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The Relationship between Obligatory Cortical Auditory Evoked Potentials (CAEPs) and Functional Measures in Young Infants

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Abstract

Finding ways to evaluate the success of hearing aid fittings in young infants has increased in importance with the implementation of hearing screening programs. Cortical auditory evoked potentials (CAEP) can be recorded in infants and provides evidence for speech detection at the cortical level. The validity of this technique as a tool of hearing aid evaluation needs, however, to be demonstrated. The present study examined the relationship between the presence/absence of CAEPs to speech stimuli and the outcomes of a parental questionnaire in young infants who were fitted with hearing aids. The presence/absence of responses was determined by an experienced examiner as well as by a statistical measure, Hotelling's T^2. A statistically significant correlation between CAEPs and questionnaire scores was found using the examiner's grading ($r_s = 0.45$) and using the statistical grading ($r_s = 0.41$), and there was reasonably good agreement between traditional response detection methods and the statistical analysis.

Key Words: Cortical auditory evoked potentials, hearing aids, infants, questionnaire

Abbreviations: ABR = auditory brainstem response; AN = auditory neuropathy/dys-synchrony; BOA = behavioral observation audiometry; CAEPs = cortical auditory evoked potentials; ECochG = electrocochleography; EEG = electroencephalography; MD = multiple disability; NAL = National Acoustic Laboratories; PEACH = Parent's Evaluation of Aural/Oral Performance in Children; SN = sensorineural

Sumario

La búsqueda de formas de evaluar el éxito de una adaptación de auxiliares auditivos en niños pequeños ha aumentado en importancia con la implementación de los programas de tamizaje auditivo. Se pueden registrar potenciales evocados auditivos corticales (CAEP) en infantes y aportar evidencia sobre la detección del lenguaje a nivel cortical. La validez de esta técnica como una herramienta para la evaluación de las necesidades de adaptación de auxiliares auditivos necesita, sin embargo, ser demostrada. El presente estudio examinó la relación entre la presencia/ausencia de CAEP ante estímulos de lenguaje y el resultado de un cuestionario a los padres de infantes a los que se adaptaron auxiliares auditivos. La presencia/ausencia de respuestas fue determinada por un examinador con experiencia, así como por un procedimiento de medición estadística: la T^2 de Hotelling. Se encon-

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tró una correlación estadísticamente significativa entre los CAEP y los puntajes del cuestionario, utilizando la gradación del examinador ($r_s = 0.45$) y utilizando la gradación estadística ($r_s = 0.41$), y existió un acuerdo razonablemente bueno entre los métodos tradicionales de detección de respuesta y el análisis estadístico.

Palabras Clave: Potenciales evocados auditivos corticales, auxiliares auditivos, infantes, cuestionario

Abreviaturas: ABR = respuestas evocadas del tallo cerebral; AN = neuropatía/dis-sincronía auditiva; BOA = audiometría por observación de comportamiento; CAEP = potenciales evocados auditivos corticales; ECochG = electrococleografía; EEG = electroencefalografía; MD = discapacidad múltiple; NAL = Laboratorios Nacionales de Acústica; PEACH = Evaluación de la Padres del Desempeño Auditivo/Oral en Niños; SN = sensorineural

As the implementation of infant hearing screening programs gains momentum worldwide, the need for ways to evaluate hearing aid fittings in very young infants becomes more important. Systematic prescriptive methods, such as NAL-NL1 (National Acoustic Laboratories—nonlinear, version 1) or DSL [i/o] (desired sensation level [input/ output]), use behavioral threshold inputs or estimates based on electrophysiological thresholds to derive target gain, but methods that verify the success of the fitting process in infants are limited. This is particularly the case before the infant is able to respond to behavioral threshold-seeking techniques and before speech recognition tests can be administered (Snik et al, 2001). For these young infants, evidence of the appropriateness of the fit may be based on direct observation of behaviors (either by behavioral observation audiometry [BOA] or parental questionnaire) or electrophysiological test outcomes.

The most common approach to verifying the fit in this young population is to use information gained from BOA, the outcomes of which are highly dependent on the infant's state (Hodgson, 1994; Bess and Humes, 2003). Ewing (Ewing and Ewing, 1944) pioneered this form of assessment and used a wide variety of noisemakers such as bells, rattles, and rustling paper to elicit a response. The technique, in brief, involves the presentation of noisemakers in the sound field at known levels and then observation of the infant's response to these sounds. These responses may take the form of eye-widening, startles, or cessation of movement. While the infant is expected to respond to ever-decreasing levels of presentation as they mature, the magnitude or presence of this improvement may be altered by the presence of cochlear recruitment or by global developmental delay (Dahle and McCollister, 1983; Hodgson, 1994; Martin and Clark, 2003). The detection of asymmetric hearing loss or auditory thresholds is also not feasible using this technique.

Parental questionnaires have been widely used in health areas such as speech pathology and psychology to document various behaviors and development, and their use is equally suited to monitoring auditory responses (Stelmachowicz, 1999; Arlinger, 2001; Sirimanna, 2001). These functional observations are more likely to be a useful measure of hearing aid effectiveness, or the relative effectiveness of different adjustments, if a structured questionnaire is used and administered pre- and postfitting or pre- and postadjustment of the hearing aids. Several questionnaires exist for parents of older children, including the "Meaningful Auditory Integration Scale" (MAIS; Robbins et al, 1991) and the "Listening Progress Profile" (LiP; Archbold, 1994), although they were designed to evaluate communication skills in children with severe to profound deafness. There are, however, very few published outcome assessment tools for infants. The Family Expectation Worksheet (FEW) is one such tool where families rate the degree of success achieved for each agreed goal (Palmer and Mormer, 1999). If any goals associated with responsiveness to sound are not met, then the appropriateness of the fit and the functionality of the hearing aids themselves are reviewed (Dillon, 2001).

Another questionnaire that is suited for use with young infants, the Parent's Evaluation of Aural/Oral Performance in Children (PEACH), consists of 11 probe areas: questions that assess listening in quiet, listening in noise, and alertness to environmental sound (Ching and Hill, forthcoming). Parents are asked to describe their baby's aural/oral skills based on real-life experiences, and scores are assigned based on the number of observed behaviors and how frequently these occur. A score of "4" is assigned if the parent can provide multiple examples to a specific question while "0" is assigned when the parent cannot recall any examples of that specific behavior. Scores to all questions within a probe area are summed to provide an overall score, and scores for subsets of questions are summed to provide two subscale scores. Normative data from normally hearing children aged 0.25 to 46 months and information about critical differences are available (Ching and Hill, forthcoming). The validity of this measure was established experimentally using the results from 30 infants and children who had severe-profound hearing loss and were consistent hearing aid users (Ching et al, 2003). These children wore hearing aids set according to three different hearing responses over a trial period of two to four weeks per fit. Parents and teachers completed PEACH or TEACH (i.e., the teacher equivalent of the PEACH questionnaire) evaluations at the end of each trial period, and their ratings of the relative effectiveness of the different gain-frequency responses were significantly correlated. For school-aged children, the frequency response rated highest by the parents and teachers was also preferred by the children using a paired-comparison task (Ching et al, 2003).

Electrophysiological techniques may also be useful tools for verifying the fit of a hearing aid in infant populations and in children with multiple disabilities. The recording of auditory brainstem response (ABR) thresholds to brief-tone stimuli (Stapells and Kurtsberg, 1991; Stelmachowicz, 1999), or auditory steady state responses (ASSR) to frequency-modulated stimuli (Perez-Abalo et al, 2001; Picton et al, 2002) provides valuable diagnostic information and threshold estimates for hearing aid prescription methods (Dillon, 2001). Recording cortical auditory evoked potentials (CAEPs) can, however, provide evidence of speech detection at the cortical level in the auditory system. Robust CAEPs can be observed to speech stimuli presented at conversational level in infants who are awake and have normal hearing (Kurtzberg, 1989; Steinschneider et al, 1992; Cone-Wesson and Wunderlich, 2003). They have also been recorded to verify the audibility of stimuli presented at conversational level in infants fitted with hearing aids or in infants who are under evaluation for hearing aid fitting (Rapin and Granziani, 1967; Gravel et al, 1989; Cone-Wesson and Wunderlich, 2003).

The validity of this technique as a tool of hearing aid evaluation needs to be demonstrated using either (1) criterion validity (i.e., the CAEP outcomes are compared with a "gold standard" measure) or (2) predictive validity where longitudinal results are reviewed in association with ongoing rehabilitative outcomes (Abramson and Abramson, 2001). The purpose of the present study was, therefore, to use criterion validity to examine the relationship between the presence/absence of CAEPs to speech stimuli presented at conversational level and outcomes from the PEACH questionnaire, in infants fitted with hearing aids. Results were examined for infants and children with evidence of sensorineural (SN) hearing loss, auditory neuropathy/dys-synchrony (AN) and those with multiple disabilities (MD). The relationship between CAEP outcomes and PEACH scores was also compared with the relationship between the electrophysiological thresholds from ABR or electrocochleography (ECochG) recordings and PEACH scores.

METHOD

Subjects

There were 31 infants and young children, 11 female and 20 male, with a corrected age of eight weeks to three years, five months (mean age, 8.8 mo [SD = 9.4]). They were all fitted nominally to the NAL-NL1 prescription prior to their cortical test. They were referred by Australian Hearing clinicians to the National Acoustic Laboratories (NAL) for cortical testing as part of their clinical evaluation. These infants had been originally referred to Australian

Hearing for habilitation from state hospital audiology departments that had diagnosed the presence of hearing impairment using ABR or ECochG thresholds to tonal and click stimuli, tympanometry outcomes, and otoacoustic emission results. The maximum output of stimuli (in dB nHL) varied by stimulus and between referring centers, from 85 dB nHL to 110 dB nHL. While it could be assumed that the true threshold, in the case of a nil response, was at least 5 dB above the maximum output level used at each clinic, it was important not to underestimate the severity of hearing loss. When a nil response at maximum output was reported, a potential range for the true threshold was therefore calculated for each test frequency, using 115 dB nHL as the maximum point, and the average of that range was recorded as the estimated threshold.

Two infants were referred for CAEP testing with no information on electrophysiological thresholds in one ear and estimates of a severe hearing loss in the other. As the electrophysiological threshold for the better ear could not be determined with certainty, it was treated as missing data. The remaining children and infants (N = 29) had a mean electrophysiological threshold for tonal stimuli (based on the average of all tested octave frequencies from 500 Hz to 4000 Hz) of 87 dB nHL in the right and 87 dB nHL in the left (Right SD = 16.1; Left SD = 16.3), with a mean electrophysiological threshold for the better ear of 83 dB nHL (SD = 16.9).

On the basis of the diagnostic test battery, 15 infants were diagnosed as having an SN hearing loss, and they had a mean estimated electrophysiological threshold for the better ear of 84 dB nHL (SD = 21.3). There were eight diagnosed as having AN (although two had missing threshold data), and they had a mean estimated electrophysiological threshold for the better ear of 80 dB nHL (SD = 9.6). There were eight other children with hearing impairment who also had MD arising from conditions such as microcephaly, CHARGE syndrome, cerebral palsy, Treacher Collins syndrome, and rubella. They had a mean estimated better-ear electrophysiological threshold of 82 dB nHL (SD = 12.7).

For the purposes of this study, participants were excluded if they wore hearing aids infrequently. This was necessary as the initial validation studies of the PEACH questionnaire were performed on participants who confirmed that their hearing aid usage was more than just occasional. Of the 31 participants in this study, three were excluded because their parents reported that they never wore their hearing aids or they wore them on occasion only. These children were still assessed using CAEPs, and their results were reported to their referring clinician for further management, but their results were not included in this study. Thus, the results from 28 infants and children are reported in this study: 15 infants with SN hearing loss, seven with AN, and six with MD.

Stimuli

The test stimuli were /m/, /g/, and /t/, which were presented using alternating polarity. They were generated from natural speech tokens consisting of an initial consonant followed by the vowel /ae/, which was extracted from a recording of running speech that was spoken by a male with an average Australian accent. The final test stimuli included very little of the vowel transition and were recorded with digitization rates of 40 kHz. They were gated off near/at a zero crossing to avoid audible clicks. These essentially vowel-free stimuli were chosen because they had a spectral emphasis in the low-, mid-, and high-frequency regions, respectively, and thus had the potential to give diagnostic information about the perception of speech sounds in different frequency regions. They were presented with an interstimulus interval of 1125 msec.

Procedure

CAEP Testing

Brain electrical activity was recorded using the Neuroscan™ system with electrodes positioned at Cz, C3, and C4 referenced to the right mastoid with forehead as ground.

Only responses recorded at Cz are reported in this study.

Stimuli were presented from loudspeakers positioned at 45° on either side of the infant. All children wore their hearing aids on their usual settings with the speaker nearest the test ear used for presentation of the stimuli while the opposite ear was occluded with the child's own earmold and hearing aid in a switched-off position. Stimuli were initially presented at 65 dB SPL in most cases with subsequent presentations either at 75 dB SPL if no response was detected at 65 dB SPL, or 55 dB SPL if a response was detected at 65 dB SPL. Many participants could not tolerate extensive testing and, therefore, it was not always feasible to test all presentation levels for all stimuli. Where possible, each stimulus was presented in a block until 100 artifact-free EEG (electroencephalography) samples were acquired and each block of stimuli was presented on two occasions with the order of the blocks randomized. If the block was not repeated because the infant grew tired of testing, responses to the single-stimulus block were grouped into odd and even stimulus presentations and their responses were separately averaged.

During cortical testing, infants were awake and seated on their parent's lap, distracted by another adult if overly active. If the infant became drowsy during testing, they were rebooked to the next available time slot or they were allowed to take a short nap before recommencing the test. Individual sweeps of the EEG activity were amplified and analog filtered on-line at 0.1–100 Hz using a 24 dB/octave slope and subsequently filtered off-line at 1–30 Hz using a zero-phase filter. The recording window consisted of a 100 msec prestimulus baseline, and a further 600 msec and artifact reject was set at -150 to +150μV.

For purposes of this study, the responses were reviewed by an examiner who was experienced in identifying infant CAEPs. The two replicated waveforms were overlaid and inspected for repeatability. The presence/absence of a repeatable response in the region of 100 msec to 400 msec after stimulus onset was recorded. The presence/absence of CAEP responses were also analyzed using a Hotelling's T^2 statistic (Flury and Riedwyl, 1988; Harris, 2001). In brief, epoched Neuroscan files were exported to MATLAB for the analyses. The analysis period always consisted of 450 points covering the 450 msec period between 50 msec and 500 msec post-stimulus onset. The number of sampling points was then reduced by averaging each group of 50 points such that the 450 msec analysis period was reduced to form a "response" condition that contained nine variables. Hotelling's T^2, which calculates the probability that the mean value of any linear combination of the nine variables is significantly different from zero, was then applied. The examiner who reviewed the infant CAEPs was blind to the outcomes from the Hotelling's T^2 analysis and the PEACH questionnaires.

PEACH Questionnaire

The PEACH questionnaire was sent to parents one week prior to the cortical testing, and they were asked to make observations about their child's auditory behavior as described in the questionnaire. On the day of cortical testing, or at an agreed time after the test, a member of the research staff who had no knowledge of the CAEP test outcome formally interviewed the parent. The final overall PEACH score was calculated and converted to a percentage. This overall score was then subtracted from the age-appropriate normative data for PEACH performance (Ching and Hill, forthcoming) to create a relative PEACH score for each participant. As an increase in the overall PEACH score could naturally be expected with increasing age, the use of the relative PEACH score in this study provided for a comparison of cortical outcomes and performance on the PEACH questionnaire with minimal influence of age as a confounding factor.

RESULTS

In cases where an outcome was not available for stimuli presented at 65 dB SPL, it was sometimes feasible to deduce the outcome for 65 dB stimuli using either 55 dB or 75 dB SPL responses. If no response to a specific stimulus was detected with a 75 dB SPL presentation level, then a nil response at 65 dB SPL could be inferred. Similarly, if a response was present at 55 dB SPL, then a response could be assumed to be present with a 65 dB SPL stimulus. Although the examiner and the statistical measure had the same set of Neuroscan epochs for analysis, the interpretation of presence/absence of a response varied in some cases. A complete set of results (i.e., for three stimuli at 65 dB SPL presentation levels in both ears) could not be established for three participants using the examiner's interpretations and for two participants using the statistical measure, so there were examiner gradings for 25 children and a statistical measure for 26 children.

Having established the presence/absence

of a response in both ears to all three stimuli for all available participants, the presence of a response to each speech stimulus in one or both ears was taken as overall evidence of detection of that speech stimulus in the sound field. As a result, an overall score of 0 to 3 was devised for each participant, where "0" was consistent with no CAEPs to any of the speech stimuli presented at 65 dB SPL, and "3" was consistent with evidence of CAEPs to all three speech stimuli presented at 65 dB SPL in one or both ears.

Table 1 shows the cortical gradings by category for the examiner and the Hotelling's T^2 analysis. It is clear that there is reasonably good agreement between the examiner and the statistical measure ($r_s = 0.65$; $n = 25$; $p < 0.001$). All cases, except for three, show agreement between the two methods to within ±1 point on the cortical grading scale.

Figure 1 shows the overall PEACH score for all participants (N = 28) as a function of their corrected age at the time when the PEACH was administered. This data is shown by category of hearing impairment. Scores for all hearing-impaired categories are below the age-appropriate normative data, which shows an increase in overall performance from 40% at 1 month of age to 60% at 8 months of age and 75% at 16 months of age. A relative PEACH score was calculated by subtracting the overall PEACH score from the age-appropriate normative data for PEACH performance. The mean relative PEACH score for all participants was -32% (SD = 19.1), indicating that on average this group of hearing-impaired infants and young children had PEACH scores 32 percentage points lower than the age-appropriate normative data for the PEACH questionnaire. In addition to the similarity between the three groups with respect to their mean better-ear electrophysiological threshold, there is no significant difference ($F[2,25] = 0.69$; $p = 0.51$) between the mean relative PEACH score for the SN group at -34% (SD = 17.8) and the AN group at -25% (SD = 14.7), and the MD group at -37% (SD = 26.7).

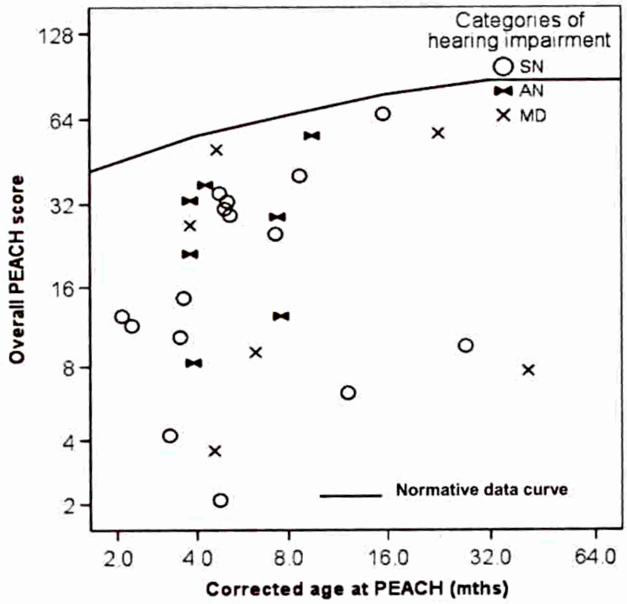

Figure 1. The overall PEACH score for all participants (N = 28) is shown as a function of their corrected age at the time of testing. The data is displayed by the category of hearing impairment (sensorineural [SN]; auditory neuropathy/dys-synchrony [AN]; multiple disability accompanying hearing impairment [MD]). Normative data is indicated by the solid curve.

Table 2 shows the number of participants by category of hearing impairment and the cortical grade achieved using the examiner's and statistical outcomes. The distribution of cortical grades appears similar across categories. There is no statistically significant relationship between category of hearing impairment and cortical grade (examiner's grade: Cramer's V = 0.27, p = 0.72; statistical grade: Cramer's V = 0.26, p = 0.73).

Figure 2 (a and b) shows the CAEP outcomes by examiner's grading (a) and by Hotelling's grading (b) as a function of the age-corrected PEACH scores for all infants and children. There is a positive correlation between the number of CAEP outcomes and age-corrected PEACH score using both the

Table 1. Number of Concordant and Discordant Cortical Gradings for the Examiner and Hotelling's T^2

	Hotelling's grading (cortical outcomes) 0	1	2	3	Total no. participants
Examiner's grading (cortical outcomes)					
0	7	2	0	0	9
1	3	0	2	0	5
2	1	2	2	1	6
3	0	2	2	1	5
Total no. participants	11	6	6	2	25

Table 2. Number of Participants by Category of Hearing Impairment and Cortical Grade Achieved

	Category of hearing impairment SN	AN	MD	
Cortical grade - examiner outcomes				Total
0	5	2	2	9
1	3	1	1	5
2	4	1	1	6
3	1	3	1	5
Total	13	7	5	25
Cortical grade – statistical outcomes				
0	7	2	3	12
1	4	1	1	6
2	2	3	1	6
3	1	1	0	2
Total	14	7	5	26

examiner's grading ($r_s = 0.45$; n = 25; p = 0.03) and the Hotelling's grading ($r_s = 0.41$; n = 26; p = 0.04).

The possibility of a relationship between the electrophysiological thresholds (i.e., existing ABR/ECochG findings) and age-corrected PEACH scores was also investigated for all participants, and no significant relationship was found (r = 0.07; n = 26; p = 0.74).

DISCUSSION

The purpose of this study was to evaluate the relationship between CAEP outcomes, using speech stimuli, and functional measures in infants and young children. All infants had been previously diagnosed with hearing impairment and fitted with hearing aids at the time of CAEP testing. As there was no significant difference between categories of hearing impairment for either the cortical grades or the age-corrected PEACH scores, the relationship between these two variables was examined for all participants combined, and a positive correlation was found. This finding suggests that recording CAEPs to speech stimuli can provide physiological evidence that these stimuli have arrived at the cortex and they are therefore potentially audible to the individual with hearing aids fitted (Näätänen and Picton, 1987; Korczak et al, 2005).

While there was a significant relationship between age-corrected PEACH scores and both methods of cortical grading in aided children, the amount of variance in the age-corrected PEACH scores that was explained by the models was not high (Hotelling's: 17%; Examiner's: 20%), suggesting that there

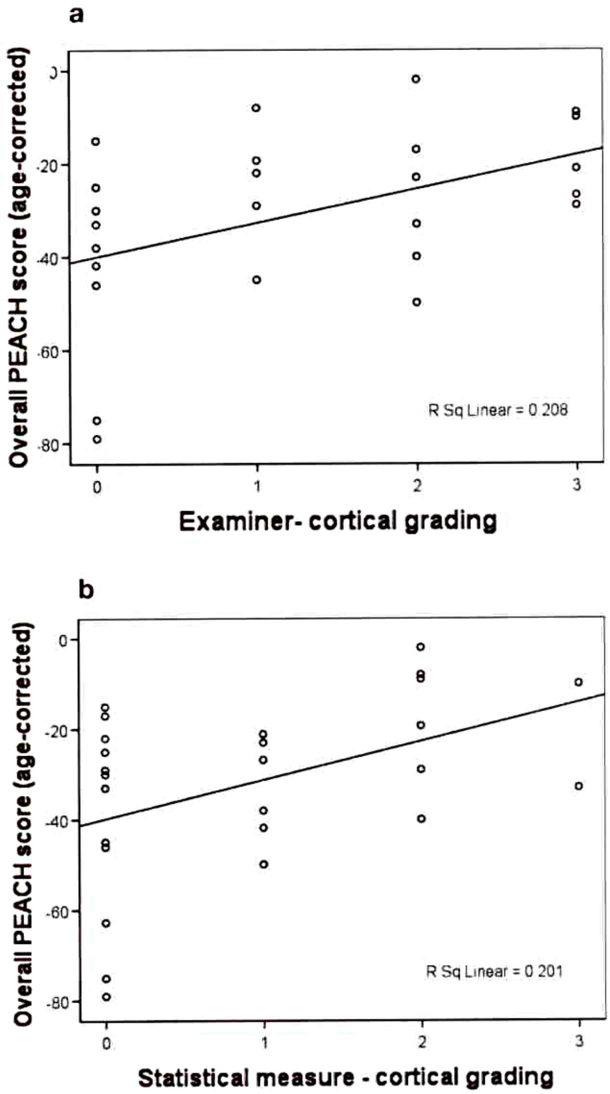

Figure 2. The CAEP outcomes as a function of the overall PEACH score (age-corrected) for all infants and children are shown: *(a)* the examiner's cortical gradings (N = 25), *(b)* the Hotelling's T^2 cortical gradings (N = 26).

are other factors that impact on the prediction of PEACH scores. It is possible that the amount of time each parent spent in observation of their child's auditory behavior varied and may have been limited by a number of factors such as how many children there were in the household, lifestyle, wellness of the infant, and, hence, competing priorities in caring for them. The opportunities to observe the infant in noisy environments were also likely to have varied. It is also possible that the researchers involved in interviewing the parents varied in their abilities to extract relevant examples from parents even though they had all had instruction in the task. A single highly experienced interviewer may have provided more consistency in the results. While identifying the additional factors that impact on the variability in outcomes may be speculated upon, it does not change the importance of our findings that CAEP outcomes to speech stimuli are significantly related to everyday auditory function in infants. Recording CAEPs to speech stimuli can therefore provide early objective indications of the aided child's ability to access speech by audition. As the presence of cortical responses and auditory function in life are both reliant on the audibility of speech, this finding should not be surprising. The significant but low correlation between the two measures is also understandable given the coarseness of the cortical grading scale used in this study, the subjective nature of the PEACH scores, and the heterogeneity of the subjects.

Other electrophysiological test results, namely ABR or ECochG, were available at the time of cortical testing for all but two infants. This information was critical in the initial diagnosis of hearing impairment and was useful subsequently in deriving target gain estimates for the fitting of hearing aids (Dillon, 2001). There was, however, no relationship between ABR/ECochG thresholds and age-corrected PEACH scores. This negative outcome may have occurred for two reasons. Firstly, the delay between the conduct of the ABR/ECochG testing and PEACH administration may potentially have had some bearing on this finding if auditory thresholds had deteriorated or improved in that time. Secondly, 46% of our infants had a better-ear ABR/ECochG estimated threshold greater than 85 dB nHL, which was the upper limit of stimulus presentation at the majority of referring clinics. Potentially, then, their true auditory thresholds may have been significantly higher, and yet they were all fitted with the same prescription, which may have lead to underfitting and poor functional performance.

Finally, the difficulties of subjective electrophysiological response detection have been highlighted previously (Hoth, 1993; Hoppe et al, 2001). In our study, two very different methods of response detection were used. Firstly, we used the traditional peak detection methods that rely on human observation of repeatable responses. Our second method was a Hotelling's T^2 analysis where each recorded epoch was reduced to nine variables, and the probability that the mean value of any linear combination of these was significantly different from zero was calculated. Although complete concordance on the presence/absence of a response was not achieved between the two methods, the correlation between them was reasonably good, and both methods predicted functional performance equally well. Where there were discrepancies between the two methods, it remains difficult to know which was right given that behavioral results were not available for these children. A recent study using adult participants whose behavioral thresholds were known indicated that the statistical method more accurately discriminates a cortical response from no response than occurs for expert human observers (Golding et al, forthcoming). If the same result could be achieved using responses from infant participants, the success of the Hotelling's T^2 response detection method would increase the objectivity of the test procedure and enable clinicians who are inexperienced at CAEP testing to concentrate on improved habilitation outcomes for their young clients rather than focusing on the complexities of CAEP recording in infants.

In summary, results from our study suggest that a significant relationship exists between CAEP and functional outcomes for aided infants. This relationship was not seen when ABR/ECochG results were similarly compared with functional performance. Our study also showed that statistical detection of CAEP responses was consistent with those of an expert examiner, thus providing an alternative and reliable method of response detection. This information is likely to complement existing test batteries and assessment tools in the verification of hearing aid fittings for infants before the age when well-defined responses can be obtained, which is normally six months or more corrected age (Moore et al, 1992).

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