

Clinical experience of using cortical auditory evoked potentials (CAEPs) in the treatment of infant hearing loss in Australia

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Abstract

This paper presents the clinical protocol that is currently being used within Australian Hearing for infant hearing aid evaluation using cortical auditory evoked potentials (CAEPs). CAEP testing is carried out in the free field at two stimulus levels (65 dB SPL, followed by 55 or 75 dB SPL) using three brief frequency-distinct speech sounds /m/, /g/ and /t/, within a standard audiological appointment of up to 90 minutes. CAEP results are used to check or guide modifications of hearing aid fittings, or to confirm unaided hearing capability.

A retrospective review of 83 client files evaluated whether clinical practice aligned with the clinical protocol. It showed that most children could be assessed as part of their initial fitting program when they were identified as a priority for CAEP testing. Aided CAEPs were most commonly assessed within 8 weeks of the fitting. A survey of 32 pediatric audiologists provided information about their perception of cortical testing at Australian Hearing. The results indicated that clinical CAEP testing influenced their approach to rehabilitation, was well received by parents, and that they were satisfied with the technique. Three case studies were selected to illustrate how CAEP testing can be used in a clinical environment. Overall, CAEP testing has been effectively integrated into the infant fitting program.

Learning objectives

The learner will describe the clinical protocols implemented at Australian Hearing for the use of cortical auditory evoked potential testing for hearing aid fitting and evaluation in young children.

Key words

cortical auditory evoked potential, hearing, hearing aid, infant

Abbreviations

3FAHL: 3 frequency average hearing loss, representing the average hearing thresholds at 500, 1000 and 2000 Hz

ABR: auditory brainstem response

ANSD: auditory neuropathy spectrum disorder

BOA: behavioural observation audiometry

CAEP: cortical auditory evoked potential

CI: cochlear implant

DNA: did not attend

DPOAE: distortion product otoacoustic emission

EEG: electroencephalogram

MPO: maximum power output

OME: otitis media effusion

NAL: National Acoustic Laboratories

PEACH: parents' evaluation of aural/oral performance of children

PG: prescribed gain

REIG: real ear insertion gain

SD: standard deviation

SPL: sound pressure level

UNHS: universal newborn hearing screening

VROA: visual reinforcement orientation audiometry

CEU questions

1. According to the Australian Hearing protocol, the following clients have priority for CAEP testing:
 - a. children with unilateral hearing loss
 - b. children with auditory neuropathy spectrum disorder
 - c. children who can provide reliable behavioural results
 - d. a&b
 - e. b&c

2. According to the Australian Hearing protocol, when CAEPs are detected for a specific speech sound at 75 dB SPL but not at 65 dB SPL, and residual electroencephalogram (EEG) noise levels are acceptable:
 - a. no change of the estimated audiogram is warranted
 - b. the audiogram is re-estimated at the corresponding frequency range by 5 dB
 - c. the audiogram is re-estimated at the corresponding frequency range by 10 dB
 - d. the audiogram is re-estimated at the corresponding frequency range by 15 dB
 - e. the client is reassessed with the CAEP test on the same day

3. According to the Australian Hearing protocol, a valid reason for not conducting a CAEP test is the child
 - a. having a severe hearing loss
 - b. having otitis media
 - c. being awake and alert
 - d. being younger than 6 months of age
 - e. not being able to perform behavioural testing

4. In which cases was CAEP testing not clinically possible or useful?
 - a. the child had a noisy electroencephalogram (EEG)

- b. the child was uncooperative
 - c. the child had a severe case of auditory neuropathy spectrum disorder
 - d. none of the above
 - e. all of the above
5. Apart from providing additional objective information when behavioural information is not available, CAEP testing potentially can be used
- a. to evaluate hearing aid fittings
 - b. to evaluate unaided ability in auditory neuropathy spectrum disorder cases
 - c. to provide additional objective information when deciding for CI candidacy
 - d. for parent counselling
 - e. all of the above

Answers: 1(b), 2(c), 3(b), 4(e), 5(e)

Introduction

Australia has national coverage of universal newborn hearing screening (UNHS) which is now operating in all states and territories under a National Framework incorporating evidence-based standards of practice¹. Babies diagnosed with a hearing loss are followed up by one of the 25 specialized Australian Hearing infant hearing fitting centers. Australian Hearing is a government-funded organization that provides audiological services including hearing aid and cochlear implant support to close to 21,000 young Australians (aged under 26 years) at no cost to families, except for a small annual device maintenance fee. For the 2012 birth year, 386 infants were fitted with their first hearing aids before 6 months of age. This figure is considered to represent all infants fitted in 2012, since Australian Hearing is the sole provider of this service.

The evaluation of hearing aid fittings for infants has long proved difficult for audiologists, due to the challenges of observing behavioural responses to sound in very young infants. Cortical auditory evoked potentials (CAEPs) are applicable to infant hearing aid evaluation and also may be regarded as the auditory evoked response technique most suited to assessing the audibility of hearing aid-amplified speech². While it is feasible to use evoked potentials such as the auditory brainstem response (ABR) and auditory steady-state response (ASSR) to assess hearing aid fitting when behavioural measures cannot be employed, recording CAEPs for this purpose has several advantages over recording early latency electrophysiological measures. First, the acoustic features that are relevant for speech detection and perception can be presented as stimuli³ which are handled reasonably well by a hearing aid. Second, the integrity of the response pathway through to the cortex can be assessed⁴, therefore the presence and absence of CAEPs correlates better with perception⁵. Third, in some cases of auditory neuropathy spectrum disorder (ANSD), a CAEP may be observed even when an ABR is absent^{6,7}. Fourth, CAEPs are proven to be reliably recorded in young awake infants with normal hearing when stimuli are presented at suprathreshold levels⁸. In hearing-impaired children, more care has to be taken however when interpreting absent CAEPs as more than

20% of the children in this group did not show detectable CAEPs, even when the sounds were audible⁹⁻¹¹.

Research involving the use of CAEPs for hearing aid evaluation at the National Acoustic Laboratories (NAL), and around the world, has made it possible to record CAEPs in a clinical setting. Earlier work has shown that CAEPs in aided children are larger than in unaided children^{12,13} and adults². Research influenced by NAL's earlier work in this area has shown that short speech sounds with low-, mid-, and high-frequency content, presented in the free field, can be used to evaluate audibility in unaided and aided clients^{5,6,10,14-22}. Golding et al.¹⁹ showed a significant correlation between CAEPs and parent observations of functional performance systematically recorded using the Parents' Evaluation of Aural/Oral Performance of Children (PEACH). Based on this information and experience, a clinical device (HEARLab™) was developed.

CAEP testing using HEARLab™ was introduced into the Australian Hearing infant clinical pathways during 2011. Infant hearing aid fittings are now systematically evaluated, when clinically appropriate, using CAEP assessment. This paper describes the clinical protocol that is currently being used within Australian Hearing. As the scientific value of CAEPs for (basic) hearing aid fitting evaluation is still under debate^{2,23-33}, there are limited published data that investigate the feasibility of using this test in a clinical setting. To address this gap in knowledge, Australian Hearing reviewed over 80 client files to evaluate whether clinical practice aligned with the clinical protocol. A survey of pediatric audiologists regarding the use of CAEPs in the clinical setting also was conducted to collect information about their perception of cortical testing at Australian Hearing. Three case studies are also provided, demonstrating the clinical use of CAEPs in infant hearing aid fitting for the three major reasons CAEP testing is conducted in the Australian Hearing clinic.

Clinical infant hearing aid fitting evaluation using cortical auditory evoked potentials (CAEPs) in Australia.

The protocol described in this section is nationally implemented by Australian Hearing³⁴. The protocol is based on a comprehensive review of international research^{2,3,5,6,9,10,13,18-20,32,35-39} into CAEPs and the clinical experience gained during the clinical development and evaluation of the HEARLab system at NAL. Aided CAEP assessment now forms part of the clinical pathway for children and other clients whose hearing aid prescription has been based on an audiogram estimated from evoked potential tests (ABR, ASSR). It was introduced into Australian Hearing's clinical program for the following reasons.

- CAEP assessment possibly may add to the information obtained using more traditional assessment techniques, such as behavioural observation audiometry (BOA), as it provides a systematic and objective means of indicating with some level of confidence that low, mid, and high-frequency emphasis speech sounds are audible to the aided child⁹⁻¹¹.
- For many children, particularly those with moderate to severe hearing loss, CAEPs can be used to demonstrate aided benefit to parents in a tangible way^{9-11,13,22}, which may encourage consistent hearing aid use.
- Where some CAEPs are absent, the pattern of results (considering both stimulus type and presentation level) may give a general guide to adjusting a child's hearing aid, in order to achieve audibility for speech at conversational levels^{2,9-11,16,22,32}. It needs to be noted that absent CAEPs not necessarily indicate a (amplified) sound is inaudible to the hearing-impaired child⁹⁻¹¹.
- Where CAEP responses are repeatedly absent, even after increases to the gain-frequency response of a child's hearing aids, results may help parents and professionals in considering moving towards cochlear implant (CI) evaluation, when combined with other audiological information.

How are CAEPs currently implemented for hearing aid fitting evaluation in Australian Hearing³⁴?

CAEPs form part of the initial fitting program for all:

- Clients whose hearing aid fitting has been based upon an audiogram estimated from evoked potentials (tone-burst ABR or ASSR), most commonly infants referred from universal newborn hearing screening.
- Children who have ANSD. Both aided and unaided CAEPs are used in ANSD management. Research into CAEPs with children with ANSD has shown that where CAEPs are present at low stimulus levels, there is a likelihood that subsequent behavioural testing will show hearing at normal levels or a mild hearing loss^{6,7}.

The test is also applicable for:

- Clients of any age who have additional disabilities that have led to a hearing aid fitting based upon minimal behavioural information or that have made it difficult to evaluate the benefit of their hearing aid fitting.
- Clients who are being considered for cochlear implantation due to poor speech perception performance or delayed speech/language development.

CAEP testing is not a priority for children who have:

- A unilateral hearing loss.
- A 3-Frequency Average Hearing Loss (3FAHL) that is estimated to be less than 45 dB HL. The value of 45 dB HL was chosen based on the assumption that a hearing loss of 45 dB or better will have a 10 dB sensation level to a 55 dB SPL speech sound. This will likely result in a CAEP response when the person is unaided⁹. As a result, the aided and unaided conditions are difficult to compare.

Figure 1 shows the Australian Hearing pathway for the initial fitting and evaluation of infants³⁴. CAEP evaluation is usually conducted after the first follow-up appointment, which allows the clinician to provide support and encouragement to the family in their management of their child's hearing aids before embarking upon the evaluation. Hearing aids are fitted according to the national protocol for pediatric amplification in Australia³⁶, recently updated to include the use of NAL-NL2 prescriptive targets derived from a behavioural audiogram that has been either estimated from evoked potential tests or measured using a behavioural procedure. For children diagnosed with ANSD, a battery of measures, including behavioural assessments and functional questionnaires, is used to derive the estimated audiogram⁴⁰.

A review appointment is conducted within two weeks of the fitting. This appointment is devoted mainly to providing support and encouragement to the family in their management of their child's hearing aids. A further appointment within 4 to 6 weeks of the first follow-up is then arranged to evaluate the effectiveness of the hearing aid fitting. This second follow-up appointment is an appropriate time for aided CAEP evaluation. This typically means that aided CAEP evaluation is completed within 8 weeks of the initial hearing aid fitting.

The first CAEP assessment is performed aided, unless the child is diagnosed with ANSD. Three brief speech stimuli (30 ms /m/, 21 ms /g/, and 30 ms /t/ with dominant frequencies at 250, 1250 and 3250 Hz, respectively) are presented in the free field through a loudspeaker at 55, 65, or 75 dB SPL, as described in Van Dun et al.²². If the infant is unsettled and it is likely not all planned stimuli and levels can be tested, the audiologist prioritizes stimulus presentations according to the assumed individual audiogram configuration and other clinical considerations such as degree of hearing loss and aided speech-o-gram³⁴. The speech-o-gram is a visual display of the long term root mean square (rms) spectrum and dynamic range of amplified speech superimposed on the child's hearing thresholds⁴¹. Audiologists use this as a guide to the expected audibility of amplified speech, and thus expected CAEPs, at chosen dB SPL levels. For example, if the main concern is aided audibility at the

higher frequencies, the clinician might opt to begin testing with the /t/-sound only. Figure 2 shows the recommended flowchart for interpretation of each separate speech stimulus³⁴. In summary:

- If a CAEP is obtained at 55 and 65 dB SPL, no change to the client's estimated hearing thresholds (and hence the hearing aid frequency response) is required.
- If a CAEP is present at 65 dB SPL, but not at 55 dB SPL (and detection would be expected based upon the NAL-NL2 aided speech-o-gram for a 55 dB SPL speech signal), the revised hearing thresholds are assumed to be one standard deviation (SD), or 10 dB^{36,42}, poorer than the original estimated thresholds at the corresponding frequency range.
- If a CAEP is present at 75 dB SPL, but not at 65 dB SPL, revised hearing thresholds are assumed to be 1 SD, or 10 dB, poorer than the original estimated thresholds at the corresponding frequency range.
- If no CAEPs are present at 65 or 75 dB SPL, revised hearing thresholds are assumed to be 1.5 SD, or 15 dB, poorer than the original estimated threshold at the corresponding frequency range.

If after hearing aid adjustment (based on the revised estimated hearing thresholds determined above) no CAEPs are present, the 75 dB SPL input aided speech-o-gram, based on the latest estimated audiogram, is inspected. If the speech-o-gram suggests that no detection of the speech spectrum in the frequency range under consideration is expected, the result is consistent with expectations. If no CAEPs are present and the audiogram has already been re-estimated to be 1.5 SD poorer than the average, the PEACH is used to determine whether there are any behavioural responses to sound in the child's real-life environment^{43,44}. This helps to determine whether the child is one of a limited number whose aided CAEPs do not reflect their hearing capacity. It is important to note that CAEPs are not always detected in some children, even when the (aided or unaided) sound is audible⁹⁻¹¹. This can be caused by straightforward reasons like the presence of middle ear disease (which always should be checked prior to performing CAEPs), but also unknown

reasons which are still subject to research (e.g, maturation, stimulus rate or speech discrimination ability). A consistent CAEP absence for multiple speech sounds, levels and visits however might be an indication that closer follow-up is warranted⁹. CAEP results combined with PEACH observations also are used to determine whether referral for cochlear implant candidacy evaluation is appropriate.

Once the audiogram has been re-estimated and the hearing aid adjusted to the new NAL-NL2 prescription targets for that hearing loss³⁶, CAEP assessment can be repeated to determine whether aid adjustments have improved audibility of the speech spectrum.

Analysis of the clinical application of CAEPs in the management of infants with hearing loss.

Objective

The routine use of CAEPs to evaluate infant hearing aid fittings is relatively new in the field of audiology in general, and within Australian Hearing's program in particular. As part of Australian Hearing's ongoing quality assurance program, the clinical application of CAEPs within infant fitting programs was reviewed using a national sample of clinical cases. This review and survey aimed to determine the uptake of the new procedure, compliance with protocols, the feasibility of using the CAEP test in daily clinical practice, and the influence of CAEPs on clinical management of infants with hearing loss.

Method

As part of Australian Hearing's quality review process, a file review conducted by the first author in the latter part of 2013 examined 87 files of all infants fitted with their first hearing aids between October and December 2012, before the age of 6 months. The file review considered the number of children for whom CAEP testing was recommended by the Australian Hearing protocols, the number actually tested, the number of children who were not tested despite indications to do so and the reasons why testing was not completed. The review also investigated the timing of the CAEP assessment within the child's program, and how often individual children were assessed.

Forty-eight Australian Hearing pediatric audiologists were invited to participate to an online survey regarding their experience with the training program, the stimuli and presentation levels typically used during a clinical appointment, clinical decision making and their opinion of the value of using CAEPs in their clinical management of infants with hearing loss. Participants for the audiologist survey were drawn from the email distribution list used for peer support within Australian Hearing.

A reminder was sent after 2 months if the survey was not returned. Thirty-two clinicians responded to the survey at the end of 2014. Surveys were anonymously completed online using SurveyMonkey. This survey was conducted with the approval of the Australian Hearing Human Research Ethics Committee (AHHREC) and conformed to National Health & Medical Research Committee (NH&MRC) guidelines.

Results

File reviews

Most children whose files were audited had completed their initial fitting program at the time of the review. The initial infant fitting program usually includes a first appointment, a fitting, an initial follow-up appointment and at least one subsequent follow up. Over the four appointments, activities such as discussion of amplification choices, ear-mold impressions, hearing aid fitting and evaluation of aided performance are carried out. Once this program is completed children commence subsequent hearing and communication improvement programs which focus on specific needs and goals.

Characteristics of the sample

Files were examined from 87 children who were first fitted with hearing aids before 6 months of age. Four cases were excluded from further review as no data were available, leaving a sample size of 83 children. Of these 83 children, 5 (6%) were identified as Aboriginal or Torres Strait Islander. Sixty-four children (77%) had bilateral hearing aid fittings.

Timing of CAEPs within the initial fitting program

Of the 83 children included in the file review, 55 children (66%) had at least one CAEP assessment completed. Of these 55 children, 53 had CAEP assessment using HEARLab during the initial fitting program. Two children had their initial CAEP assessment prior to amplification as they were

diagnosed with ANSD, and CAEPs were used as part of a battery of tests to ascertain if they required amplification. Both of these children were identified as having absent responses to some or all speech sounds tested and were subsequently fitted with hearing aids within 2-3 weeks of their CAEP assessment. Figure 3 shows that of those 55 children who had CAEPs to evaluate their hearing aid fitting, 35 (64%) had the assessment within 8 weeks of their fitting.

Number of CAEP appointments

Of the 55 children that were CAEP tested during their initial fitting program, Figure 4 shows the number of CAEP appointments that were conducted for each individual child. Repeat testing usually followed the audiogram being re-estimated and hearing aids being adjusted based on the initial CAEP assessment. Subsequently further assessment(s) were carried out to evaluate the effectiveness of the new aid adjustments.

Thirty-eight children (69%) were only assessed once with HEARLab, although optimally children should come in for a second CAEP appointment to verify a modified hearing aid fitting. More often, once the fitting, follow up, CAEP and aid adjustment were completed, the child was old enough to complete behavioural testing. When behavioural information becomes available, more emphasis is placed on fitting to a prescription based on the behavioural audiogram obtained using Visual Reinforcement Orientation Audiometry (VROA). Of the 6 children (11%) who had two or more HEARLab assessments, one child had more than four assessments over a period of 5 months because of a deteriorating hearing loss that required frequent aid adjustment and evaluation via CAEP testing. This child went on to be implanted, a decision supported by the fact that consistent aided CAEPs could not be achieved. In 3 cases the child attended but did not complete the assessment because the child fell asleep or was not in the ideal state for testing. If this occurs, typically a new appointment is booked as soon as possible.

Reasons why CAEP assessment was not performed

Of the 83 children included in the file review, twenty-eight children (33%) did not receive a CAEP assessment. Figure 5 shows the reasons why CAEP testing was not used to evaluate fittings. Fifteen of the aided children had a mild or unilateral hearing loss. Thus according to Australian Hearing protocol, they were not prioritized for aided CAEP assessment.

This means that the remaining 68 children were eligible for CAEP testing. Of these 68 children, 13 (19%) did not get tested with CAEPs, although they should have been according to the Australian Hearing CAEP protocol.

- Four children failed to attend the scheduled CAEP appointment.
- Equipment was unavailable in 3 cases.
- Three children had otitis media effusion (OME) which prevented testing.
- Two children were fitted with hearing aids close to 6 months of age due to other family priorities. It was hence possible to assess them using VROA within two months of fitting. Since reliable behavioural thresholds are preferred for deriving a hearing aid prescription, the clinical program for these two children changed focus from objective CAEP assessment to behavioural assessment.
- In one case no valid reason was given.

Of the reasons stated above, only the last case (1 child, or 2%) possibly was not tested because of incorrectly following the protocol.

Audiologist Survey

CAEP experience

Of the 32 out of 48 clinicians that responded (a 67% response rate), 18 (56%) had conducted CAEP testing for more than 2 years in their clinic. Eight (25%) had performed CAEP evaluations for less than 6 months. Two (6%) had performed more than 30 CAEP assessments in the last 12 months. Sixteen (50%) had tested between 10 and 30 clients in the last year.

Clients tested

Figure 6 shows the distribution of the ages of clients who had been tested at least once by a pediatric clinician (multiple answers were possible). As can be observed from Figure 6, all but one clinician (97%) had tested the target age group, which is infants fitted at < 6 months of age. At this age generally no reliable behavioural testing can be obtained.

Appointment length

A complete appointment (including impressions, hearing aid check, setting up the equipment, settling the child, performing the CAEP test, explaining the results, and hearing aid fitting adjustment) generally took 60 minutes or shorter (indicated by 23 or 72%); 12 clinicians (38%) indicated that testing lasted 45 minutes or less, and 6 (19%) indicated 90 minutes or more. This shows that testing time can vary considerably. Test time may be influenced by the experience of the clinician, the availability of a second clinician to assist and distract the child, the protocol used (number of stimuli used and intensity levels chosen), and the state of arousal of the child. The last reason was perceived by the audiologist as the most likely reason for such a large variability in appointment times. The majority (23 or 72%) of clinicians tested at two stimulus presentation levels, as recommended by the flow chart in Figure 2.

Satisfaction with CAEP assessment

Table 1 presents answers to 6 questions related to interpretation, reception, and satisfaction with CAEP testing. The majority of the users agreed with the statements. The clinicians were also invited to provide voluntary comments to questions 1 to 4 in Table 1, and to the 3 questions below:

- How do you predominantly use the information provided by the system?
- Can you provide two examples where you think cortical testing was not useful?
- Can you provide two examples where you think cortical testing was useful?

In response to the 7 questions above, the clinicians noted that (in descending order of occurrence; out of 30 clinicians that left comments):

- The results were used to verify or modify hearing aid fittings (27 out of 30).
- CAEPs were used for counselling parents to reinforce the need for a hearing aid, or to reassure them that the hearing aid was providing sufficient amplification (17).
- If no aided CAEPs were observed with multiple visits, CAEP testing provided additional information for the decision process towards cochlear implantation. Conversely, if CAEPs were observed when none were expected, the decision towards cochlear implantation was delayed until more (behavioural) information became available (17).
- The results were used in conjunction with other information e.g., parent feedback, the PEACH⁴⁴ and the estimated audiogram based on electrophysiological measures (13).
- The results provided additional information on unaided ability in ANSD cases (12).
- The results provided earlier reassurance than when using behavioural paradigms that speech was being detected with the hearing aids (10).
- It can be useful for clients who cannot provide reliable behavioural feedback, e.g. with developmental delays (9).
- Occasionally CAEPs were not detected when it was believed that the sound was audible, given the estimated audiogram and despite testing under optimal conditions (low electroencephalogram (EEG) noise, good impedance, child alert and settled, tympanograms consistent with normal middle ear function, and hearing aids matched to target). It has been shown non-detected CAEPs are a possibility in young children⁸⁻¹¹. Conversely, CAEPs were occasionally detected while it was believed that the sound was inaudible, a inevitable consequence of using a statistical paradigm^{15,20}. This highlights the need to combine CAEP results with other available information to provide an overall picture and, importantly, to avoid confusing families (7).

- Parents found it hard to relate CAEP results with the (aided) audiogram (4).
- Statistical results were sometimes difficult to interpret. For example, statistical presence of a response to a specific speech sound at a lower level occasionally coincided with the statistical absence at a higher level (3).
- Parents became frustrated if results were inconclusive or not matching expectations (1).

Difficulties with test procedure

According to the clinicians, CAEP testing was occasionally not clinically possible or difficult (in descending order of occurrence; out of 30 clinicians that left comments):

- Children with a noisy EEG were difficult or impossible to test. Noise was related to child behaviour (e.g., movement), additional disabilities or seizures (10 out of 30).
- Technical malfunctions with the recording system could cause issues as well. Examples include broken (electrode) cables, high electrode impedances, and software issues (1).
- Parents were against the use of the test and preferred to wait until behavioural responses were available (1).

Detailed case studies

Three detailed case studies were selected to illustrate how CAEP testing can be used in a clinical environment.

Case study 1. Cochlear Implant candidacy

This child was referred to Australian Hearing via the UNHS program. Table 2 shows the tone-burst auditory brainstem response (ABR) test results for the 4 audiometric frequencies. There were no responses at 95 dB nHL at all test frequencies. Based on the corrections suggested by Vander Werff et al.³⁹, an estimated behavioural audiogram was derived (Table 3). According to the procedure described by Vander Werff et al.³⁹, the threshold for 500 Hz tone-burst (in dB nHL) had to be corrected (improved) by 10 dB to provide an estimated behavioural threshold (in dB HL). Hence, the ABR threshold for 500 Hz in Table 2, which was at least 100 dB nHL, was corrected to 90 dB HL. Similarly, 1, 2 and 4 kHz were corrected by -5, 0 and +5 dB, respectively, to convert from dB nHL to dB HL. Typically a child with ABR results suggesting a severe or profound hearing loss will be offered a simultaneous referral to a CI agency along with a referral to Australian Hearing. This family however wished to defer CI agency referral until further information from a hearing aid trial indicated whether or not the child had aided access to speech sounds.

The child was fitted with hearing aids at 6 weeks of age based on the estimated behavioural audiogram in Table 3. Initial aided CAEP testing was conducted 2 weeks later at the first follow up appointment. Figure 7 shows the grand averages of the CAEPs to three speech stimuli /m/, /g/ and /t/ at 65 and 75 dB SPL via a loudspeaker when the child was bilaterally aided. The figure also shows the associated p-values of the statistical test incorporated in the HEARLab system. A p-value of 0.05 or smaller indicates a high likelihood of a CAEP being present. No CAEPs were detected for any speech sounds at all tested intensities. In accordance with Australian Hearing protocols the estimated audiogram was assumed to be 1.5 SD (or 15 dB worse) than originally estimated at all

frequencies. The hearing aids were then adjusted to meet NAL-NL2 targets at 50, 65 and 80 dB SPL inputs for this new estimated audiogram (see Table 4).

The child was subsequently reassessed at the age of 3 months using aided CAEPs in the free field while bilaterally aided with inputs of 65 and 75 dB SPL for all 3 speech sounds. Again, p-values shown in Table 5 were not significant at either conversational (65 dB SPL) or elevated (75 dB SPL) speech levels. This suggested at least a profound hearing loss and little or no benefit from hearing aids. Results were explained to the parents and CI agency referral was suggested as the next step in this child's program management. Reports on these results were sent to the family's early intervention service and CI centre, where further testing was conducted. Eventually, the child went on to receive bilateral CIs at 5 months of age. The child's parents emailed the audiologists to say *"Thank you so much for the information you gave us on the previous testing as it helped us with our decision to proceed with the implants."*

Case study 2. Ensuring audibility

This child was referred to Australian Hearing via the UNHS program. Diagnostic ABR results (Table 6) were used to estimate a bilateral mild sloping to moderately severe sensorineural hearing loss (Table 7). The child was fitted with bilateral hearing aids at 5 weeks of age based on the estimated hearing thresholds.

Aided CAEP testing was conducted in the free field at 4.5 months of age. Figure 8 shows the CAEPs at 65 and 55 dB SPL of speech sounds /m/, /g/ and /t/ and the p-values associated with the different waveforms. At 65 dB SPL, all speech sounds evoked a CAEP, suggesting audibility across the speech frequency spectrum. According to the child's estimated audiogram (Table 7) and the NAL-NL2 speech-o-gram (dark grey highlighted areas in Figure 9), audibility was expected for low, mid and high frequency speech sounds at 55 dB SPL. Although the speech-o-gram only indicates predicted audibility for 50 dB SPL presentation levels, one can assume that if audibility is expected at 50 dB SPL then it is also expected at 55 dB SPL. As shown in Figure 8, CAEPs at 55 dB SPL indicated

audibility only for speech sound /t/. Australian Hearing protocols determined that the audiogram should be re-estimated to be 1 SD (10 dB) worse for low- and mid-frequency speech sounds. The hearing aids were consequently adjusted to meet the NAL-NL2 targets for 50 dB SPL input.

A subsequent follow up was conducted one month later at 5.5 months of age. The CAEP waveforms and p-values, (see Figure 10), suggest that there was now good audibility for all speech sounds at conversational (65 dB SPL) and for /g/ and /t/ at softer levels (55 dB SPL). Typically when the gain of a hearing aid is increased, the audiologist will conduct an informal test of loudness tolerance or “maximum power output (MPO) check” via moderate and loud intensity impulse sounds to ensure the child is not overamplified. No tolerance issues were detected to impulse sounds in the clinic setting via MPO check and the child’s parents reported no discomfort to sounds in everyday listening environments. The parents were reassured about appropriateness of hearing aid settings and a resulting email was sent by the mother to the audiologists where she commented: *“We feel very relieved, as our faith has been restored in the hearing aids as a result of what we discovered from the results.”*

Case study 3. Decision to fit hearing aids in case of ANSD

This child was referred to Australian Hearing via the UNHS program. Diagnostic audiology assessment showed clear cochlear microphonics on reversal of click stimulus polarity during ABR, and distortion product otoacoustic emissions (DPOAEs) were present in both ears, indicating ANSD.

Unaided CAEP testing in the free field was conducted at Australian Hearing at the age of 3 months. Figure 11 shows responses to (and corresponding p-values of) all three speech sounds /m/, /g/ and /t/ at 65 dB SPL. Responses also were obtained at 55 dB SPL for /g/ and /t/, but were inconclusive for /m/ due to high noise levels. Although there appeared to be a possible wave form in response to the /m/ stimuli, this may be caused by the background noise. A PEACH⁴⁴ diary, which records the parents’ observations of hearing responses in daily environments over a period of time, was given to

the child's parents to complete. A retest of speech sound /m/ at 55 dB SPL was planned one month later.

At the age of 4.5 months, the child had significant responses to /m/ at 55 dB SPL, as shown in Figure 12. The PEACH diary also was scored and results indicated that the child's auditory function in everyday life situations was within 1 SD of normally hearing children of the same age and developmental level.

The combined results suggested that the child was able to detect both conversational (65 dB SPL) and soft level (55 dB SPL) speech sounds whilst unaided. This justified the earlier decision not to aid but to monitor the child's auditory responses via the PEACH diary and to conduct behavioural tests as soon as appropriate. VROA was not conducted until the child was 24 months old (Figure 13) due to the presence of developmental delay and health problems. VROA results showed hearing thresholds within the normal range.

The child's parents reported no hearing difficulties at that time and amplification via hearing aids was deemed to have no or limited benefit. Monitoring continued via functional questionnaires, speech testing when appropriate, and behavioural hearing assessment. The family was advised to consider the use of a wireless remote microphone system if the child showed hearing difficulty in noise at a later stage. CAEP testing was useful in confirming the parents' initial observations of responses to soft sounds and in supporting the decision not to proceed with hearing aid fitting.

Discussion and conclusion

This paper presented the clinical protocol for CAEP use that is currently being applied in the 25 Australian Hearing infant fitting centres across Australia. The file review of 68 cases eligible for CAEP testing (out of 87 files) indicated that in 81% (55 out of 68) of the cases CAEP testing was carried out when it was deemed necessary by the Australian Hearing CAEP protocol. This means that most children could be assessed in their initial fitting program when they were identified as a priority for CAEP testing. In 17% (12 out of 68) of the cases, reasons for not testing were outside the control of the clinician. Only in 2% of the cases (1 out of 68), the protocol – possibly – was not followed (with no valid reason provided). This shows that both the uptake of the new CAEP procedure and compliance with the Australian Hearing CAEP protocol is high. The review found that CAEP assessment is often achieved within a standard audiological appointment of up to 90 minutes. The aided CAEPs were most commonly tested within 8 weeks of the fitting. It is encouraging that there were few barriers (equipment being unavailable or the child not being in a good state of alertness for testing) to complete the test protocol. This indicates the feasibility of using CAEP testing in daily clinical practice.

Pediatric audiologists indicated that CAEP testing influenced their approach to rehabilitation, was well received by parents, and that they were satisfied by the technique. Some audiologists reported, however, that parents were frustrated with inconclusive results, or results that did not match expectations. This frustration can be addressed by appropriate explanation of the limitations of the testing, and clear explanation of the next steps, e.g. CAEP retesting or a different assessment technique. Conversely, clinical experience shows as well that parents experience similar frustration when behavioural test results are inconclusive. The three case studies highlighted the four main situations where CAEP testing can be useful, more specifically to evaluate hearing aid fittings, indicate unaided audibility in ANSD cases, provide additional objective information when deciding on CI candidacy, and assist with parent counselling.

Overall, the review of the use of CAEPs in Australian Hearing clinics indicates that CAEPs can be effectively integrated into infant fitting programs and provide valuable information where behavioural testing is unreliable or impossible. Clinical verification of the CAEP testing method is still ongoing, however, and research questions still remain. For example, to what extent does fine-tuning of a hearing aid fitting using the Australian Hearing clinical CAEP protocol result in a significant increase of CAEP presence at the second assessment? Does CAEP assessment contribute to a hearing aid fitting which is significantly closer to hearing aid target fitting than without? Do behavioural outcomes improve when CAEPs are used early on to evaluate and adjust the hearing aid fitting. Finally, does CAEP assessment result in a significantly earlier decision to proceed with cochlear implantation?

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Figures

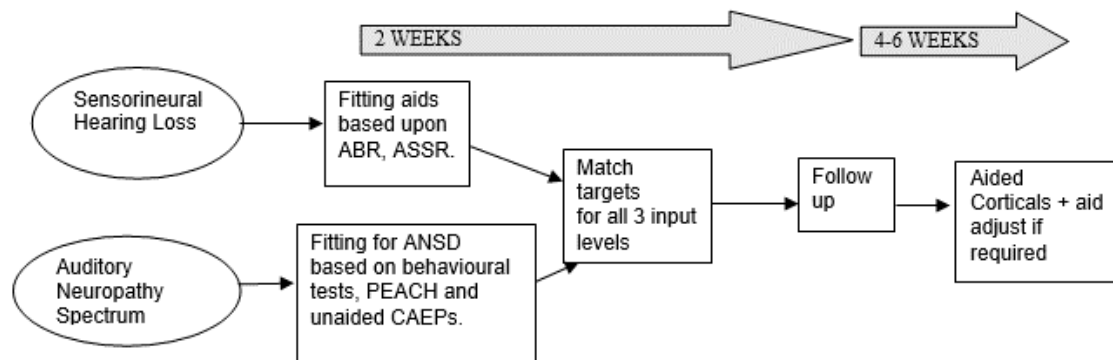


Figure 1: Clinical pathway for aided CAEP assessment within Australian Hearing pediatric program.

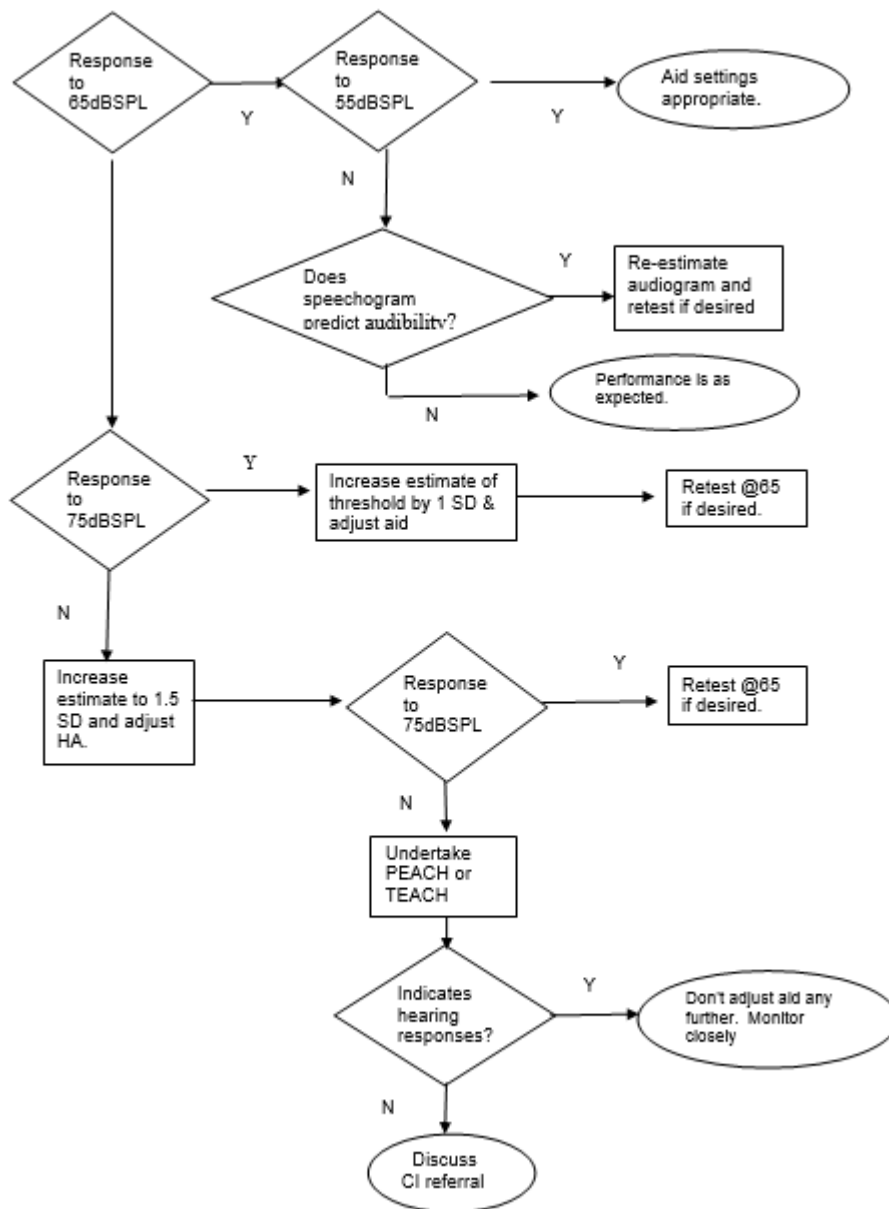


Figure 2: Aid adjustment per speech stimulus.

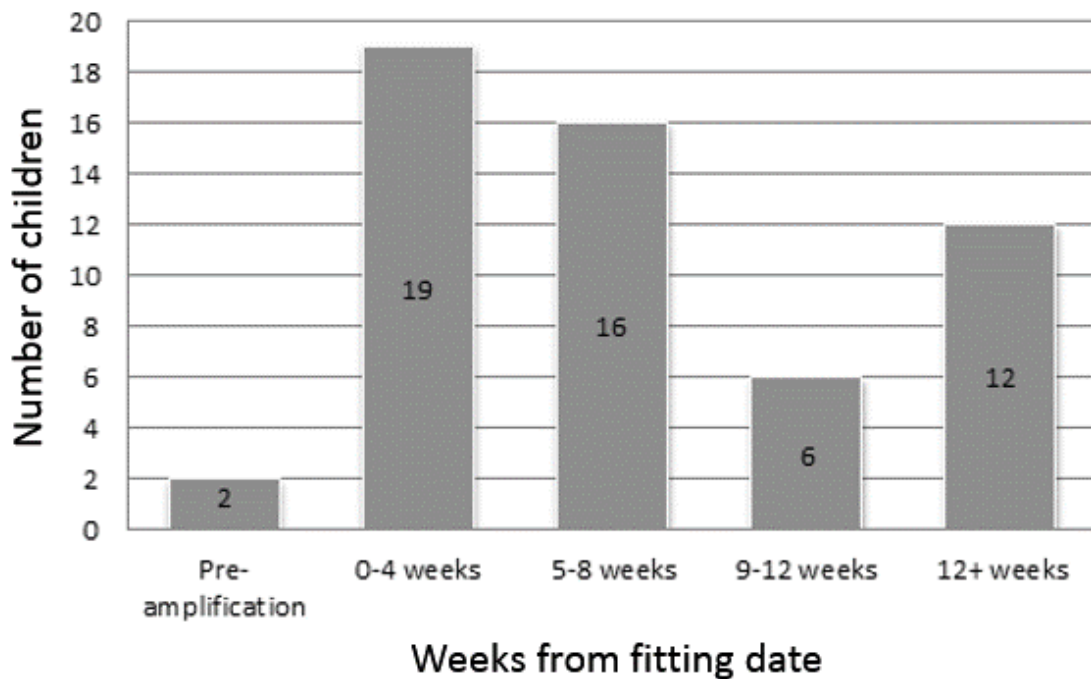


Figure 3: Interval between fitting and first CAEP assessment

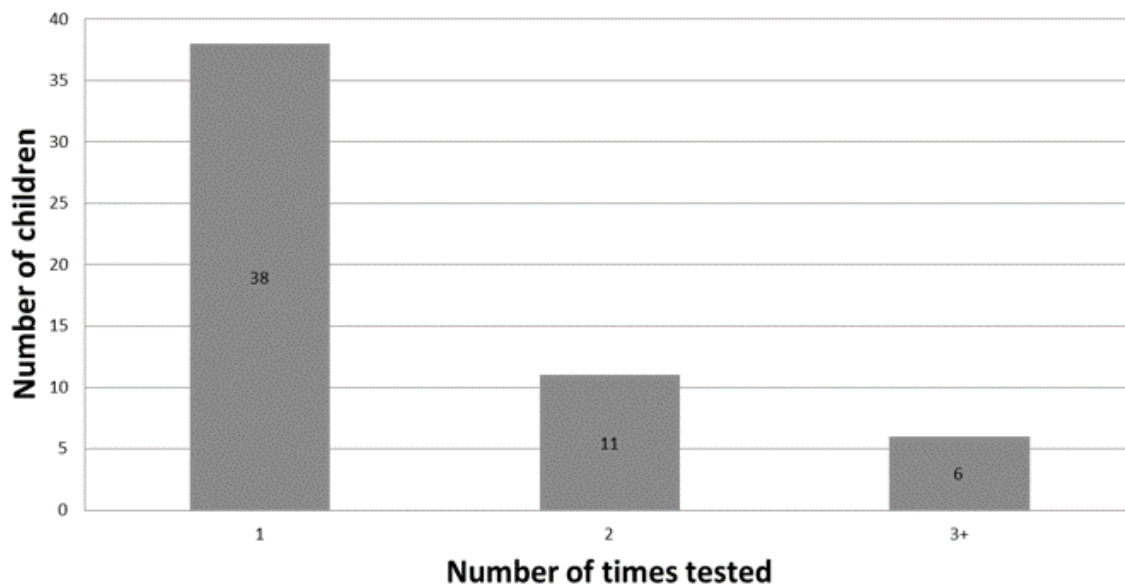


Figure 4: How often were CAEPs used in infant fitting programs?

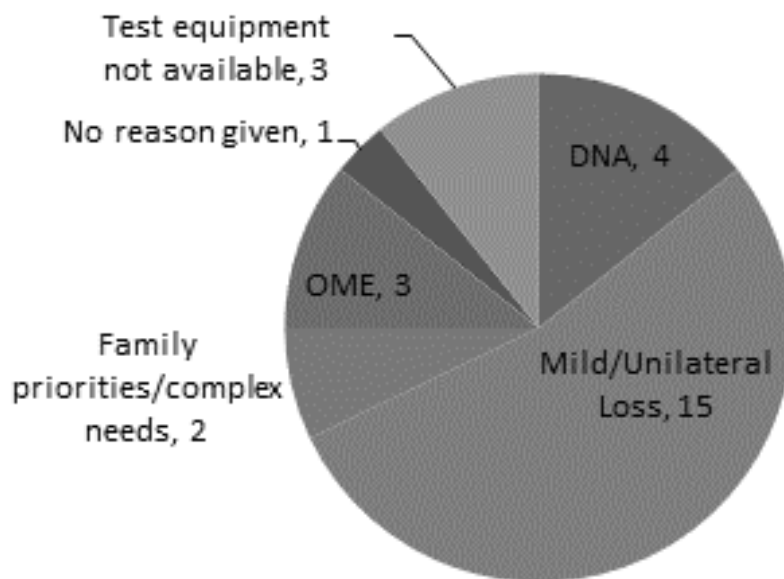


Figure 5: Reasons why CAEP assessment was not performed in the infant fitting program (n=28).

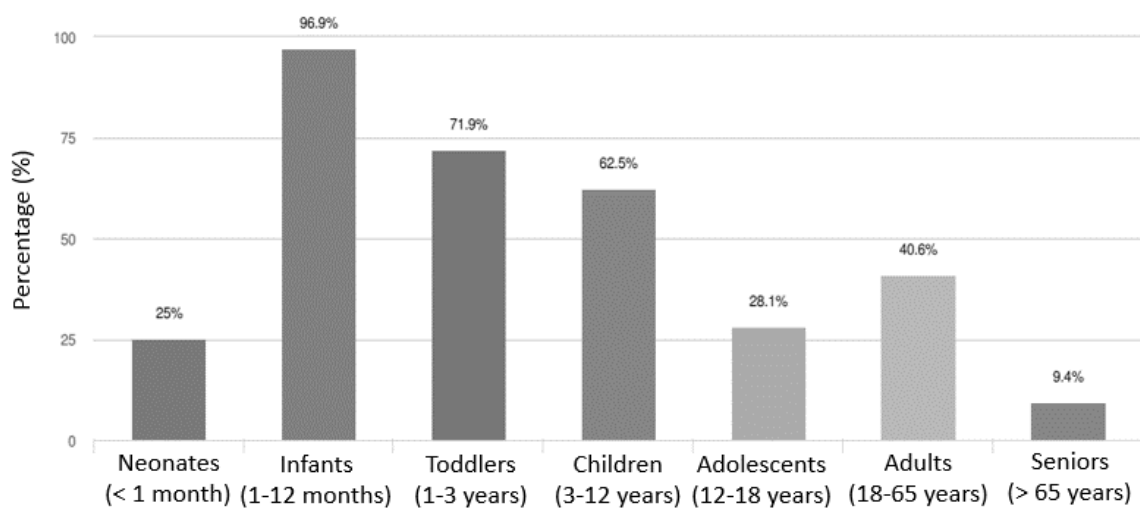


Figure 6. What client groups/patients have you assessed using the HEARLab system?

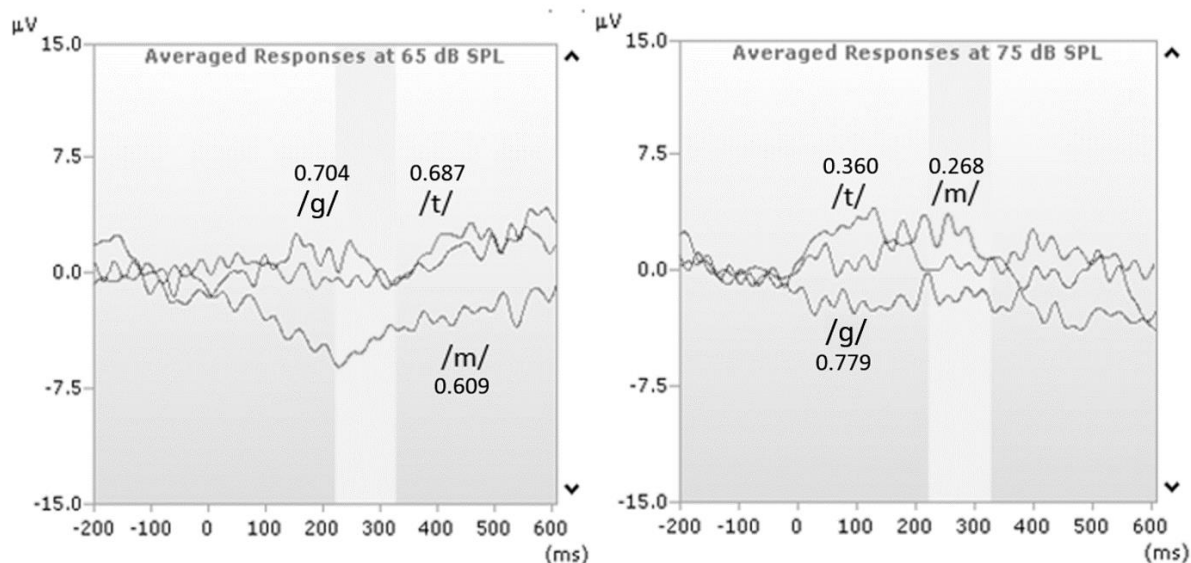


Figure 7. Case study 1: CI candidacy. Absent responses to speech stimuli /m/, /g/ and /t/ at 65 and 75 dB SPL via a loudspeaker when bilaterally aided. Statistical p-values for every speech sound are provided ($p \leq 0.05$ indicates a high likelihood of a CAEP being present).

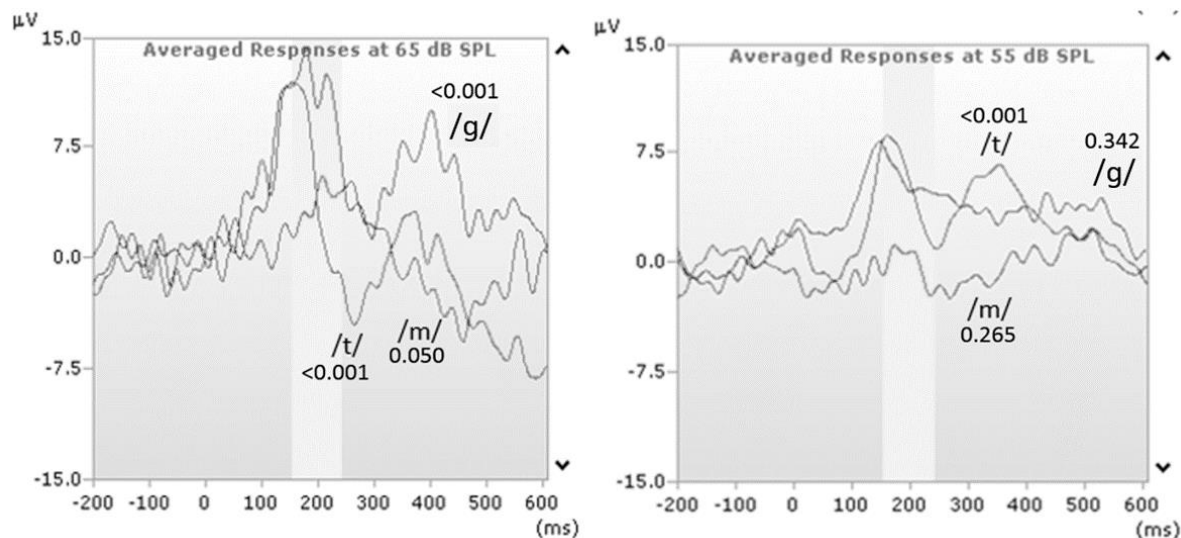


Figure 8. Case study 2: Ensuring audibility, first visit. Present responses to speech stimuli /m/, /g/ and /t/ at 65 dB SPL, and to the /t/ stimulus at 55 dB SPL via a loudspeaker when bilaterally aided. Statistical p-values for every speech sound are provided ($p \leq 0.05$ indicates a high likelihood of a CAEP being present).

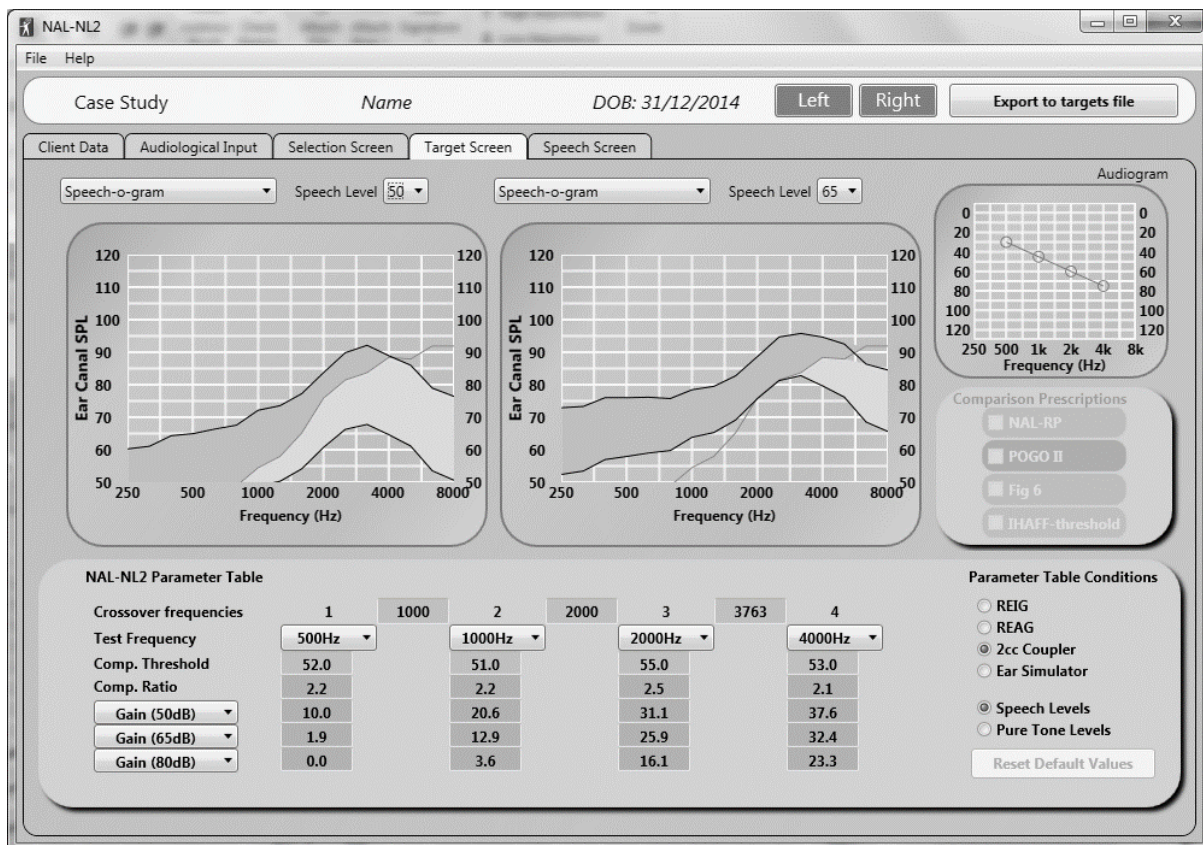


Figure 9. Case study 2: Ensuring audibility. Expected audibility for 50 and 65 dB SPL speech as indicated by NAL-NL2 speech-o-gram.

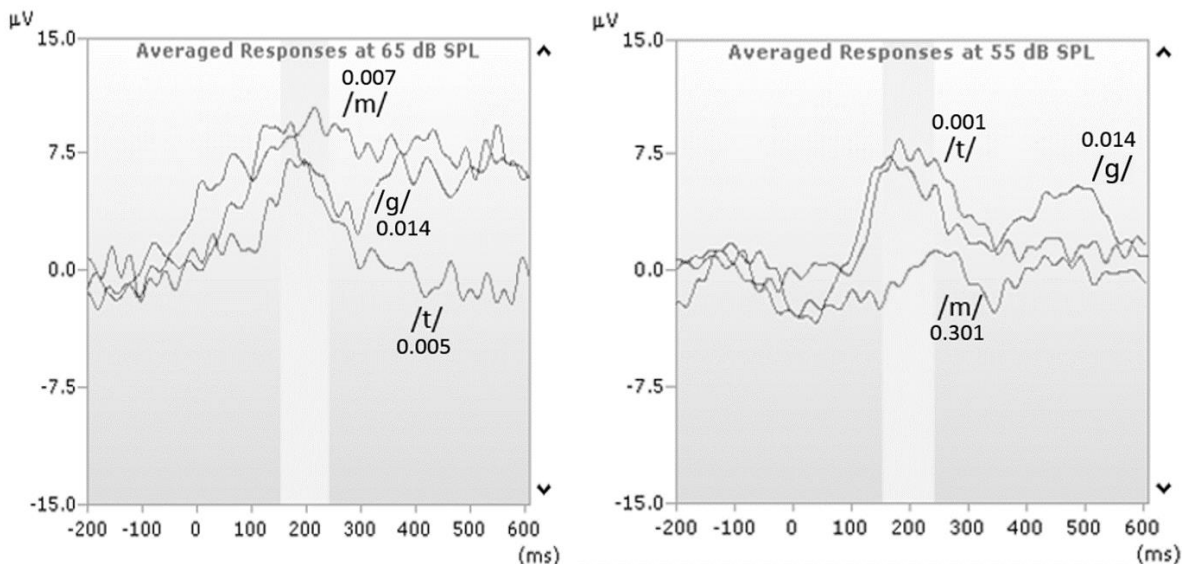


Figure 10. Case study 2: Ensuring audibility, second visit. Present responses to speech stimuli /m/, /g/ and /t/ at 65 dB SPL, and to the /g/ and /t/ stimuli at 55 dB SPL via a loudspeaker when bilaterally aided. Statistical p-values for every speech sound are provided ($p \leq 0.05$ indicates a high likelihood of a CAEP being present).

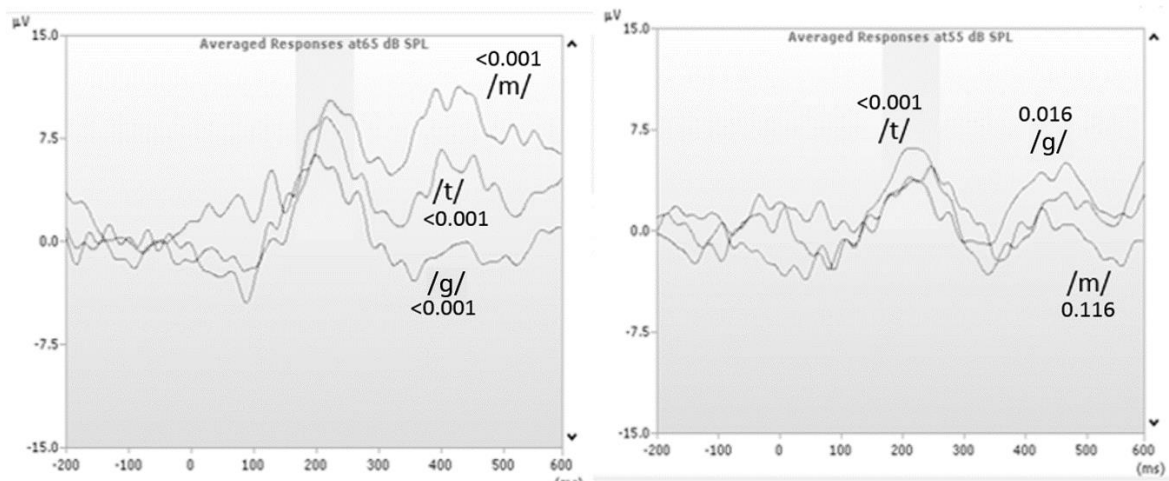


Figure 11. Case study 3: ANSD, first visit. Present responses to speech stimuli /m/, /g/ and /t/ at 65 dB SPL, and to the /g/ and /t/ stimuli at 55 dB SPL via a loudspeaker when bilaterally aided. Statistical p-values for every speech sound are provided ($p \leq 0.05$ indicates a high likelihood of a CAEP being present).

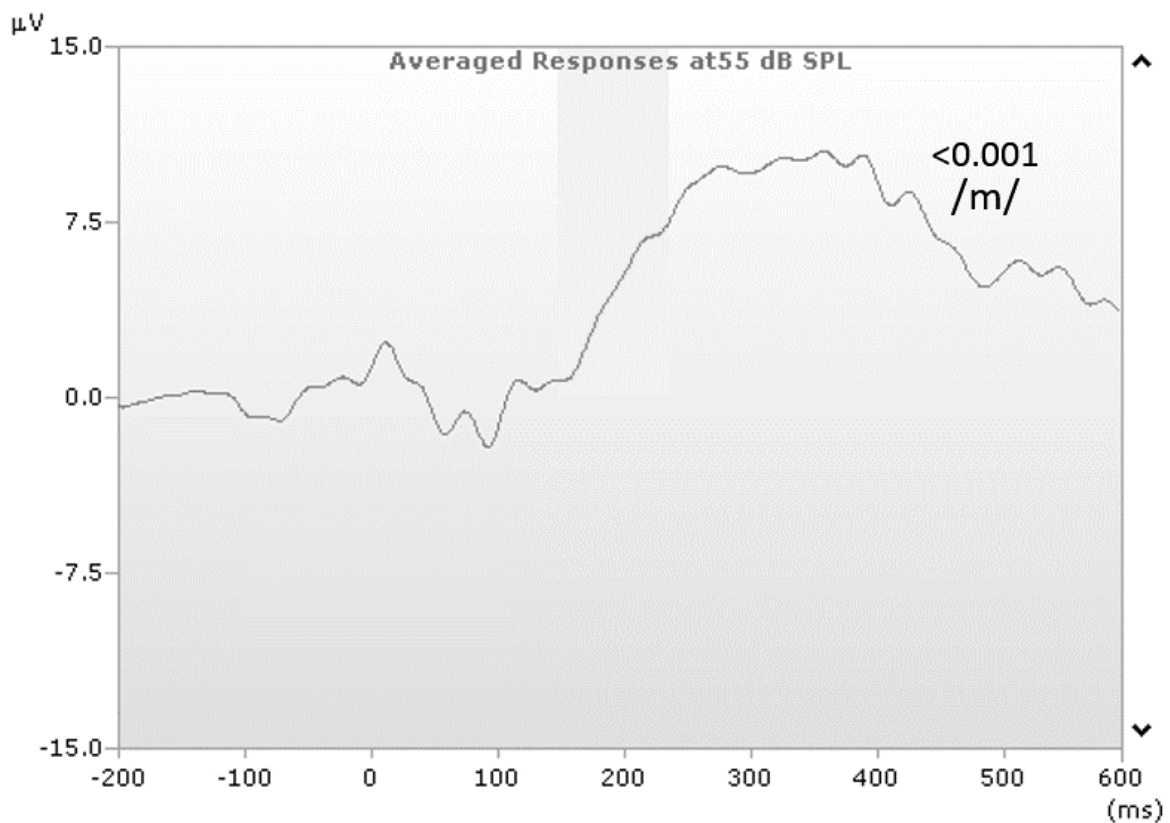


Figure 12: Case study 3: ANSD, second visit. Present response at 55 dB SPL when testing /m/ only (statistical p-value ≤ 0.05).

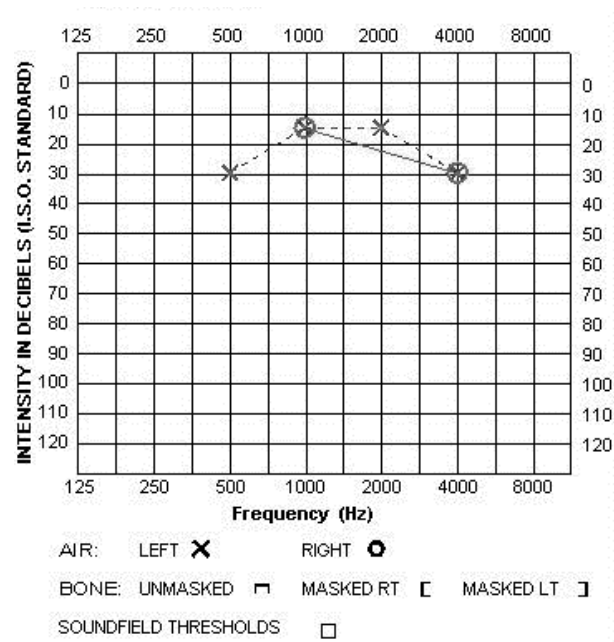


Figure 13. Case study 3: ANSD. Latest audiogram obtained using play audiometry at the age of 2 years and 10 months. It is incomplete as testing had to be discontinued due to child's attention.

Table 1. Additional questions from the HEARLab user survey.

Questions	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
[1] The CAEP results influence my approach to rehabilitation	1 (3%)	0 (0%)	0 (0%)	21 (66%)	10 (31%)
[2] The CAEP results are clinically consistent with behavioural results, where applicable.	0 (0%)	0 (0%)	3 (9%)	24 (75%)	5 (16%)
[3] The CAEP results are easy to interpret.	0 (0%)	1 (3%)	1 (3%)	21 (66%)	9 (28%)
[4] The CAEP results are positively received by parents.	1 (3%)	0 (0%)	2 (6%)	21 (66%)	8 (25%)
[5] I would recommend CAEP testing to other Audiologists who do not have the HEARLab system.	1 (3%)	0 (0%)	0 (0%)	16 (50%)	15 (47%)
[6] Overall, how would you rate your satisfaction with CAEP testing (using the HEARLab test system)?	0 (0%)	0 (0%)	0 (0%)	21 (68%)	10 (32%)

Table 2. Case study 1: CI candidacy. Tone-burst auditory brainstem response (ABR) test results at diagnosis (in dB nHL). For conversion purposes, >95 dB nHL is taken equal to 100 dB nHL, a lower limit of the estimated hearing loss.

Frequency (in Hz)	500	1000	2000	4000
Right	>95	>95	>95	>95
Left	>95	>95	>95	>95

Table 3. Case study 1: CI candidacy. Resulting estimated behavioural audiogram (in dB HL) using dB nHL to dB HL correction, derived from Vander Werff et al³⁹. The values in Table 2 are corrected by -10, -5, 0 and +5 dB for frequencies 0.5, 1, 2 and 4 kHz, respectively, to convert from dB nHL to dB HL.

Frequency (in Hz)	500	1000	2000	4000
Right	90	95	100	105
Left	90	95	100	105

Table 4. Case study 1: CI candidacy. Estimated audiogram adjusted for CAEP results.

Frequency (in Hz)	500	1000	2000	4000
Right	105	110	115	120
Left	105	110	115	120

Table 5. Case study 1: CI candidacy. Statistical p-values for the aided 3 speech sounds at 2 stimulus levels.

	/m/	/g/	/t/
75 dB SPL	0.617	0.418	0.705
65 dB SPL	0.639	0.505	0.318

Table 6. Case study 2: Tone-burst auditory brainstem response (ABR) testing results at diagnosis (in dB nHL). 'DNT' signifies 'Did Not Test' and thresholds at 1 kHz are interpolated from the thresholds at 0.5 and 2 kHz.

Frequency (in Hz)	500	1000	2000	4000
Right	40	DNT	60	70
Left	40	DNT	70	80

Table 7. Case study 2: Resulting estimated behavioural audiogram (in dB HL) using dB nHL to dB HL correction, derived from Vander Werff et al.³⁹.

Frequency (in Hz)	500	1000	2000	4000
Right	30	45	60	75
Left	30	50	70	85

References

1. Bromley M, Wake M, Leigh G, et al. National framework for neonatal hearing screening. 2013;1–67.
2. Korczak PA, Kurtzberg D, Stapells DR. Effects of sensorineural hearing loss and personal hearing aids on cortical event-related potential and behavioral measures of speech-sound processing. *Ear Hear*. 2005;26(2):165–185.
3. Kurtzberg D, Stapells DR, Wallace IF. Event-related potential assessment of auditory system integrity: Implications for language development. In: Vietze PM, Vaughan HG, eds. *Early identification of infants with developmental disabilities*. New York: Grune & Stratton; 1988:160–180.
4. Kraus N, McGee TJ, Koch DB. Speech sound representation, perception, and plasticity: a neurophysiologic perspective. *Audiol Neurotol*. 1998;3(2-3):168–182.
5. Dillon H. So, baby, how does it sound? Cortical assessment of infants with hearing aids. *Hear J*. 2005;58(10):10–17.
6. Pearce W, Golding M, Dillon H. Cortical auditory evoked potentials in the assessment of auditory neuropathy: Two case studies. *J Am Acad Audiol*. 2007;18(5):380–390.
7. Rance G, Cone-Wesson B, Wunderlich J, Dowell R. Speech perception and cortical event related potentials in children with auditory neuropathy. *Ear Hear*. 2002;23(3):239–253.
8. Cone B, Whitaker R. Dynamics of infant cortical auditory evoked potentials (CAEPs) for tone and speech tokens. *Int J Pediatr Otorhinolaryngol*. 2013;77(7):1162–1173.
9. Van Dun B, Carter L, Dillon H. Sensitivity of cortical auditory evoked potential detection for hearing-impaired infants in response to short speech sounds. *Audiol Res*. 2012;2:e13:65–76.
10. Chang H-W, Dillon H, Carter L, Van Dun B, Young S-T. The relationship between cortical auditory evoked potential (CAEP) detection and estimated audibility in infants with sensorineural hearing loss. *Int J Audiol*. 2012;51(9):663–670.
11. Gardner-Berry K, Ching TYC, Chang H-W, Hou SYL. Cortical auditory evoked potential detection rates at different sensation levels in infants with sensory/ neural hearing loss and auditory neuropathy spectrum disorder. *Semin Hear*. 2015;In prep.
12. Rapin I, Graziani LJ. Auditory-evoked responses in normal, brain-damaged, and deaf infants. *Neurology*. 1967;17(9):881–894.
13. Barnet AB. EEG audiometry in children under three years of age. *Acta Otolaryngol*. 1971;72:1–13.
14. Almeqbel A. Speech-evoked cortical auditory responses in children with normal hearing. *South African J Cogn Dev*. 2013;60:38–43.

15. Carter L, Golding M, Dillon H, Seymour J. The detection of infant cortical auditory evoked potentials (CAEPs) using statistical and visual detection techniques. *J Am Acad Audiol*. 2010;21(5):347–356.
16. Carter L, Dillon H, Seymour J, Seeto M, Van Dun B. Cortical auditory-evoked potentials (CAEPs) in adults in response to filtered speech stimuli. *J Am Acad Audiol*. 2013;24(9):807–22.
17. Durante AS, Wieselberg MB, Carvalha S, et al. Cortical auditory evoked potential evaluation of speech detection in adult hearing aid users. 2014;26(5):367–373.
18. Golding M, Purdy S, Sharma M, Dillon H. The effect of stimulus duration and inter-stimulus interval on cortical responses in infants. *Aust New Zeal J Audiol*. 2006;28(2):122–136.
19. Golding M, Pearce W, Seymour J, Cooper A, Ching T, Dillon H. The relationship between obligatory cortical auditory evoked potentials (CAEPs) and functional measures in young infants. *J Am Acad Audiol*. 2007;18(2):117–125.
20. Golding M, Dillon H, Seymour J, Carter L. The detection of adult cortical auditory evoked potentials (CAEPs) using an automated statistic and visual detection. *Int J Audiol*. 2009;48(12):833–842.
21. Purdy SC, Sharma M, Munro KJ, Morgan CLA. Stimulus level effects on speech-evoked obligatory cortical auditory evoked potentials in infants with normal hearing. *Clin Neurophysiol*. 2013;124(3):474–480.
22. Van Dun B, Dillon H, Kania A. Cortical auditory evoked potentials (CAEPs) in (un)aided normal-hearing and hearing-impaired adults. *Semin Hear*. 2015;Accepted.
23. Billings CJ. Uses and limitations of electrophysiology with hearing aids. *Semin Hear*. 2013;34(4):257–269.
24. Billings CJ, Papesh MA, Penman TM, Baltzell LS, Gallun FJ. Clinical use of aided cortical auditory evoked potentials as a measure of physiological detection or physiological discrimination. *Int J Otolaryngol*. 2012;2012:1–14.
25. Billings CJ, Tremblay KL, Miller CW. Aided cortical auditory evoked potentials in response to changes in hearing aid gain. *Int J Audiol*. 2011;50(7):459–467.
26. Billings CJ, Tremblay KL, Souza PE, Binns MA. Effects of hearing aid amplification and stimulus intensity on cortical auditory evoked potentials. *Audiol Neurotol*. 2007;12(4):234–246.
27. Easwar V, Glista D, Purcell DW, Scollie SD. The effect of stimulus choice on cortical auditory evoked potentials (CAEP): Consideration of speech segment positioning within naturally produced speech. *Int J Audiol*. 2012;51(12):926–931.
28. Easwar V, Glista D, Purcell DW, Scollie SD. Hearing aid processing changes tone burst onset: effect on cortical auditory evoked potentials in individuals with normal audiometric thresholds. *Am J Audiol*. 2012;21(1):82–90.

29. Easwar V, Purcell DW, Scollie SD. Electroacoustic comparison of hearing aid output of phonemes in running speech versus isolation: Implications for aided cortical auditory evoked potentials testing. *Int J Otolaryngol.* 2012;2012:1–10.
30. Jenstad LM, Marynewich S, Stapells DR. Slow cortical potentials and amplification - Part II: Acoustic measures. *Int J Otolaryngol.* 2012;2012:1–14.
31. Marynewich S, Jenstad LM, Stapells DR. Slow cortical potentials and amplification - Part I: N1-P2 measures. *Int J Otolaryngol.* 2012;2012:1–11.
32. Tremblay KL, Billings CJ, Friesen LM, Souza PE. Neural representation of amplified speech sounds. *Ear Hear.* 2006;27(2):93–103.
33. Tremblay KL, Kalstein L, Billings CJ, Souza PE. The neural representation of consonant-vowel transitions in adults who wear hearing aids. *Trends Amplif.* 2006;10(3):155–162.
34. King A, Carter L, Van Dun B, Zhang V, Pearce W, Ching TYC. *Australian Hearing Aided Cortical Evoked Potentials Protocols.*; 2014.
35. Garinis AC, Cone-Wesson BK. Effects of stimulus level on cortical auditory event-related potentials evoked by speech. *J Am Acad Audiol.* 2007;18(2):107–116.
36. King AM. The national protocol for paediatric amplification in Australia. *Int J Audiol.* 2010;49:S64–S69.
37. Martin BA, Tremblay KL, Stapells DR. Principles and applications of cortical auditory evoked potentials. In: Burkard RF, Eggermont JJ, Don M, eds. *Auditory evoked potentials: Basic principles and clinical application.* Philadelphia: Lippincott Williams and Wilkins; 2007:482–507.
38. Sharma A, Martin K, Roland P, et al. P1 latency as a biomarker for central auditory development in children with hearing impairment. *J Am Acad Audiol.* 2005;16(8):564–573.
39. Vander Werff KR, Prieve BA, Georgantas LM. Infant air and bone conduction tone burst auditory brain stem responses for classification of hearing loss and the relationship to behavioral thresholds. *Ear Hear.* 2009;30(3):350–368.
40. King AM, Purdy SC, Dillon H, Sharma M, Pearce W. Australian Hearing protocols for the audiological management of infants who have auditory neuropathy. *Aust New Zeal J Audiol.* 2005;27(1):69–77.
41. Dillon H. *Hearing aids.* 2nd ed. New York: Thieme Medical Publishers; 2012.
42. Stapells DR, Gravel JS, Martin BA. Thresholds for auditory brain stem responses to tones in notched noise from infants and young children with normal hearing or sensorineural hearing loss. *Ear Hear.* 1995;16(4):361–371.
43. Bagatto MP, Scollie SD. Validation of the Parents' Evaluation of Aural/Oral Performance of Children (PEACH) Rating Scale. *J Am Acad Audiol.* 2013;24(2):121–125.

44. Ching TYC, Hill M. The parents' evaluation of aural/oral performance of children (PEACH) scale: Normative data. *J Am Acad Audiol.* 2007;18(3):220–235.