able to understand the conversation?

Using THE LOAN hearing aid and the speech processor on P1:

Can’t understand

Using YOUR OWN hearing aid and the speech processor on P2:

Can’t understand
5. You are watching a movie or T.V. program at home on the Television. How well are you able to understand the program?

Using THE LOAN hearing aid and the speech processor on P1:

1 2 3 4 5 6 7 8 9 10

Can’t understand

Using YOUR OWN hearing aid and the speech processor on P2:

1 2 3 4 5 6 7 8 9 10

Can’t understand

6. You are having a conversation with a small group of people in a quiet room. How well are you able to understand the conversation?

Using THE LOAN hearing aid and the speech processor on P1:

1 2 3 4 5 6 7 8 9 10

Can’t understand

Using YOUR OWN hearing aid and the speech processor on P2:

1 2 3 4 5 6 7 8 9 10

Can’t understand

7. You are having a conversation with a familiar person with continuous noise (such as a tap running or a noisy fan) in the background. How well are you able to understand the conversation?

Using THE LOAN hearing aid and the speech processor on P1:

1 2 3 4 5 6 7 8 9 10

Can’t understand

Using YOUR OWN hearing aid and the speech processor on P2:

1 2 3 4 5 6 7 8 9 10

Can’t understand
8. How well you are able to hear music in general?

Using THE LOAN hearing aid and the speech processor on P1:

1 2 3 4 5 6 7 8 9 10

Can’t understand

Using YOUR OWN hearing aid and the speech processor on P2:

1 2 3 4 5 6 7 8 9 10

Can’t understand

9. How would you rate the clarity and naturalness of people’s voices in general?

Using THE LOAN hearing aid and the speech processor on P1:

1 2 3 4 5 6 7 8 9 10

Can’t understand

Using YOUR OWN hearing aid and the speech processor on P2:

1 2 3 4 5 6 7 8 9 10

Can’t understand

10. How well are you able to hear environmental sounds (e.g. telephone ringing, microwave beeps, birds, doorbell) in general?

Using THE LOAN hearing aid and the speech processor on P1:

1 2 3 4 5 6 7 8 9 10

Can’t understand

Using YOUR OWN hearing aid and the speech processor on P2:

1 2 3 4 5 6 7 8 9 10

Can’t understand
11. Do you have a preference for either of the speech processor programmes?

When using THE LOAN hearing aid:

☐ P1 was better ☐ P2 was better ☐ No difference

When using YOUR OWN hearing aid:

☐ P1 was better ☐ P2 was better ☐ No difference

12. In general, what is your preferred hearing aid when listening to speech in QUIET environments?

☐ THE LOAN hearing aid ☐ YOUR OWN hearing aid ☐ No difference

13. In general, what is your preferred hearing aid when listening to speech in NOISY environments?

☐ THE LOAN hearing aid ☐ YOUR OWN hearing aid ☐ No difference

14. In general, what is your preferred hearing aid when listening to MUSIC?

☐ THE LOAN hearing aid ☐ YOUR OWN hearing aid ☐ No difference

15. Please include any other relevant observations or comments you have about the use of the 2 hearing aids and the 2 programmes.

_________________________________________________________________________________
_________________________________________________________________________________
_________________________________________________________________________________
_________________________________________________________________________________
_________________________________________________________________________________

Thank you again for taking the time to complete this questionnaire.
APPENDIX 2: Individual subject results

Subject 1

Summary of questionnaire results for Subject 1

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<th>p value</th>
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<tr>
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</tr>
<tr>
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<tr>
<td>bimodal device combination</td>
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Subject 2

Summary of questionnaire results for Subject 2

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<th>p value</th>
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Subject 3

Speech perception results (%) for Subject 3

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<td>sentences</td>
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Summary of questionnaire results for Subject 3

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Subject 4

Speech perception results (%) for Subject 4

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Summary of questionnaire results for Subject 4

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Subject 5

Summary of questionnaire results for Subject 5

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Subject 6

Summary of questionnaire results for Subject 6

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Subject 7

Speech perception results (%) for Subject 7

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<th>50dB</th>
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Summary of questionnaire results for Subject 7

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Subject 8

Speech perception results (%) for Subject 8

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<th>50dB</th>
<th>60dB</th>
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<th>60dB</th>
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Summary of questionnaire results for Subject 8

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Subject 9

Summary of questionnaire results for Subject 9

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Subject 10

Summary of questionnaire results for Subject 10

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**Subject 11**

![Speech perception results (%) for Subject 11](image1)

Summary of questionnaire results for Subject 11

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**Subject 12**

![Speech perception results (%) for Subject 12](image2)

Summary of questionnaire results for Subject 12

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Subject 13

Speech perception results for Subject 13

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<td>60dB words</td>
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<td>S/N sentences</td>
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Summary of questionnaire results for Subject 13

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Subject 14

Speech perception results for Subject 14

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Summary of questionnaire results for Subject 14

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### APPENDIX 3: Analysis of variance for speech perception scores

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<th>CUNY sents.</th>
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<td>phons.</td>
<td>vowel</td>
<td>cons.</td>
</tr>
<tr>
<td>Subject</td>
<td>P</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>HA</td>
<td>P</td>
<td>0.078</td>
<td>0.039</td>
<td>0.112</td>
</tr>
<tr>
<td>CI</td>
<td>P</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>HA*CI</td>
<td>P</td>
<td>0.768</td>
<td>0.620</td>
<td>0.220</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R²</td>
<td>73.35</td>
<td>72.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R²(adj)</td>
<td>71.29</td>
<td>70.78</td>
</tr>
</tbody>
</table>

HA = hearing aid (ADRO or no-ADRO)

CI = speech processor Map (ADRO or no-ADRO)

HA*CI = interaction between the two predictors - type of hearing aid and type of cochlear implant Map

P = probability of no significant difference between samples (p<0.05 indicates significant difference)

S = represents the standard distance data values fall from the fitted values

R² = the amount of variation in the samples that is explained by the predictors

R²(adj) = is a modified R² that has been adjusted for the number of terms in the model
Author/s: Hollow, Rodney David

Title: An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid

Date: 2011

Citation: Hollow, R. D. (2011). An evaluation of speech perception when introducing ADRO to adults who use both a cochlear implant and a contralateral hearing aid. Masters Research thesis, Dept. of Otolaryngology, Faculty of Medicine, Dentistry & Health Sciences, The University of Melbourne.

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