In: Deafness, Hearing Loss and the Auditory System ISBN: 978-1-60741-259-5
Editors: D. Fiedler and R. Krause, pp.301-311

Chapter 14

SIGNS OF BINAURAL PROCESSING WITH BILATERAL COCHLEAR IMPLANTS IN THE CASE OF SOMEONE WITH MORE THAN 50 YEARS OF UNILATERAL DEAFNESS

Celene McNeill[1,2*]***, William Noble***[3,4] ***and Anna O'Brien***[5]
[1]Healthy Hearing & Balance Care.
[2]Macquarie University, Australia.
[3]University of New England, Australia.
[4]University of Iowa.
[5]National Acoustic Laboratories, Australia.

ABSTRACT

A case is presented of a 70-year-old man with a profound sensorineural hearing loss in the right ear since childhood and who developed sudden severe hearing loss in the left ear at age 63. Eventually, after he received cochlear implants in both ears, he started to present behavioural auditory processing skills associated with binaural hearing, such as improved ability understanding speech in the presence of background noise, and sound localization. Responsiveness and outcomes were measured using cortical auditory evoked potentials, speech perception in noise, sound localization performance , and a self-rating questionnaire. The results suggest that even after more than 50 years of unilateral deafness it is possible to develop binaural interaction and sound localization.

INTRODUCTION

Plasticity of the auditory brain has been of increasing interest, especially since the advent of cochlear implants. Pre-lingually deaf children have responded well to electric auditory stimulation and the earlier the intervention the more their auditory processing skills are

---

* Corresponding author: 1204/1 Newland St, Bondi Junction NSW, Australia 2026, E-mail: cmcneill@tpg.com.au

similar to those of normal hearing children. Adults with acquired profound hearing loss also present very good outcomes but these have been reported to correlate negatively with duration of deafness and absence of previous auditory stimulation (Tyler and Summerfield, 1996). Adults with long-term deafness have been considered less likely to develop good auditory outcomes with cochlear implantation. However, outcomes of electric stimulation in long-term deafness have not been widely explored.

The present study is of a 70 year-old male, profoundly deaf in the right ear since childhood. He had experienced the common problems associated with a unilateral hearing loss such as head shadow effects, difficulty understanding speech in noise and inability to localize sounds. At the age of 63 he developed a sudden severe sensorineural hearing loss in his left ear and a hearing aid was fitted, with limited success. Six months later he received a cochlear implant in the right ear and retained a hearing aid in the left ear. After three years he stopped wearing the hearing aid for lack of perceived benefit and received an implant in that ear. Two years following constant bilateral electric stimulation he began showing signs of binaural function.

Unilateral hearing loss is known to alter neuronal activation and binaural interactions in the auditory pathways. Khosla et al. (2003) found reduction in ipsilateral-contralateral amplitude differences for N1-P2 by measuring cortical auditory evoked potential (CAEP) in patients with profound left ear deafness. This finding indicates reorganisation in the auditory cortex in unilateral left deafness, with cortical activation increasing in the left hemisphere. In contrast, patients with unilateral right deafness have not shown evidence of reduced ipsilateral-contralateral amplitude differences. This suggests there is less compensatory plasticity increase in activation of the left hemisphere with deafness in the right ear alone.

This case study is of a 70 year-old male (P.M.) with a profound sensorineural hearing loss in the right ear since childhood and a later onset fluctuating moderate-severe sensorineural hearing loss in the left ear. The duration of profound hearing loss in the right ear was longer than 50 years and was attributed to mumps in early childhood. P.M. first became aware of his profound hearing loss in the right ear at school when he was 8 years old. In 2001 he had a sudden hearing loss in the left ear, which was diagnosed as secondary endolymphatic hydrops. Computerized tomography scans of the temporal bones revealed an asymmetry in size of the cochlear aqueducts, the left being larger than the right.

TEST METHODS, MEASURES AND RESULTS

Speech Perception and Auditory Evoked Potentials

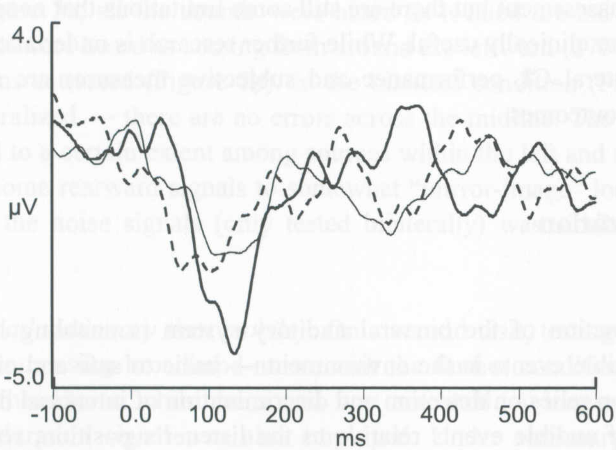
P.M. was referred to the audiologist for hearing aid assessment after the episode of sudden left hearing loss, and a hearing aid was fitted in the left ear. Hearing levels in the left ear continued to fluctuate, making it difficult to programme the hearing aid. P.M. was not considered a suitable candidate for a cochlear implant, as audiological assessment showed aided speech recognition scores of 95% with his left hearing aid in free-field using CID sentences. This result was above CI candidacy guidelines at the time, which recommend aided speech scores in quiet worse than 70% as a criterion for implantation (Dowell et al., 2003). Furthermore, the right ear had not had auditory stimulation for over 50 years, which was considered a contra-indication for implantation. In spite of this it was agreed that an implant in the right ear would be attempted, as there was "nothing to lose".

P.M's CAEP with the CI in the right ear and hearing aid in the left ear were recorded using a high frequency stimulus 6 months and 9 months after implantation to follow his cortical responses. The stimulus was selected based on previous evidence for robust cortical responses to 4 kHz tone bursts in adult CI users (Kelly et al., 2005). Changes were also expected for cortical responses in this frequency region based on previous evidence for high frequency cortical reorganisation in humans with acquired hearing loss (e.g. Dietrich et al., 2001; Thai-Van et al., 2003). The results 6 months following cochlear implantation showed auditory responses elicited via a CI even after more than 50 years of unilateral auditory deprivation. Changes in speech scores over time and differences in performance comparing left hearing aid, right implant and bimodal stimulation also reflected the CAEP results.

Speech test performance became very poor in the left ear after implantation of the right ear, but the hearing loss was fluctuating at this time and more difficult speech material was used for post-CI testing. Despite this, at nine months post-CI the CUNY speech scores indicated that bimodal listening was superior to the CI alone.

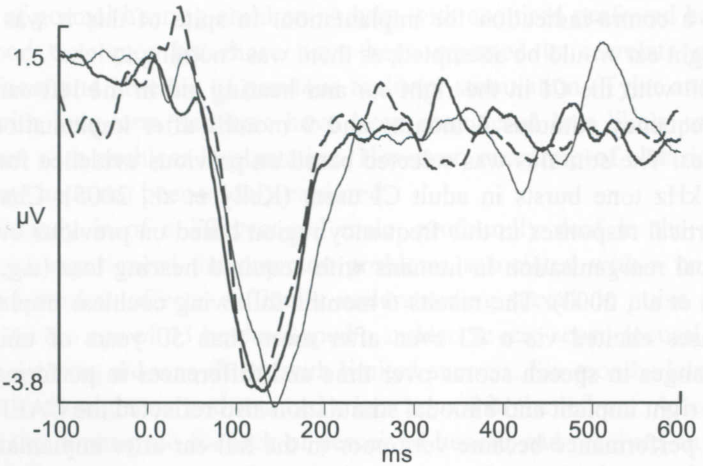
Eighteen months after implantation P.M. reported great satisfaction with the implant. He was using bimodal stimulation (CI in the right ear and hearing aid in the left ear) but reported that he was relying mostly on the CI. He was back at work and reporting significant improvement in hearing ability.

The difference in bimodal listening compared to CI or hearing aid alone was evident in the cortical responses at six and nine months post-CI (Figure 1 and 2). These show a binaural interaction effect, with different cortical responses in the bimodal condition than with either device alone. Hearing in the left ear continued to deteriorate. Speech scores with the hearing aid alone deteriorated to 20% using BKB/A in quiet, in spite of hearing aid optimisation. P.M. started to rely more and more on the right CI alone for hearing and communication. After three years of attempted bimodal hearing, and the left ear having deteriorated so greatly, P.M. had his left ear implanted in 2005.



Thicker line: hearing aid alone,
Dashed line: CI alone
Thinner line: bimodal

Figure 1. CAEP 6 months post-CI.



Thicker line: hearing aid alone
Dashed line: CI alone
Thinner line: bimodal

Figure 2. CAEP at 9 months post-CI.

Twelve months after receiving the second implant P.M. scored 90% with bilateral implants for BKB/A sentences presented at 65 dB SPL in babble noise at +10 dB signal-to-noise ratio.

CAEP with bilateral implants was attempted but waveforms resulted in a large artefact so that it was not possible to objectively determine whether a cortical response was present. This illustrates one of the problems of CAEP recordings in bilateral CI users (McNeill et al, 2009). The artefact usually occurs when the speech processor is activated and lasts at least as long as the duration of the stimulus (Gilley et al, 2005). Distribution of the artefact on the scalp varies according to type of CI and mode of stimulation, and although it can occur with unilateral CIs it is more prominent with bilateral stimulation. CAEP has the potential to be a fast and reliable tool for CI assessment but there are still some limitations that need to be overcome in order to make it more clinically useful. While further research is undertaken regarding the use of CAEP with bilateral CI, performance and subjective measures are relied on to assess responsiveness and outcomes.

Auditory Localization

Background

A primitive function of the binaural auditory system is enabling listeners to tell the whereabouts of audible events in the environment — basic to safe and effective orientation. This hearing function relies on detection and discrimination of interaural differences that vary with the location of audible events relative to the listener's position; referred to as spatial hearing (Blauert, 1983) or auditory localization (Mills, 1972). For human listeners, sounds occurring at points away from the body's midline, and containing energy up to about 1200 Hz, can be spatially distinguished on the basis of differences in phase relations between the two ears. As energy in a signal extends higher in frequency, becoming more complex, the head casts an increasingly marked acoustic shadow, which in turn yields detectable interaural differences in the overall level of the signal at any position away from the body's midline.

Cochlear implants do not allow reliable detection of low-frequency phase differences, but the shadowing effect of the head is a biophysical given, hence people with bilateral implants should be able to detect the whereabouts of complex sounds on the basis of interaural level differences. Studies confirm that bilateral CI users are indeed able to localize such sounds (Dunn et al., 2008; Litovsky et al., 2004; van Hoesel & Tyler, 2003).

Test procedure

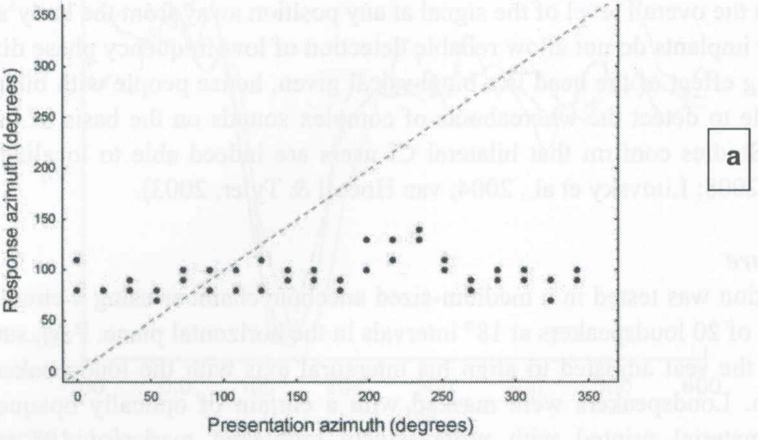
Localization was tested in a medium-sized anechoic chamber using a circular array (1.7-meter radius) of 20 loudspeakers at 18° intervals in the horizontal plane. P.M. sat in the centre of the array, the seat adjusted to align his interaural axis with the loudspeakers at 90° and 270° azimuth. Loudspeakers were masked with a curtain of optically opaque acoustically transparent material printed with progressively numbered marks at 10° intervals. The listener's task was to identify the number judged closest to the source, on each trial, by reference to the numbers on the curtain or a map of the loudspeaker layout. On an initial set of trials, the listener kept his head stationary during each trial, while fixating a point at 0°. In a repeat test session the same procedure was used, followed by groups of trials in which he was free to move his head.

Various signals were used in groups of 40 trials, with random presentation (each loudspeaker activated twice), and sound level at 65 dB, but jittered at random through ±3 dB. Tests were conducted under conditions of both bilateral and unilateral CI listening.

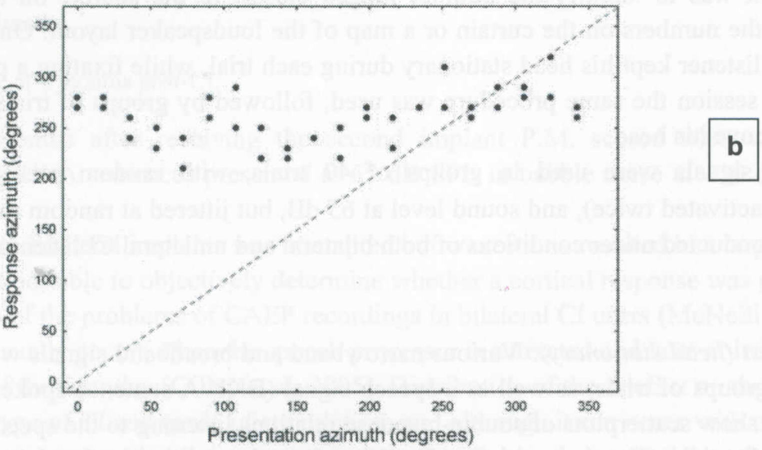
Results

Initial test (head stationary): Various narrowband and broadband signals were employed in different groups of trials, as well as a speech signal (BKB/A sentence spoken by a male). Figures 3a-c show scatterplots of source-response relations listening to the speech signal with both CIs, under right CI only, and left only. When listening with only the right CI activated, as indicated in Figure 3a, all the sounds were heard as located around the rightward (90°) loudspeaker; and all were heard as coming from around the leftward (270°) loudspeaker when only the left CI was activated (Figure 3b). In the bilateral condition (Figure 3c) all signals were correctly lateralized — there are no errors across the midline. The data also show that P.M. discriminated to a certain extent among sources within the left and right hemifields, but that he attributed some rearward signals to somewhat "mirror-image" locations in front. His performance with the noise signals (only tested bilaterally) was similar to that shown in Figure 3c.

Repeat test (head stationary then mobile): On a second visit, testing was repeated under bilateral CI conditions using broadband noise, with the further condition added of allowing P.M. to move his head/torso while the sound was activated. A longer (2-sec.) as well as shorter (0.9-sec.) duration signal was also employed. Under stationary listening for both durations, and under mobile listening for the shorter signal the outcome was essentially the same as that shown in Figure 3c. Under mobile listening with a 2-sec. signal, there were signs that the front-rear signals were resolved to their correct regions (Figure 4).



Speech, left only



Speech, bilateral

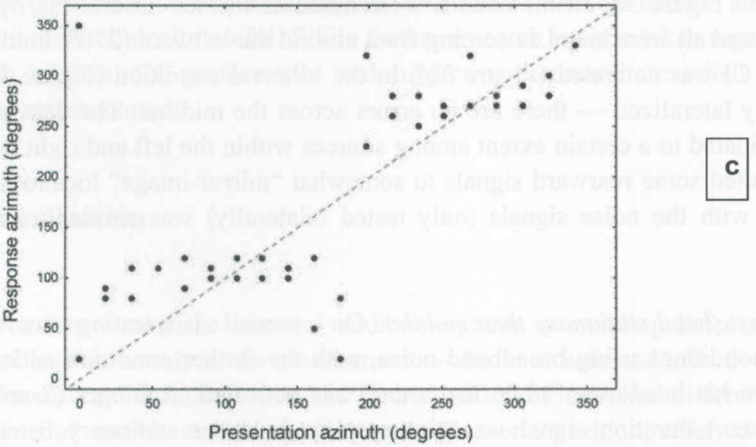


Figure 3. Localization response patterns for male speech with a) right CI only, b) left CI only and c) bilateral CIs.

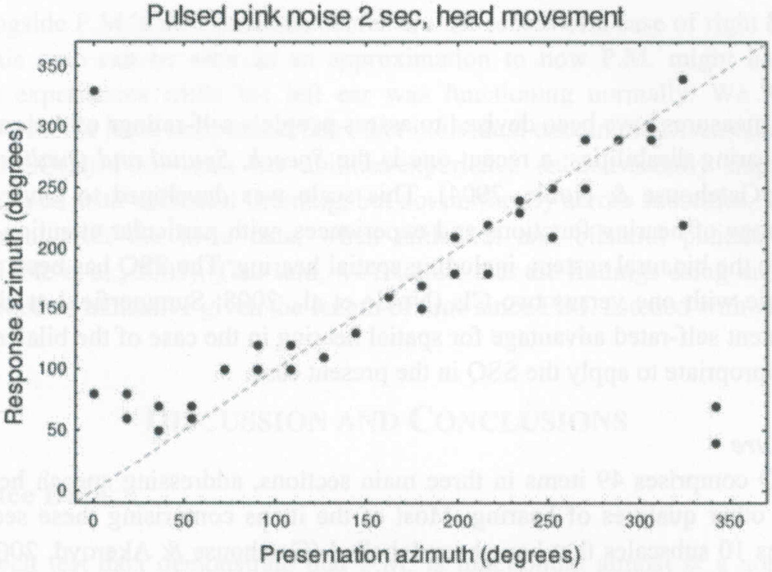


Figure 4. Localisation response pattern for 2 second broadband stimulus, head mobile.

Table 1. P.M.'s self-ratings on ten SSQ subscales compared with the averages of 36 bilateral CI patients; right-hand column shows SSQ benefit (from second implant) scores. [In square brackets next to P.M.'s SSQ scores are scores of a case of unilateral deafness.]

SSQ Subscales *Speech*	P.M. (n = 1)	CI+CI (n = 36)	P.M. benefit scores
Speech in quiet	9.5 [7.5]	8.1 (1.3)	+5.0
Speech in noise	6.5 [6.0]	5.7 (1.9)	+4.0
Speech in speech contexts	8.3 [8.3]	5.3 (2.2)	+3.8
Multiple speech-stream processing and switching	6.0 [4.2]	4.1 (2.2)	+2.0
Spatial			
Localization	7.2 [0]	5.8 (2.3)	+4.2
Distance and Movement	6.8 [0.5]	5.7 (1.9)	+3.6
Quality Sound quality and naturalness	5.8 [9.4]	6.9 (2.0)	+4.0
Identification of sound and objects	5.6 [9.4]	6.6 (2.1)	+3.6
Segregation of sounds	8.7 [2.7]	6.0 (2.2)	+4.3
Listening effort*	5.0 [2.0]	6.1 (1.8)	+4.0

Self-rating

Background

Various measures have been devised to assess people's self-ratings of their abilities in the domain of hearing disabilities; a recent one is the *Speech, Spatial and Qualities of Hearing* scale (SSQ: Gatehouse & Noble, 2004). This scale was developed to cover as broad as possible a range of hearing functions and experiences, with particular attention to capacities that implicate the binaural system, including spatial hearing. The SSQ has been applied in the case of people with one versus two CIs (Noble et al., 2008; Summerfield et al., 2006), and revealed evident self-rated advantage for spatial hearing in the case of the bilateral CI profile. Thus, it is appropriate to apply the SSQ in the present case.

Test procedure

The SSQ comprises 49 items in three main sections, addressing speech hearing, spatial hearing and other qualities of hearing. Most of the items comprising these sections can be aggregated as 10 subscales that have been labelled (Gatehouse & Akeroyd, 2006) Speech in Quiet, Speech in Noise, Speech in Speech Contexts, Multiple Speech-Stream Processing and Switching, Localization, Distance and Movement, Sound Quality and Naturalness, Identification of Sound and Objects, Segregation of Sounds, and Listening Effort. Each item is accompanied by a 0-10 scoring ruler such that zero represents complete inability with respect to the item in question, and 10 represents perfect ability.

A paper-pencil version of the SSQ was mailed to P.M, which he completed and returned. Shortly thereafter, a new version of the SSQ was sent to him with the request he complete that. This new version — SSQ(B) — is currently under development for use as a benefit measure. Respondents are asked to rate each item on a –5-to-+5 scoring ruler in terms of whether their abilities and experiences are much worse (-5), unchanged (0) or much better (+5) as a consequence of whatever intervention has been undertaken. In the case of P.M. the intervention of interest was the acquisition of a second CI. It was fully recognized (and explained to P.M.) that applying the SSQ(B) in his case was purely exploratory, given that he had been using two implants for three years, and thus may not be able to rate his abilities and experiences now against those he remembered from three years previously, when he had a CI in the right ear and a hearing aid in the left. P.M. nonetheless felt able to respond to the SSQ(B).

RESULTS

In Table 1 are the self-ratings of P.M. on the ten subscales of the SSQ, and, for comparison, the averages (SD's in brackets) of 36 bilateral CI cases from the University of Iowa Hospital (Noble et al., 2008). P.M. rates his abilities in the speech and spatial domains higher than the Iowa sample, although it can be noted from the standard deviation values that his ratings are within the Iowa range. There is also a measure of similarity between this case and the Iowa sample in the relative ranking of the subscales (P.M.'s Speech in Noise rating might be seen as aberrant in this respect, and we return to that in the Discussion). By contrast, the ratings on three of the four qualities subscales are lower than the Iowa sample. In square brackets alongside P.M.'s SSQ subscale scores are the scores of a case of right ear unilateral deafness. This case can be seen as an approximation to how P.M. might have rated his abilities and experiences while his left ear was functioning normally. We return to the comparisons with the Iowa sample and this other individual case in the Discussion section.

On the SSQ(B) P.M. rates his abilities/experience as consistently improved under bilateral compared with unilateral listening, but not uniformly across subscales. This outcome is in agreement with the Iowa data, when unilateral and bilateral patients' scores are compared (Noble et al., 2008). That said, we reiterate that the findings using the SSQ(B) can only be regarded as indicative given the length of time since P.M. listened with only one CI.

DISCUSSION AND CONCLUSIONS

Performance Data

The speech test data demonstrate that P.M. is functioning almost at a normal hearing level when listening to a purely auditory signal in background noise. This highly proficient performance is echoed in his self-ratings. It can be assumed, from the CAEP observations in his earlier (bimodal) profile, that the bilateral CI condition is enabling binaural processing of speech.

The localization performance data from the initial test session, with immobile listening, demonstrate the evident contrast between unilateral and bilateral listening. There are no reliable cues to direction with only one CI activated and the sensation experienced would lead to attribution to a source more or less in line with the activated side. By contrast, interaural level differences become available with two devices active, leading to accurate lateralization and a degree of azimuthal discrimination. Because of the geometry of interaural differences it is not straightforward to distinguish sources at "mirror-image" positions behind and in front of the interaural axis. The repeat session confirmed the latter outcome for stationary listening. The condition in which the listener was free to move during signal presentation showed some resolution of front/back reversals, especially when the signal is 2-sec. rather than 1-sec. Such resolution is feasible because the change of interaural differences under head movement is in one direction when a sound is in the front hemifield, and in the opposite direction when the sound is in a "mirror-image" location to the rear.

Self-rating Data

The particular history of the present case, namely, most of his life with normal hearing in one ear, makes comparison with typical CI patients difficult to predict. At interview, P.M. reported a lifelong involvement in stage acting and singing, which could explain his particularly high self-ratings for speech understanding. We also note a strong influence of visual input in speech understanding: On an item of the SSQ asking how he gets on when not all conversation members are in sight P.M. gave a very low rating (which pulls down his speech-in-noise average score). He also observed that he was quite conscious of the reduction in quality and identifiability of sounds since becoming reliant solely on electric stimulation (and was aware of the livelier quality of what he hears on the side that was more recently normal). These features may account for the lower Qualities ratings than found in the Iowa sample.

It is instructive to note the sharp contrasts in Spatial and certain Qualities ratings between P.M. and the case of unilateral deafness. In the latter case Spatial hearing is rated as non-existent, but naturalness and identifiability are rated very highly. These contrasts are telling as regards the substantial benefit for spatial hearing provided by bilateral implantation, whilst also indicating the loss of quality that flows from the limited patterning available by this means of connection to the audible world. Nonetheless it confirms that the provision of bilateral auditory information, despite degraded signal quality and the age of the brain, can enable cortical plasticity to take place and auditory processing skills to develop.

REFERENCES

Blauert, J. (1983). *Spatial hearing*. Cambridge, Mass.: MIT Press.

Dietrich, V., Nieschalk, M., Stoll, W., Rajan, R. & Pantev, C. (2001). Cortical reorganization in patients with high frequency cochlear hearing loss. *Hearing Research*, *158*, 95-101.

Dowell, R., Hollow, R. & Winton, L. (2003). Changing selection criteria for cochlear implants – the Melbourne experience. Cochlear N95506 ISSI.

Dunn, C. C., Tyler, R. S., Oakley, S., Gantz, B. J. & Noble, W. (2008). Comparison of speech recognition and localization performance in bilateral and unilateral cochlear implant users matched on duration of deafness and age at implantation. *Ear & Hearing*, *29(3)*, 352-359.

Gatehouse, S. & Akeroyd, M. (2006). Two-eared listening in dynamic situations. *International Journal of Audiology*, *45(Supplement 1)*, S120-S124.

Gatehouse, S. & Noble, W. (2004). The Speech, Spatial and Qualities of Hearing Scale (SSQ). *International Journal of Audiology*, *43(1)*, 85-99.

Gilley, P. M., Sharma, A., Finley, C. C., Panch, A. S., Martin, K. & Dorman, M. (2005). Minimization of cochlear implant stimulus artefact in cortical auditory evoked potentials. *Clinical Neurophysiology*, *116*, 648-657.

Kelly, A. S., Purdy, S. C. & Thorne, P. R. (2005). Electrophysiological and speech perception measures of auditory processing in experienced adult cochlear implant users. *Clinical Neurophysiology*, *116*, 1235-1246.

Khosla, D., Ponton, C. W., Eggermont, J. J., Kwong, B., Dort, M. & Vasama, J. P. (2003). Differential ear effects of profound unilateral deafness on the adult human central auditory system. *Journal of the Association for Research in Otolaryngology*, *4*, 235-249.

Litovsky, R. Y., Parkinson, A., Arcaroli, J., Peters, R., Lake, J., Johnstone, P., et al. (2004). Bilateral cochlear implants in adults and children. *Archives of Otolaryngology, Head and Neck Surgery*, *130*, 648-655.

McNeill, C., Sharma, M. & Purdy, S. C. (2009). Are cortical auditory evoked potentials useful in the clinical assessment of adults with cochlear implants? *Cochlear Implants International*, *10*, 78-84.

Mills, A. W. (1972). Auditory localization. In J. V. Tobias (Ed.), *Foundations of modern auditory theory* (*Vol. II*, 303-348). New York: Academic Press.

Noble, W., Tyler, R. S., Dunn, C. & Bhullar, N. (2008). Unilateral and bilateral cochlear implants and the implant-plus-hearing aid profile: Comparing self-assessed and measured abilities. *International Journal of Audiology*, *47*, 505-514.

Summerfield, A. Q., Barton, G. R., Toner, J., McAnallen, C., Proops, D., Harries, C., et al. (2006). Self-reported benefits from successive bilateral cochlear implantation in post-lingually deafened adults: randomised controlled trial. *International Journal of Audiology*, *45*, S99-S107.

Thai-Van, H., Micheyl, C., Moore, B. C. J. & Collet, L. (2003). Enhanced frequency discrimination near the hearing loss cut-off: a consequence of central auditory plasticity induced by cochlear damage? *Brain*, *126*, 2235-2245.

Tyler, R. S. & Summerfield, A. Q. (1996). Cochlear implantation: Relationships with research on auditory deprivation and acclimatization. *Ear & Hearing*, *17(3)*, 38S-50S.

van Hoesel, R. J. & Tyler, R. S. (2003). Speech perception, localization, and lateralization with bilateral cochlear implants. *Journal of the Acoustical Society of America*, *113(3)*, 1617-1630.