International Journal of Audiology 2012; Early Online: 1–8

Original Article

The relationship between cortical auditory evoked potential (CAEP) detection and estimated audibility in infants with sensorineural hearing loss

Hsiu-Wen Chang*, Harvey Dillon†, Lyndal Carter†, Bram Van Dun† & Shuenn-Tsong Young*

*Hearing and Speech Engineering Laboratory, Institute of Biomedical Engineering, National Yang-Ming University, Taipei, Taiwan,
†National Acoustic Laboratories, Chatswood, NSW, Australia

Abstract

Objective: To determine the effectiveness of objective statistical detection in CAEP testing to evaluate audibility in young infants with sensorineural hearing loss. *Design:* CAEP recordings to speech-based stimuli were made at three presentation levels (55, 65, or 75 dB SPL) when a group of hearing-impaired infants were either aided or unaided. Later-obtained behavioral audiograms were used as the gold standard against which to evaluate the accuracy of the automatic detection of the presence/absence of CAEP responses. *Study sample:* Participants were 18 infants with confirmed sensorineural hearing loss. *Results:* Higher sensation levels led to a greater number of present CAEP responses being detected. More CAEP waveforms were detected in the aided condition than in the unaided condition. *Conclusion:* Our results suggest that the presence/absence of CAEP responses defined by the automatic statistical criterion was effective in showing whether increased sensation levels provided by amplification were sufficient to reach the cortex. This was clearly apparent from the significant increase in cortical detections when comparing unaided with aided testing.

Key Words: Cortical auditory evoked potential (CAEP); hearing aids; amplification; audibility; infants

Infants with hearing loss are at risk of abnormal or delayed speech and language development. The availability of effective newborn hearing screening programs worldwide could facilitate early identification and early intervention of hearing loss. The benefit of this has been well documented by Yoshinaga-Itano et al (1998), who showed that hearing-impaired children who are identified early and receive immediate intervention services demonstrate higher receptive and expressive language skills in early childhood.

The negative impact of hearing loss on language development can be potentially alleviated not only by initiating intervention services soon after identification but also by providing appropriate amplification. An accurate pure-tone audiogram is the first step of hearing-aid fitting. Prescriptive methods, such as the NAL-NL1 (Byrne et al, 2001; Dillon, 2001) and DSL method (Seewald et al, 2005), require behavioral threshold inputs to calculate the target gain of the hearing aid. When it is not feasible to obtain reliable and consistent behavioral audiograms, such as in newborns and infants under the developmental age of six months, the current protocols (American Academy of Audiology, 2003) suggest that hearing aids should be set to an estimated audiogram based on electrophysiological thresholds such as the tone-burst auditory brainstem response (ABR). Information regarding the appropriateness of hearing-aid fitting may be achieved by behavioral observation audiometry combined with parental questionnaires. While the evaluation of hearing-aid fitting can be established with reasonable certainty in infants who are old enough developmentally to respond reliably to behavioral threshold-seeking techniques, this is not possible in young infants. The recognized benefits of early identification/intervention have increased the need for an objective technique to evaluate hearing-aid fitting in young infants.

Previous research findings suggest that the cortical auditory evoked potential (CAEP) can be used as an objective tool to evaluate whether amplified speech sounds are audible in infants and children fitted with hearing aids (Gravel et al, 1989; Sharma et al, 2005; Golding et al, 2006). The presence of CAEP responses elicited by speech is viewed as an objective indication of the audibility of speech sounds (Hyde, 1997). Purdy et al (2004) reasoned that if a hearing aid enables speech to elicit cortical responses, then the presence of the cortical response provides evidence that the amplified speech stimuli have been detected.

Correspondence: Shuenn-Tsong Young, Hearing and Speech Engineering Laboratory, Institute of Biomedical Engineering, National Yang-Ming University, No. 155, Sec. 2, Linong Street, Taipei 112, Taiwan. E-mail: young0210@gmail.com

(Received 18 July 2011; accepted 26 April 2012)

ISSN 1499-2027 print/ISSN 1708-8186 online
DOI: 10.3109/14992027.2012.690076

Abbreviations

ABR	Auditory brainstem response
CAEP	Cortical auditory evoked potential
EEG	Electroencephalography
ESL	Estimated sensation level
NAL	National Acoustic Laboratories
SL	Sensation level
VRA	Visual reinforcement audiometry

Korczak et al (2005) demonstrated that the use of amplification increased the presence of measurable cortical responses in a group of hearing-impaired adults and also improved their behavioral performance. Golding et al (2007) further indicated that the number of speech sounds for which a CAEP is elicited is positively correlated with auditory function in infants and young children fitted with hearing aids. A series of case studies has been reported on the potential use of CAEP to confirm that speech stimuli have been successfully transmitted to the level of the auditory cortex in aided infants and children (Rapin & Graziani, 1967; Gravel et al, 1989; Sharma et al, 2005). Sharma et al (2002, 2005) further employed CAEP latency changes to monitor the development of central auditory pathways in hearing-impaired children fitted with hearing aids or cochlear implants in clinical settings.

It has been common practice to detect the presence/absence of CAEP responses using visual inspection of waveform morphology. However, this involves subjective human decisions, and the applied criteria varies across studies. Sharma et al (2005), for instance, visually identified P1 in children with hearing loss as the first robust positivity in the waveform. Visual observation is very reliant on prior experience of identifying CAEP waveforms, and hence clinicians with different experience, training, or biases may arrive at different outcomes. To solve the inherent difficulties of identifying CAEP waveforms, the responses were analyzed independently by two experienced judges to add objectiveness in the interpretation of CAEP waveforms in Rance et al (2002). In another study, responses were decided to be present if certain criteria regarding scalp topography and polarity inversion were met (Korczak et al, 2005). The above-mentioned criteria usually require off-line processing of CAEP waveforms, which may limit their potential applications in clinical settings. Given the challenges of visual identification of CAEP waveforms, an automatic statistical criterion has been applied in a commercially clinical system recently made available.

The widespread clinical implementation of objective statistical detection technique in CAEP testing requires its usefulness to be assessed in evaluating audibility in infants with hearing impairment. CAEP testing was conducted in a group of hearing-impaired infants in aided and unaided conditions. Follow-up test sessions were arranged to repeat the aided cortical testing when the infants' prescribed hearing aids were adjusted in gain at the discretion of the case-managing audiologist. Pure-tone behavioral audiograms were later retrieved from the infants' audiological charts when the threshold-seeking technique was developmentally appropriate. The audibility of speech sounds at the time of cortical testing was estimated using the later-obtained behavioral hearing thresholds. The purpose of the present study was to test the hypothesis that the cortical responses identified by an automatic statistical criterion in hearing-impaired infants when they were either aided or unaided are valid indicators of the audibility of speech sounds by examining the relationship between the automatic detection of the presence/absence of CAEP responses and the estimated audibility of speech sounds.

Method

Subjects

Infants, who had confirmed bilateral hearing impairment and were newly fitted with hearing aids, were recruited as this group of subjects mostly resembles typical hearing-impaired infants who are likely to receive CAEP measurement in clinical settings. The presence of hearing impairment was diagnosed at state hospital audiology departments using tone-burst ABR, otoacoustic emission results, and tympanometry soon following a bilateral refer on newborn hearing screening. Participants were included if the type of hearing loss was sensorineural. Those who were diagnosed with auditory neuropathy or hearing loss with conductive components were not included. These infants were still assessed using CAEP but their results were not included in this study.

This study reported CAEP responses recorded from 18 infants (7 males and 11 females), who were all clients of Australian Hearing and were referred to the National Acoustic Laboratories (NAL) for cortical testing as part of their clinical evaluation. As their mean age at hearing-aid fitting was 2.8 months (SD = 1.7 months), the parameters for the initial hearing-aid fitting for these infants were set to the estimated behavioral audiograms derived from their diagnostic tone-burst ABR results by the case-managing audiologists. Their ages ranged from 2.7 to 10.5 months (mean = 6.7 months, SD = 2.3 months) at the initial CAEP testing session. The later-obtained behavioral audiograms showed a mean hearing threshold (mean of the values from 0.5 to 4 kHz) of 62 dB HL (SD = 16.0 dB HL) in the better ear.

Equipment and stimuli

Brain electrical activities were recorded using the HEARLab™ system (Frye Electronics, Tigard, USA). The electrodes were positioned at Cz referenced to the left mastoid with the forehead as ground. Electrode impedances were maintained below 5 kohms. A headband or surgical tape was used to reduce slippage of the electrodes during the testing.

The test stimuli used in this study were speech sounds, since our primary interest in recording CAEPs was to evaluate the perception of speech by infants with hearing loss. The speech stimuli /m/ (duration of 30 ms), /g/ (duration of 20 ms), and /t/ (duration of 30 ms), identical to those used by Golding et al (2009) and Carter et al (2010), were extracted from a recording of running speech that was spoken by a female with a typical Australian accent. The stimuli were gated off near a zero crossing in order to reduce audible clicks. The final test stimuli included very little of the vowel transition and were recorded at a digitization rate of 44.1 kHz. The /m/, /g/, and /t/ speech sounds were chosen because their spectral contents are predominantly in the low-, mid-, and high-frequency regions, respectively, and thus can potentially provide diagnostic information about the audibility of speech sounds in different frequency regions. The stimuli were presented with an alternating onset polarity to reduce the contaminating effects of stimulus artifact upon the waveform.

Procedure

Before CAEP testing, the infant's prescribed hearing aids and earmolds were inspected and the batteries were replaced to ensure that the aids would work properly throughout the testing. Age-appropriate tympanometry and otoscopy were performed to determine if the infant was experiencing middle-ear dysfunction. When this occurred, the evoked CAEP responses were not included in the analysis of results. Coupler measurements using speech-shaped noise at 55, 65, and 75 dB SPL were conducted to document the frequency responses of the infant's prescribed hearing aids on the same day as the cortical testing was performed. Free-field calibration of the HEARLab™ system was also performed before each testing session. The calibration process involves obtaining the frequency response of a free field environment (room acoustics and sound field frequency response) and creates a filter equal in shape to the inverse of the loudspeaker/room response. This filter was applied to the speech stimuli prior to their presentation to equalize the complex signals that are to be presented in that environment.

Most of the CAEP testing took place in the electrophysiology room at NAL. Four of the infants were tested in a quiet office room at their hearing centers using a portable HEARLab™ system, since their caregivers could not travel to NAL. During the testing, the speech stimuli were initially delivered at 65 dB SPL (impulse time constant); the presentation level was increased to 75 dB SPL if no CAEP response was evident, while it was decreased to 55 dB SPL if a CAEP response was present at 65 dB SPL. The loudspeaker was positioned directly in front of and 1 metre away from the infant, who was seated on his/her caregiver's lap.

Aided CAEP testing was conducted first with the infant wearing both of his/her hearing aids at their prescribed settings. Where necessary, a silent video was played to keep the infant awake and alert for as long as possible. If the infant was overly active, he/she was distracted by another adult or the examiner herself using quiet and age-appropriate toys. Unaided testing was then performed with the infant not wearing either of his/her hearing aids if the infant was still sufficiently settled. The recording was paused or discontinued when the infant became too restless for reliable test results to be obtained.

During the acquisition of EEG responses, the residual noise was monitored to assess the quality of the averaged CAEP responses. This noise was calculated as the SD of voltages across epochs divided by the square root of the number of accepted epochs, all averaged across time from 100 to 550 ms after stimulus onset. The presence/absense of CAEP responses was defined by an automatic statistical criterion as described by Golding et al (2009) and Carter et al (2010). Briefly, the sampling points of each accepted epoched EEG file from 50 ms to 500 ms after stimulus onset were divided into nine data bins. Within the analysis period of 450 ms, each data bin contains the amplitude of the EEG response for the duration of 50 ms. For the statistical analysis, the sampling points within each data bin were averaged and nine variables were obtained for each epoched EEG file. The applied statistic, Hotelling's T2 (Flury & Riedwyl, 1988) tests the probability that any linear combination of the nine variables has a mean value significantly different from zero. A resulting p value calculated by the automatic statistics indicates the likelihood that the evoked response is different from random noise. The statistical detection technique was found to be at least as sensitive as experienced clinicians in identifying CAEP responses in both adults and infants with normal hearing. In this study, a p value ≤ 0.05 was taken to indicate that a CAEP response was likely to be present; such a result would occur by chance one time in twenty. Since residual noise in the recorded CAEP responses could affect the reliability of the statistical analysis results, a low residual noise level was a prerequisite to assuming that the resulting p value > 0.05 indicated the absence of convincing evidence that a CAEP response was present.

In the present study, each speech stimulus was presented until the criterion for stopping EEG acquisition was met. When the automatic statistics indicated $p \leq 0.05$, at least 100 artifact-free EEG samples was collected at a stimulus presentation level in order to avoid the spurious increase in responses that appeared to be present and to offer a good chance of completing a number of recording runs before fatiguing the infant. This reduced the incidence of aborting an assessment due to inability to maintain the infant in a suitable recording state. On the other hand, an EEG response with $p > 0.05$ had to reach a residual noise level of less than 3.20 μV to meet the stop-averaging criterion.

The protocol used in this study was approved by the Australian Hearing Human Research Ethics Committee. Informed consents were obtained from the caregivers of all of the infants. A report of the test results was sent to the infants' case-managing audiologists for audiological management purposes, and one copy of the report was also sent to physicians and early intervention agencies when this was requested by the parents.

Data analysis

Individual sweeps of the EEG activity were amplified and analog filtered online by a high-pass filter at 0.003 kHz using a 6 dB/octave slope and by a low-pass filter at 0.004 kHz using a12 dB/octave slope. The evoked responses were hardware-sampled at 16 kHz, downsampled to 1 kHz for the EEG display, and further filtered using a low-pass filter at 0.030 kHz for subsequent processing and display. The recording window consisted of a 200 ms prestimulus baseline and a further 600 ms poststimulus time. The threshold for artifact rejection was set at ±110 μV, and this was performed after baseline correction.

Behavioral audiograms were subsequently obtained independently of CAEP testing when the threshold-seeking technique was developmentally appropriate for any individual infant. The infants' behavioral hearing thresholds for narrow-band warble tones using visual reinforcement audiometry (VRA) were measured by their case-managing audiologists at Australian Hearing centers. The obtained behavioral hearing thresholds were measured at a mean age of 13 months (SD = 3 months).

The stimulus presentation levels (55, 65, or 75 dB SPL) were subtracted from the later-obtained behavioral hearing thresholds to provide the estimated sensation levels (ESLs) at the time of CAEP testing. Specifically, the ESL in the unaided condition was calculated as the maximum value (across frequency) of the 1/3-octave spectral level of the stimuli minus the threshold level of the infant at the corresponding frequencies. The ESL of the speech stimulus in the aided condition was derived by adding the coupler gain and age-appropriate average real-ear-to-coupler difference to the unaided ESL. Hearing thresholds and stimulus presentation levels were both expressed in units of dB SPL in the ear canal in the computations. The relationship between the estimated audibility and the presence/absence of CAEP responses revealed by the automatic statistical criterion was investigated.

Results

Of the 18 infants, nine participated in a single CAEP testing session. The other nine returned for repeated aided CAEP tests, of whom four were tested twice while the other five received three repeated aided CAEP tests, each 1 to 4 months apart. Among all the subjects, there were three infants who were not tested in the unaided condition as

Table 1. General data for each individual infant.

Subject	Numbers of CAEP responses			3FA tone-burst ABR (dB nHL)		Coupler gain (dB SPL) for 65 dB SPL input to the better ear (0.5/1/2/4 kHz)		
	Unaided	Aided	Total	Right Ear	Left Ear	Test 1	Test 2	Test 3
A	3	6	9	53.3	56.7	2/12/14/20	–	–
B	6	10	16	55	55	0/11/12/16	6/17/18/19	–
C	2	3	5	46.7	56.7	3/12/14/21	–	–
D	0	2	2	93.5	100	22/32/35/31	–	–
E	6	4	10	53.3	56.7	2/8/14/21	–	–
F	3	10	13	95	58.3	3/10/21/22	0/12/20/21	9/24/26/28
G	6	3	9	37.5	42.5	0/4/10/10	–	–
H	3	18	21	50	55	4/12/22/22	1/13/24/25	2/5/10/12
I	0	7	7	55	60	0/3/14/21	6/20/24/29	–
J	0	11	11	92.5	95	24/32/38/27	34/44/50/33	–
K	3	14	17	50	61.7	8/16/16/20	5/12/19/14	13/20/24/18
L	3	6	9	40	60	2/8/20/16	–	–
M	6	18	24	62.5	67.5	0/6/14/16	3/7/18/10	2/18/16/20
N	2	10	12	56.7	61.7	6/16/27/24	10/14/19/19	3/19/20/16
O	3	4	7	80	75	24/29/26/22	–	–
P	6	12	18	65	65	7/15/16/17	12/19/14/13	–
Q	3	3	6	45	45	3/10/14/18	–	–
R	3	3	6	62.5	67.5	10/19/24/29	–	–

Tests 1, 2, and 3 are the first, second, and third cortical testing sessions, respectively; '–' indicates no coupler gain measured since the infant did not participate in the follow-up session.

they were not sufficiently settled to allow for further testing following the aided condition. When their parents were later contacted for further CAEPs, one of the infants was experiencing middle-ear infection and the other two were going to have cochlear implantation soon. The 18 infants' mean age at testing was 7.4 months (range = 3 ~ 15 months, SD = 2.8 months).

Table 1 lists the total numbers of CAEP responses recorded from each individual infant and the three-frequency average (from 0.5 to 2 kHz) tone-burst ABR hearing thresholds of each infant. The coupler gain measured from their prescribed hearing aids in the better ear using speech-shaped noise at 65 dB SPL for each CAEP testing session was also provided. The mean coupler gain was 7 dB SPL (SD = 8 dB) at 0.5 kHz; 15 dB SPL (SD = 9 dB) at 1 kHz; 20 dB SPL (SD = 8 dB) at 2 kHz; and 20 dB SPL (SD = 6 dB) at 4 kHz.

Estimation of audibility and grand average waveforms

In total, 202 infant-generated CAEP responses met the stop-averaging criterion and were included in the analysis of audibility estimation. The mean artifact-free EEG samples collected was 165 (SD = 34.7, median = 167) for each individual CAEP response. The CAEP responses were not included when the CAEP testing had to be discontinued before the stopping criterion was met due to the infant appearing too restless during the recording.

Fifty-eight of the 202 CAEP responses were recorded when the infants were not wearing either of their hearing aids, and the remainder were evoked in the binaurally aided condition. Figure 1 shows the grand average waveforms for the three speech stimuli recorded in aided and unaided conditions. For the unaided CAEP testing, the presentation levels of each speech stimulus were found to be near or below the infants' behavioral hearing thresholds. As indicated in Table 2, the mean ESLs were −7.8, −0.6, and −0.1 dB for the /m/, /g/, and /t/ sounds, respectively. When the infants were aided, the mean ESLs for the three speech sounds ranged from 3.2 to 21 dB, with the level being lowest for the /m/ sound. The mean hearing-aid coupler gains from 0.5 to 4 kHz listed in Table 1 indicate that the lowest ESL for the /m/ sound probably resulted from a lower prescribed gain at low frequency, as revealed by the mean coupler gain being 7 dB SPL at 0.5 kHz.

Performance outcomes for the automatic statistical criterion

A p value was generated for each of the 202 speech-evoked CAEP waveforms using the automatic statistical criterion. Each resulting p value elicited either in the aided or unaided condition was paired

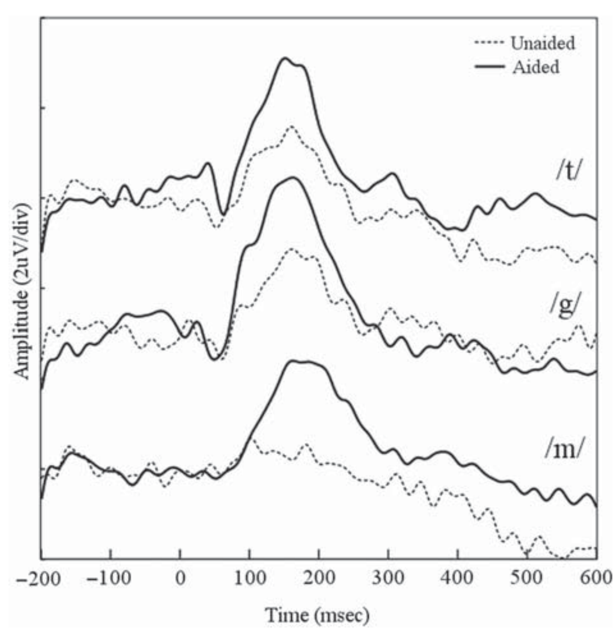

Figure 1. Grand average waveforms for the three speech stimuli under aided and unaided conditions.

Table 2. Summary of mean ESLs for the three stimulus sounds in the unaided and aided CAEP testing conditions.

	Unaided condition			*Aided condition*		
Speech stimulus	*Mean ESL (dB)*	*SD*	*N*	*Mean ESL (dB)*	*SD*	*N*
/m/	−7.8	13.8	20	3.2	11.9	47
/g/	−0.6	11.4	19	21.0	11.0	48
/t/	−0.1	16.4	19	16.0	11.8	49

N indicates the number of the CAEP waveforms recorded for the corresponding speech stimulus.

with the SL estimated at the presentation level of each speech stimulus for further analysis.

To determine whether statistically significant p values were more likely to be obtained for stimuli estimated to be audible than for stimuli estimated to be inaudible, the ESLs for all stimuli with $p \leq 0.05$ (i.e. response present) were compared to those with $p > 0.05$ (i.e. response absent). The mean ESL was 13 dB for stimuli with the response present and 4 dB for stimuli with the response absent. This difference in sensation levels was highly significant ($p < 0.0001$). The grand averages of those waveforms identified as having present or absent CAEP responses by the automatic statistic criterion were also shown in Figure 2.

The sensitivity of the automatic statistical criterion incorporated in the HEARLab™ system was investigated by calculating the ratio between the number of present CAEP responses (as indicated by $p \leq 0.05$) versus the total number of stimuli presented at a specific positive ESL range. The calculated sensitivities for three different ESL ranges (i.e. 0, 10, and 20 dB) are listed in Table 3, which indicates that the unaided and aided conditions combined achieved detection rates of 62.6%, 68.4%, and 69.2%, respectively. Increased ESLs led to a greater number of present CAEP responses being detected. Figure 3 shows the grand averages of CAEP responses to stimuli presented at increasing ESL ranges. It can be noted that cortical response amplitudes increase with higher ESLs. The peak amplitude of the grand average of CAEP responses recorded at ESL below the behavioral threshold is 0.22 μV (baseline to peak). The enhancement of amplitudes was noted to increase from 2.06 μV to 4.02 μV in the two group averages of responses recorded at positive ESLs.

Table 3. Sensitivity of the automatic statistical criterion for detecting CAEP responses at different positive ESL ranges.

ESL (dB)	*Number of detections ($p \leq 0.05$) (A)*	*Number of waveforms (B)*	*Number of subjects*	*Sensitivity (%) (A/B)*
> 0	87	139	17	62.6
> 10	67	98	16	68.4
> 20	36	52	11	69.2

Effect of amplification

Whether the automatic detection criterion was capable of identifying the presence of speech-evoked CAEP waveforms when the infant tested was wearing hearing aids was investigated by analyzing the CAEP responses evoked from 14 (nine girls and five boys) infants who had completed both the aided and unaided CAEP testing during the same visit. The infants' ages ranged from 2.7 to 13 months (mean = 7.5, SD = 3.6 months), and they had been wearing their hearing aids for a mean of 4.6 months (SD = 3.4 months) at the time of testing. One of the infants was tested on the day of initial hearing-aid fitting.

Table 4 lists the corresponding mean ESLs for each stimulus sound in the unaided and aided conditions. For unaided CAEP testing, the stimulus presentation levels were estimated to be below the infants' behavioral hearing thresholds by a mean of 3–9 dB for the three speech sounds. The ESLs were increased to 4–22 dB when amplifications were provided.

The McNemar test was used to determine whether more CAEP waveforms were assigned significant p values in the aided condition than in the unaided condition. The results showed that there were

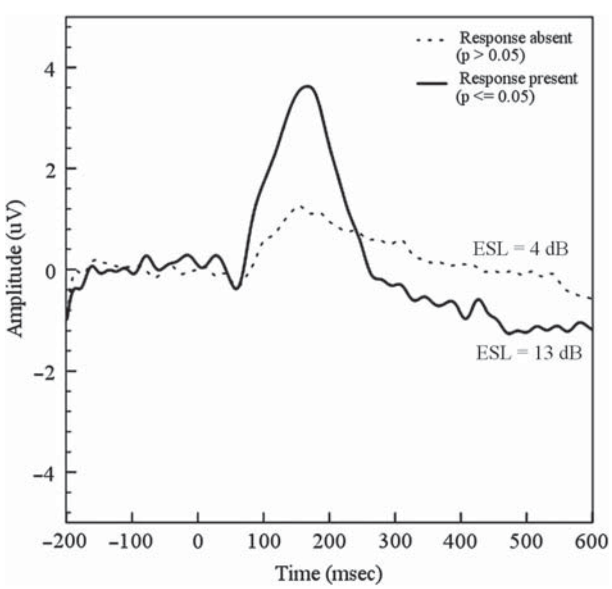

Figure 2. The grand average waveforms for present and absent CAEP responses identified by the automatic statistic criterion.

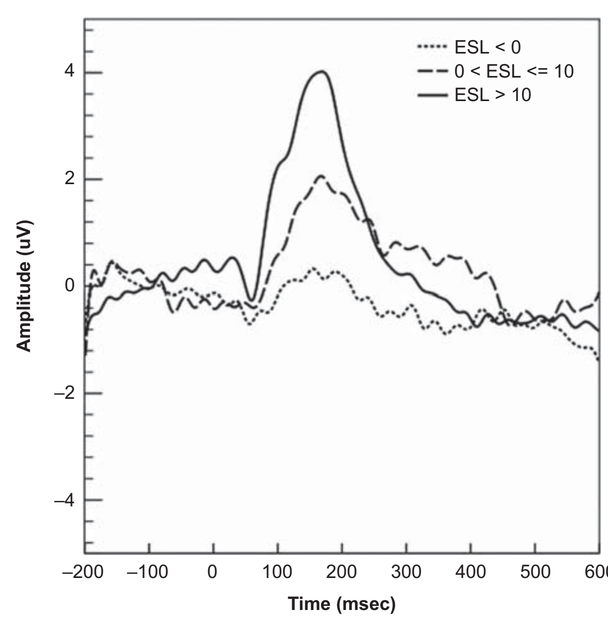

Figure 3. The grand averages of CAEP responses to speech stimuli presented at three specific ESL ranges.

Table 4. Summary of mean ESLs for the three stimulus sounds in unaided and aided CAEP testing conditions for the subset of children who had completed both the aided and unaided CAEP testing during the same visit. The number of stimuli for which a response was detected and the total numbers of stimuli presented are also given.

	Unaided condition				*Aided condition*			
	Mean ESL (dB)	*SD*	*Number of detections*	*Number of waveforms*	*Mean ESL (dB)*	*SD*	*Number of detections*	*Number of waveforms*
/m/	−9	14	6 (42.9%)	14	4	12	2 (14.3%)	14
/g/	−3	11	2 (14.3%)	14	22	11	12 (85.7%)	14
/t/	−6	13	3 (21.4%)	14	19	12	12 (85.7%)	14

significantly more CAEP responses present for /g/ and /t/ sounds when they were amplified than when they were unamplified ($p < 0.01$). There was no significant increase in responses present for the /m/ sound ($p = 0.63$), with instead fewer responses being detected in the aided condition.

Discussion

This study investigated the usefulness of an automatic statistical criterion in detecting CAEP responses when infants were either aided or unaided in clinical settings. The results of this study demonstrate that: (1) statistically significant CAEP responses as revealed by the automatic statistics are mostly recorded to speech stimuli with higher ESLs; (2) detection sensitivity increases with ESLs; and (3) more CAEPs are detected when the response waveforms are evoked in aided condition.

Our results showed that the mean ESL in the aided condition was significantly lower for the /m/ sound than for the /g/ and /t/ sounds. There are two possible explanations for this: (1) the lower ESL received by the aided infants listening to the /m/ sound may be due to less amplification being prescribed by NAL-NL1 at low frequencies (Dillon, 2001), and (2) the uncertainty in estimating behavioral thresholds by correcting tone-burst ABR thresholds. Predicted behavioral hearing thresholds that underestimate the actual hearing loss, or hearing aids fitted conservatively by clinicians concerned about overamplification damaging the remaining hearing may result in an underamplification of the speech sounds.

Previous researchers have investigated the benefits of hearing aids based on visual detection of the cortical responses elicited in unaided and aided conditions. The results revealed considerable variability across studies. Some found that the aided condition lowers the threshold of the cortical responses and improves the waveform morphology (Rapin & Graziani, 1967; Gravel et al, 1989; Kurtzberg, 1989; Korczak et al, 2005), but some did not find effects of amplification (Tremblay et al, 2006; Billings et al, 2007; Billings et al, 2011). Objective CAEP response judgments were implemented in the present study to identify the presence/absence of cortical responses, which makes this the first study to use an objective method to detect the CAEP responses recorded in a group of hearing-impaired infants. Automatic statistics have previously been used to detect CAEP responses in adults and infants with normal hearing. For both the adult- and infant-generated CAEP responses, the performance outcomes of the automatic technique were shown to be at least equal to those for judgments made by experienced humans (Carter et al, 2010; Golding et al, 2009). Our results showed that the automatic statistical criterion detected 62.6% (87/139) of the cortical responses evoked by stimulus sounds that were estimated to be audible (i.e. ESL > 0), and the sensitivity increased with the ESL. The reported results are applicable to hearing-impaired infants aged between 3 and 15 months.

The sensitivity found in our study was lower than that found in a study involving 25 hearing-impaired infants between 8 and 30 months of age (unpublished data). This discrepancy might be due to our study predicting audibility based on ESLs instead of true SLs. One of the major steps in computing the ESL is the infants' behavioral hearing thresholds for pure tones using VRA. We used CAEP testing to evaluate an infant's ability to detect speech sounds at the level of the auditory cortex, while narrow-band warble tones were used to obtain the behavioral audiogram. Estimating the SL for speech sounds based on thresholds measured with narrow-band signals requires several assumptions:

1. The appropriate bandwidth over which to sum the power of the speech signals for hearing-impaired infants (we arbitrarily used 1/3-octave bands, given that no other information was available).
2. The appropriate amount by which a threshold measured with a signal duration of 1–2 seconds should be increased in order to estimate when a speech sound of only 30 ms measured with an impulse sound level meter (time constant of 35 ms) will be audible (we used 3 dB).
3. The appropriate allowance that should be made when more than one 1/3-octave band has a similar SL (we made no allowance).
4. The effect on stimulus amplitude of nonlinearities (particularly amplitude compression) in the hearing aid.
5. The unknown effects of maturation on the hearing thresholds. For children whose hearing loss is detected in newborn screening, the behavioral measurements cannot be made until long after hearing aids are fitted. The hearing loss might have progressed or changed during that time. Calculating the audibility of speech sounds based on thresholds inferred from measurements of ABRs or auditory steady-state responses introduces the additional inaccuracy implicit in the inferred thresholds.

In short, estimating when a speech sound is audible based on narrow-band (e.g. pure-tone) behavioral thresholds is very inexact, which is precisely why it is valuable to have a method for directly observing the effects of audibility in the auditory cortex, which is what the measurement of evoked cortical potentials could provide.

This study reported detectability of CAEP responses identified solely by the automatic statistical criterion. One would wonder that if visual detection of the waveforms had taken place, would the detection sensitivity have been increased? We visually inspected 52 cortical responses evoked by stimulus sounds with ESLs of 20 dB or higher. As shown in Table 3, the automatic statistics detected 36 CAEP responses, while four more CAEP responses could be identified if visual inspection of waveform morphology was involved.

These four waveforms were recorded from three infant participants. Reviewing all their CAEP responses collected in the same testing session, it was also noted that there were statistically significant CAEP waveforms evident either at lower stimulus presentation level or for the speech stimulus containing overlapping spectral information (e.g. /g/ and /t/ sounds). As a result, it is recommended to repeat CAEP recordings when there are cortical detections at neighboring stimulus intensities or with speech sounds containing adjacent or overlapping frequencies. It is also good practice to combine other audiological information available about the child tested and use CAEP testing as an objective tool to cross-check the child's auditory performance.

Korczak et al (2005) suggested that recording cortical responses to speech stimuli would be helpful in assessing the benefit of hearing aids in hearing-impaired infants and children, based on a preliminary study of five school-aged children. The present study has further demonstrated that an objective detection method revealed more significant CAEP responses when amplification was used in a group of hearing-impaired infants. We also found that the CAEP response was less likely to be evident at lower ESLs, suggesting that low sensation levels could not overcome the hearing loss sufficiently to stimulate the higher parts of the auditory pathways. This finding is also in line with the behavioral performance data reported by Ching et al (2010), indicating that children preferred a higher gain than would have been prescribed by NAL-NL1. As indicated in Table 4, the /g/ and /t/ sounds presented at higher ESLs evoked more statistically significant CAEP responses, while the /m/ sound with a mean ESL of 4 dB in the aided condition was not sufficiently loud to elicit a CAEP response. The implication of these results is that statistically significant CAEP responses ($p \leq 0.05$) revealed by the automatic statistical criterion are likely to confirm that the SL is sufficient to achieve audibility.

Measuring aided cortical responses with the assistance of a statistical detection method may provide audiologists with additional information that would make it possible to confirm that amplified sound is being processed at the level of the auditory cortex and also help in solving the inherent difficulties of interpreting infant CAEP waveforms. This objective test would facilitate audiologists in managing diverse populations who receive amplification, such as very young infants without behavioral audiograms or with partial but not complete electrophysiological results, in whom hearing-aid fitting should be evaluated as soon as possible. Moreover, measuring CAEPs may also benefit difficult-to-test children and those infants and children who are not developing appropriate auditory skills as expected based on their measured ABR responses. For the purpose of audiological management, CAEP testing can be repeated at different time points to document the change in CAEP latency, since immaturity of the auditory system appears to be reflected in delayed latency (see Sharma et al, 2005).

Conclusions

A number of limitations need to be considered regarding the present study.

First, it is important to note that a present CAEP response in the aided condition does not necessarily indicate that the hearing aids are providing effective amplification, as the automatic statistics may identify a CAEP response recorded to a signal that is barely audible. A speech signal that is audible slightly above hearing threshold is clearly not sufficient for appropriate speech and language development.

Second, given that the HEARLab system is designed for clinical use, eye movements are not monitored for practical reasons. There is built-in rejection of any epoch with sample values exceeding ±110 μV. Eye blink activity smaller in amplitude, however, might be missed by the amplitude rejection criterion. Thus, eye blinks that were not rejected could result in possible contamination in the averaged CAEP responses reported in the present study. But, as eye blinks are not time-locked to the speech stimulus, those artifacts will be "smeared out" over the averaged waveform and likely not be of consequence for the morphology of the acutual cortical waveform unless one only records a few number of epochs.

Nevertheless, our results demonstrated that higher ESLs resulted in more statistically significant CAEP responses and increased detection sensitivity. It was concluded that the presence/absence of CAEP responses defined by the automatic statistical criterion was effective in showing whether increased SLs provided by amplification were sufficient to reach the auditory cortex. This was clearly apparent from the significant increase in cortical detections when comparing unaided with aided testing.

Acknowledgments

The support of National Acoustic Laboratories and the Australian Hearing Centers is gratefully acknowledged. The authors thank the infants and their families for their enthusiastic participation in this study. We would also like to acknowledge insightful comments by two anonymous reviewers. This research was supported by a Graduate Students Study Abroad grant sponsored by the National Science Council of Taiwan (NSC97-2917-I-010-102).

Declaration of interest: The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

References

American Academy of Audiology. 2003. Pediatric Amplification Protocol. Washington (DC): National Academic Press.

Billings C.J., Tremblay K.L. & Miller C.W. 2011. Aided cortical auditory evoked potentials in response to changes in hearing aid gain. *Int J Audiol*, 50, 459–467.

Billings C.J., Tremblay K.L., Souza P.E. & Binns M.A. 2007. Effects of hearing aid amplification and stimulus intensity on cortical auditory evoked potentials. *Audiol Neurootol*, 12, 234–246.

Byrne D., Dillon H., Ching T., Katsch R. & Keidser G. 2001. NAL-NL1 procedure for fitting nonlinear hearing aids: Characteristics and comparisons with other procedures. *J Am Acad Audiol*, 12, 37–51.

Carter L., Golding M., Dillon H. & Seymour J. 2010. The detection of infant cortical auditory evoked potentials (CAEPs) using statistical and visual detection techniques. *J Am Acad Audiol*, 21, 347–356.

Ching T.Y.C., Scollie S.D., Dillon H. & Seewald R. 2010. A cross-over, double-blind comparison of the NAL-NL1 and the DSL v4.1 prescriptions for children with mild to moderately severe hearing loss. *Int J Audiol*, 49, S4–S15.

Dillon H. 2001. *Hearing Aids*. Sydney: Boomerang Press.

Flury B. & Riedwyl H. 1988. *Multivariate Statistics: A Practical Approach.* London: Chapman and Hall.

Golding M., Dillon H., Seymour J. & Carter L. 2009. The detection of adult cortical auditory evoked potentials (CAEPs) using an automated statistic and visual detection. *Int J Audiol*, 48, 833–842.

Golding M., Dillon H., Seymour J., Purdy S. & Katsch R. 2006. Obligatory cortical auditory evoked potentials (CAEPs) in infants: A five year review. *National Acoustic Laboratories Research & Development Annual Report 2005/2006*, 15–19.

Golding M., Pearce W., Seymour J., Cooper A., Ching T. et al. 2007. The relationship between obligatory cortical auditory evoked potentials (CAEPs) and functional measures in young infants. *J Am Acad Audiol*, 18, 117–125.

Gravel J.S., Kurtzberg D., Stapells D.R., Vaughan H.G. & Wallace I.F. 1989. Case studies. *Semin Hear*, 10, 272–287.

Hyde M. 1997. The N1 response and its applications. *Audiol Neurootol*, 2, 281–307.

Korczak P.A., Kurtzberg D. & Stapells D.R. 2005. Effects of sensorineural hearing loss and personal hearing aids on cortical event-related potential and behavioral measures of speech-sound processing. *Ear Hear*, 26, 165–185.

Kurtzberg D. 1989. Cortical event-related potential assessment of auditory system function. *Semin Hear*, 10, 252–261.

Purdy S.C., Katsch R., Dillon H., Storey L., Sharma M. et al. 2004. Aided cortical auditory evoked potentials for hearing instrument evaluation in infants. In: R.C. Seewald & J.M. Bamford (eds.), *A Sound Foundation through Early Amplification.* Proceedings of the Third International Conference, Stafa, Switzerland: Phonak AG, pp. 115–127.

Rance G., Cone-Wesson B., Wunderlich J. & Dowell R. 2002. Speech perception and cortical event related potentials in children with auditory neuropathy. *Ear Hear*, 23, 239–253.

Rapin I. & Graziani L.J. 1967. Auditory-evoked responses in normal, brain-damaged, and deaf infants. *Neurology*, 17, 881–894.

Seewald R., Moodie S., Scollie S. & Bagatto M. 2005. The DSL method for pediatric hearing instrument fitting: historical perspective and current issues. *Trends Amplif*, 9, 145–157.

Sharma A., Dorman M.F. & Spahr A.J. 2002. A sensitive period for the development of the central auditory system in children with cochlear implants: Implications for age of implantation. *Ear Hear*, 23, 532–539.

Sharma A., Martin K., Roland P., Bauer P., Sweeney M.H. et al. 2005. P1 latency as a biomarker for central auditory development in children with hearing impairment. *J Am Acad Audiol*, 16, 564–573.

Tremblay K.L., Kalstein L., Billings C.J. & Souza P.E. 2006. The neural representation of consonant-vowel transitions in adults who wear hearing aids. *Trends Amplif*, 10, 155–162.

Yoshinaga-Itano C., Sedey A., Coulter D. & Mehl A. 1998. Language of early- and later-identified children with hearing loss. *Pediatrics*, 102, 1161–1171.